VR Enhanced Upper Extremity Motor Training for Post-Stroke Rehabilitation: Task Design, Clinical Experiment and Visualization on Performance and Progress

Shih-Ching Yeh[1], Albert Rizzo[2], Margaret McLaughlin[1], Thomas Parsons[2]
[1]Integrated Multimedia Systems Center, [2] Institute for Creative Technologies
University of Southern California
shihchiy@usc.edu , arizzo@usc.edu, mmclaugh@usc.edu, TParsons@ict.usc.edu

1. Background &Overview

Stroke is the leading cause of serious, long-term disability among American adults. Each year over 700,000 people suffer a new or recurrent stroke, and nearly 500,000 (71%) survive with some form of enduring neurological disability. Upper extremity (UE) motor impairment is a common consequence of stroke and often produces significant challenges for patients as they engage in everyday instrumental activities of daily living [1][2]. Fortunately, research has shown that such lost UE function can be recovered or improved via systematic, repetitive and task-oriented motor training. However, motor-training tasks used for conventional therapy are questionable due to limited capacity to systematically control stimulus presentations and to precisely capture motor response performance in real time. Virtual reality (VR) enhanced motor training is an emerging therapeutic modality that can serve to deliver UE motor training tasks within consistent, yet modifiable simulated functional environments that mimic real world challenges [3][4]. Further, with the use of advanced sensing systems in VR, a large quantity and wide variety of high quality data can be captured to serve the rehabilitation process. As well, game features can be integrated into the VR training to enhance motivation and promote therapeutic focus and adherence.

We build a VR interactive task: Static Reaching Task. It is designed to have patients reach multiple virtual targets in 3D space with synchronized forearm and hand movement on their paretic side, shown in Fig. 1. The challenges in developing and applying such a system to stroke rehabilitation are addressed below. 1) What strategies we can conduct the precise translated between real world and virtual movements so as to actively drive the patient's behavior? 2) What general forms of kinematic measures can be defined or derived via collected data so as to suitably represent the patient's behavior? 3) How can we quantitatively detect the patient's current status or evaluate the patient's progression via the use of such a VR interactive system?

In this paper, we first describe the system architecture with respect to each division's design and implementation so that it can meet the challenges 1) mentioned above. Then we introduce a variety of interaction measures with regard to their definition, derivation and representation so as to meet the challenge 2). Next we describe a clinical pilot test on stroke patients. And we propose a methodology to detect and visualize the patient's current status and progression via the collected data, in response to challenge 3).

Fig. 1

Given :
Shoulder Position : (x_s, y_s, z_s)
Pitch Angle : A_p
Yaw Angle : A_y
Entension Length : L

Assume :
T arg etPosition : (x_t, y_t, z_t)

Then :

$$x_t = x_s + L\cos(A_p)\cos(A_y)$$
$$y_t = y_s + L\sin(A_p)$$
$$z_t = z_s + L\cos(A_p)\sin(A_y)$$

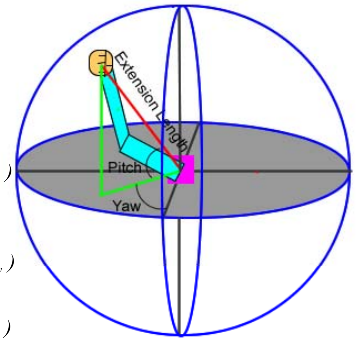

Fig. 2

2. Design of VR System

To construct such an interactive virtual environment, shutter glasses are used to perceive the 3D world of virtual environment and the tracking device, Flock of Birds, is used to interact with virtual environment. Within the virtual environment, multiple cube-shaped targets are distributed simultaneously in 3D space. The subject, with trackers attached to his hands, has to extend the forearm to reach any one of the targets as desired without order requirement. The subject's hand has to move back to a start position between each reaching task.

The target position is a crucial factor in detecting the patient's ability to reach a specific zone in 3D space. It is positioned in a semi-spherical zone that is calibrated to each patient's current range of motion. A certain location within the semi-spherical zone requires a specific combination of pitch, yaw and extension of arm length. Thus, difficulity level can be distinguished according to various settings of the target's position via pitch, yaw and extension of arm length. The algorithm to set the position of the target is given in Fig. 2.

A mapping mechanism is carefully designed to convert measures from the physical world to the virtual environment. An accurate mapping can ensure that the system will drive the patient's activity such that he/she will behave in a way dictated by the therapist's rehabilitation design. First, target position in virtual world has to be allocated accurately with respect to the shoulder joint in real world. Thus, the tracker is put on the patient's shoulder joint upon the activation of program so as to set the initial position, shown in Fig. 3. And the arm length is measured. Second, the hand must have a fixed starting position in the physical world for each trial so that performance can be compared among trials. Thus, the start position in the virtual environment has to map with the start position in the physical world. Visual signs are given in both virtual environment and real world, shown in Fig. 4.


Fig. 3

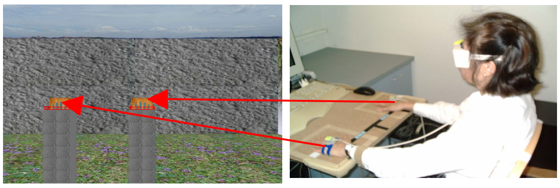
Fig. 4

3. Kinematic Measures

Kinematic measures are designed to evaluate the patient's behavior quantitatively. Status or progression can be visualized from these kinematic measures. Three types of kinematic measures are defined and used: performance time, movement efficiency and moving speed. They are derived from the position and orientation data of the hand tracker, recorded through the whole operation period at a data acquisition rate 60Hz.

Performance time (PT) is defined as the period between the time when the virtual hand started to move from the start position and the time the virtual hand reaches a target in 3D space. It is an index to indicate the moving speed without regard to the moving path. A lower value reveals a higher speed.

Movement efficiency (ME) is defined as the ratio of the actual moving path over the shortest moving path. The shortest moving path is the linear distance between the start position and the position of the virtual target. The actual moving path is the accumulation of linear distance for each time interval through the process of reaching. ME is an index of the patient's moving stability. A lower value of ME indicates a better moving stability.

Moving speed (MS) is defined as the ratio of the actual moving path over performance time. It is an index to indicate moving speed with respect to the moving path. Further, it is in direct proportion to ME while it is in inverse proportion to PT. Thus, it can also represent the integration of speed and stability. A higher value implies a greater degree of integrated speed and stability.

The equations to calculate ME and MS are given in Fig. 5.

4. Clinical Pilot Test

A three-month clinical experiment using this VR task (along with 3 others) was conducted from the USC Keck School of Medicine. Time since the stroke and severity of impairment are the two crucial factors that determine the extent to which patients can hope to improve motor function through the therapeutic process. Thus, the patient who volunteers to be a subject must first be screened. We first screened patient volunteers to see if they could meet the inclusion criteria: 1) stroke at least one month prior to the pilot trial; 2) over the age of 18 years; 3) able to attend 12 training sessions. Subjects were also examined to see if they had a Mini-Mental Status Exam score below 24, significant limitations in passive range of motion, or no active movement in the hemiparetic UE. Five subjects passed the screening and participated in the test. On the first day of participation, the subject was introduced to the VR task, the dynamic reaching test, and tried it out. After the learning session, the subject attended 12 training sessions. Assistance was provided by a physical therapist to avoid any improper movement that might cause pain or injury. Simultaneously, behavioral assessments were applied at three points: pre-training, mid-training (between the 6th and 7th visits) and post-training. Motor performance was evaluated via a standard arm function test: TEMPA. Severity of motor deficit was determined with the UE portion of the Fugl_Meyer [5], a measure of motor function.

5. Case Study: Visualization of Status &Progression

To visualize the current status in regard with each kinematic measure, we map each target's 3D position onto one zone in a pitch-yaw 2D chart that is then coordinated with each kinematic measure to generate a 3D performance map, shown in Fig. 6. Performance of each practice session, containing twenty targets in 3D space, can be visualized via a single performance map. And progression can be visualized from a set of performance maps across different time points. Moreover, all values are classified into three levels and labeled with different colors where red, blue and green stand for "Excellent", "Good" and "Fair" respectively. Further, the trend line across different time points can be derived via the average value of each practice session for each kinematic measure.

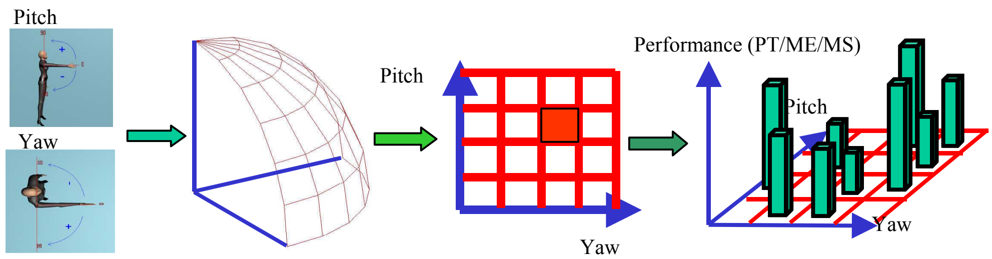

Fig. 6

Since a huge amount of data is collected, subject 103 with one single test case with reaching range 45%~60% (expected extension of arm-length ratio) is selected for case study and representing test results. The information of this selected test case (twenty targets) is presented in Fig. 7. This selected test case is practiced five times as listed in Fig. 8.

The performance maps of kinematic measure MS, for all practice sessions, are displayed in Fig. 9. It shows that most zones turn into "Excellent" level after five practice sessions while half of them are at "Good" level and the other half are at "Fair" level at the first practice session. The trend line, shown in Fig. 10, also shows that average performance of PT is in a positive trend toward better performance from first practice session to fifth practice session. Namely, performance PT is improved after five practice sessions.

```
Trial size  pit   yaw   % of arm length
1     3     15    45    45
2     3     15    -15   60
3     3     0     60    50
4     3     45    75    45
5     3     30    45    50
6     3     15    90    60
7     3     75    60    60
8     3     0     75    60
9     3     0     45    45
10    3     75    45    50
11    3     15    60    45
12    3     60    30    50
13    3     0     15    45
14    3     0     30    60
15    3     15    30    50
16    3     90    15    50
17    3     30    30    45
18    3     60    60    60
19    3     45    15    45
20    3     0     -15   50
```

Fig. 7

$$ME = \frac{Actual\ Moving\ Path}{Shortest\ Path} \qquad MS = \frac{Actual\ Moving\ Path}{Performance\ Time}$$

Fig. 5

Session ID	Date
PS1	02-21-06
PS2	02-22-06
PS3	02-28-06
PS4	03-01-06
PS5	03-03-06

Fig. 8

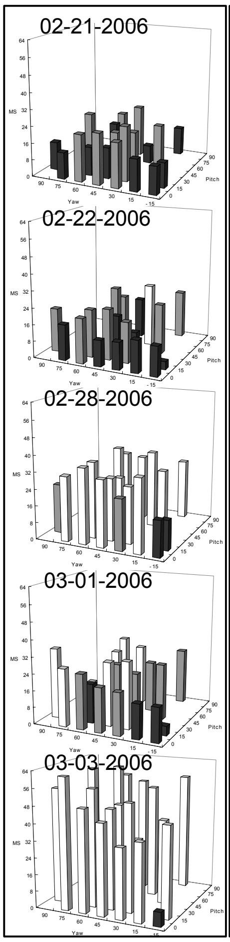

Fig. 9 MS

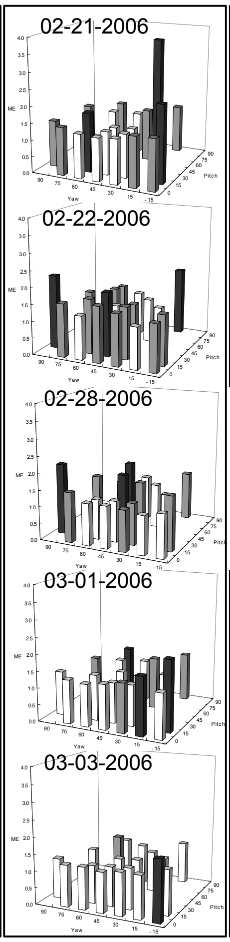

Fig.11 ME

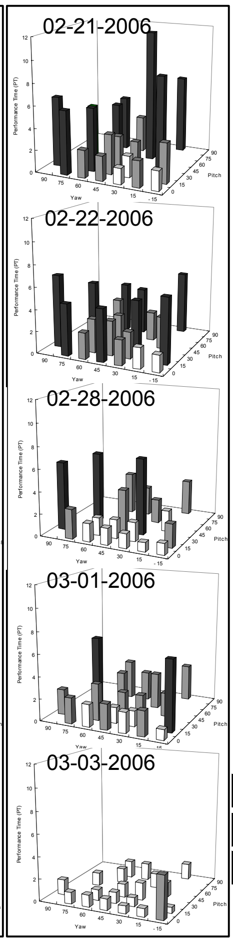

Fig. 13 PT

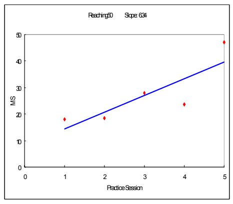

Fig. 10

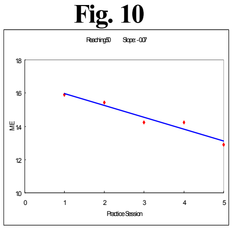

Fig. 12

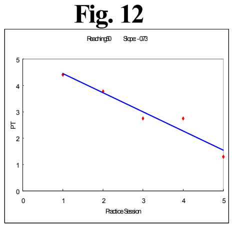

Fig. 14

(white)	MS>27	ME<1.4	PT<2
(grey)	19<MS<27	1.4<ME<1.7	2<PT<4
(black)	MS<19	ME>1.7	PT>4

Fig. 15 Level Classification

The performance maps of kinematic measure ME, for all practice sessions, are displayed in Fig. 11. It shows that the percentage of “Excellent” level is increased after five practice sessions. The trend line, shown in Fig. 12, also shows that average performance of ME is in a negative trend toward better performance from first practice session to fifth practice session. Namely, performance ME is progressed after five practice sessions.

The performance maps of kinematic measure PT, for all practice sessions, are displayed in Fig. 13. It shows that most zones turn into “Excellent” level at fifth practice sessions. The trend line, shown in Fig. 14, also shows that average performance of PT is in a negative trend toward better performance from first practice session to fifth practice session. Namely, performance PT is advanced after five practice sessions.

Further, they are classified into three levels and labeled with different textures in each Fig., shown in Fig. 15.

6. Conclusion &Future work

A VR enhanced upper extremity motor training task is designed well both in patient-specific need and in therapy perspective. The system equippes with an important feature which is the capability to actively drive human kinematic behavior via a combination setting of environmental parameters. Further, it is successfully applied to a clinical pilot test on five stroke patients.

Representative kinematics measures: Performance Time, Movement Efficiency and Moving Speed are defined suitably to represent kinematic features. Methodology is proposed to visualize the status and progression on a base of kinematics measures. The case study clearly reveales the patient’s current status of hand arm movement with respect to his/her motion range composed of pitch, yaw and arm length. Further, progression is found and visualized quantitatively over a series of practice sessions on all three kinematic measures.

In regard with the future work, new technology advances need to be investigated such that system interfaces, such as 3D displays or tracking devices, can be replaced with more portable and cheaper devices. Such efforts can pragmatically evolve this interactive system into a home based rehabilitation tool. A larger scale clinical test on a larger sample of patients and with healthy controls is underway so that the functionality of the system can be verified and/or improved. Further, automatic diagnostic tools that measure current status and progression are being developed in our lab for future clinical use.

Reference

1. Mayo NE, Wood-Dauphinee S, Cote R, Durcan L, Carlton J. Activity, participation, and quality of life 6 months poststroke. Arch Phys Med Rehabil. 2002;83:1035-1042.
2. Jonsson AC, Lindgren I, Hallstrom B, Norrving B, Lindgren A. Determinants of quality of life in stroke survivors and their informal caregivers. Stroke. 2005;36:803-808.
3. Holden MK. Virtual environments for motor rehabilitation: review. Cyberpsychol Behav. 2005:8 (3):187-211.
4. Weiss PL, Katz N. The potential of virtual reality for rehabilitation. J Rehabil Res Dev. 2004;41 (5):vii-x.
5. Fugl-Meyer AR, Jaasko L, Leyman, I, Olsson S, Steglind S (1975). The post-stroke hemiplegic patient. 1. A method for evaluation of physical performance. Scand J Rehab Med, 7, 13-31.