An Integrated System: Virtual Reality, Haptics and Modern Sensing Technique (VHS) for Post-Stroke Rehabilitation

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ABSTRACT

In this paper, we introduce an interdisciplinary project, involving researchers from the fields of Physical Therapy, Computer Science, Psychology, Communication and Cell Neurobiology, to develop an integrated virtual reality, haptics and modern sensing technique system for post-stroke rehabilitation. The methodology to develop the system includes identification of movement pattern, development of simulated task and diagnostics. Each part of the methodology can be achieved through several sub-steps that are described in detail in this paper. The system is designed from Physical Therapy perspective that can address the motor rehabilitation needs of stroke patients. The system is implemented through stereoscopic displays, force feedback devices and modern sensing techniques that have game-like features and can capture accurate data for further analysis. Diagnostics and evaluation can be made through an Artificial Intelligence based model using collected data and clinical tests have been conducted.

Categories and Subject Descriptors

H.5.2 **[Information Interfaces and Presentation]**: User Interfaces - Evaluation/methodology, Haptic I/O, User-centered design

J.3 **[Computer Applications]**:Life and Medical Sciences – Health

General Terms

Measurement, Experimentation, Human Factors

Keywords

virtual reality, haptics, visual sensing, stroke rehabilitation, physical therapy

1. INTRODUCTION

Stroke has been the leading cause of severe, long-term disability among American adults [1]. During the early post-stroke period, the impaired limb is not completely paralyzed but has limited movement capability. Studies show that the loss of function can be improved with rehabilitation therapy through some type of intensive practice [1]. However, such therapy requires physical motor action that is sometimes limited by the patient's motivation. As well accurate measurement of motor action is required to produce data for diagnostics and evaluation. The integration of virtual reality, haptics and modern sensing technology can be a potential way to address these challenges.

2. METHODOLOGY TO DEVELOP SYSTEM

2.1 Methodology

The methodology to develop the system is shown as Figure 1.

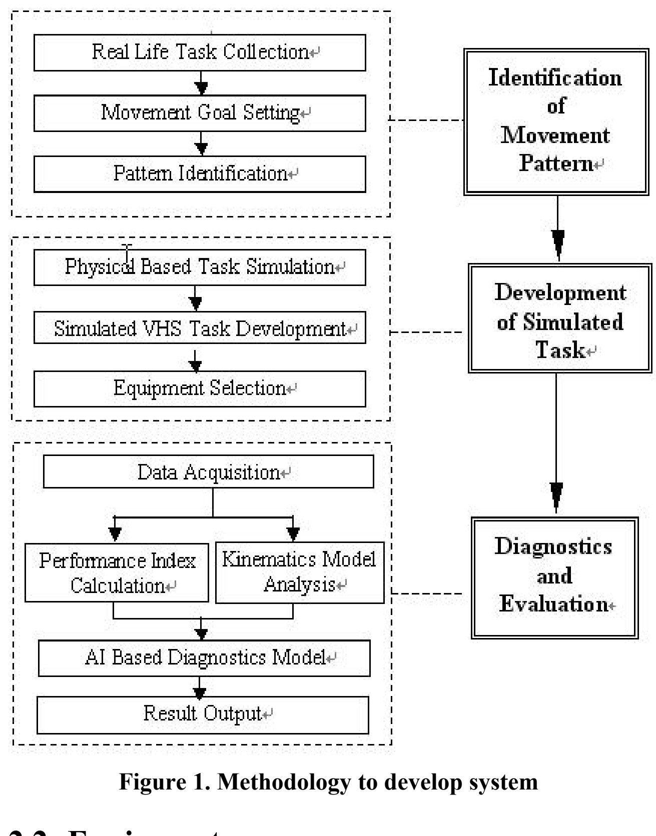

Figure 1. Methodology to develop system

2.2 Equipments

Stereoscopic displays, force feedback devices and a Sensing/Tracking system are used for task simulation. Equipment is selected based on the fit of simulated task features, shown in Tables 1-3.

Table 1. Display Required Features

Display	Required Features
Head Mounted Display	Panoramic view
Auto-Stereo Display	No glasses
Shutter Glasses	Wider range of sweet spot

Table 2. Force Feedback Device Required Features

Force Feedback Device	Required Features
PHANToM	Single tip or dual tips operation
CyberGrasp	Hand operation

Table 3. Sensing / Tracking System Required Features

Sensing / Tracking System	Required Features
Magnetic Tracking System	Multiple points 6DOF data
Visual Sensing System [2]	Visual hull data

3. SYSTEM DEVELOPMENT

3.1 Identification of Movement Pattern

Six patterns of movement are identified according to their functional goals derived from daily real-life tasks, shown in Table 4. In general, these tasks are simulated via physical tools for stroke patients to practice motor actions. However, these traditional physical based rehabilitation tasks do not typically provide accurate measurement of motor movement, such as fingertip force or 6 DOF joint action needed to evaluate change in performance during stroke rehabilitation. Through Virtual-Haptics-Sensing (VHS), tasks for each pattern movement are simulated and various types of data are collected. Also, analysis models are developed for diagnostics and evaluation using collected data.

Table 4. Identification of movement goal

Movement Pattern	Movement Goal	Real-Life Tasks
Isolated Finger Movement	Press, Point, Lift	Press a button, Point to a spot on plan, Lift a switch
Coordinated Thumb and Index Movement	Pinch, Squeeze	Pinch a solid object, Squeeze a plastic bag
Coordinated Single Hand Movement	Grasp	Grasp a bottle
Wrist/Forearm Movement	Twist	Twist a screw driver
Coordinated Arm and Shoulder	Extend, Stretch	Hang a map on the wall
Coordinated Torso and Limb Movements	Posturize	Greeting

3.2 Development of Simulated Task

3.2.1 Isolated Finger Movement

Two tasks, "Ball Array" and "Space Tube", are developed for isolated finger movement, as shown in Figures 2-3. These two tasks are operated through a single PHANToM device where a finger adapter is attached (see Figure 4). In these applications, HMD, auto-stereoscopic display or shutter glasses can be used to perceive a 3D stereo effect.

The task, "Ball Array", requests user to navigate through 3D space, with a claw, to reach several specified flashing targets while avoid touching non-target balls in the array. After reaching the target, it is attached to the claw and the user's fingertip can perceive the weight of the target. The user then has to move the target into a trashcan. Hierarchical difficulty levels of challenge can be created by manipulating the weight of the target and the size and distribution of the "obstructing" ball array.

The task, "Space Tube", requires the user to move a ball through a 3D tube maze. There are several barriers that are set inside the tube that the user has to push through in the course of completing the maze. Again, hierarchical difficulty levels of challenge can be created by manipulating the size and configuration of the tube maze, the weight and size of the ball and the required pushing force to break through the various barriers.

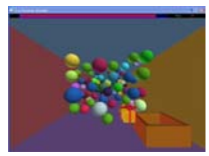
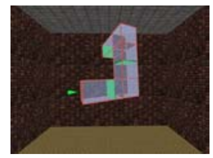


Figure 2. Ball Array Figure 3. Space Tube Figure 4. Finger operation

3.2.2 Coordinated Thumb and Index Movement

The "Pinch and Squeeze Cube" task, was developed to test and train coordinated thumb and index movement, (see Figure 5). It is operated through the integration of dual PHANToMs which interface with the thumb and index fingers, as shown in Figure 6. This application can run on an HMD, autostereoscopic display or with shutter glasses to perceive a 3D stereo effect.

The task requires the user to handle a clamp to pinch a cube and squeeze it, such that the cube can be placed into a hall with a specified width. While pinching the cube, the user can perceive the weight of the cube and the cube appears to be deformed while it is "squeezed". Variables such as the weight and size of the cube, friction of the cube surface and width of the hall target space can be adjusted to manipulate difficulty level.


Figure 5. Pinch Cube Figure 6. Finger & Thumb operation

3.2.3 Coordinated Single Hand Movement

The task, "Object Grasping", was developed for coordinated single hand movement, as shown in Figure 7. The Cyber Grasp is used for the task operation (see Figure 8) and either an HMD, autostereoscopic display or shutter glasses can be used to perceive the 3D stereo effect.

The task requests user to grasp objects that are of different shapes and sizes. During the task operation, user can perceive the shape and size of the object and these factors are manipulated to create hierarchical movement challenges.


Figure 7. Object Grasping Figure 8. Hand operation

3.2.4 *Wrist/Forearm Movement*

The task, "Spatial Rotation", was developed for wrist/forearm movement [3] rehabilitation, as shown in Figures 9-10. A magnetic tracker is attached to different real life objects that the user can hold in their hand to acutate the graphic objects on the screen

In this task, two sets of blocks with the same configuration appear on the screen in different orientations. One of them is a static target configuration and the user is required to translate and rotate the other identical block into superimposition with the target. Through the holding of real life objects, the user can practice the activity in a manner more relevant to real world grasping challenges. Difficulty level can be manipulated in terms the complexity of the block configuration, block orientation settings, and relative position between two blocks

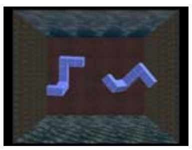

Figure 9. Spatial Rotation **Figure 10. Wrist operation**

3.2.5 *Coordinated Arm and Shoulder Movement*

The "Object Reaching" task was developed for coordinated arm and shoulder movement training, as shown in Figures 11-12. A Head Mounted Display (HMD) is used to perceive 3D stereo and a panoramic 6DOF effect. Two magnetic trackers are used to track the left and right hands for interaction and one tracker is attached to the HMD to track head movement. The task requires the user to stretch their arms in a specified orientation and distance so that the hand can reach specified targets distributed in 3D space. The user can intuitively perceive the target space while performing wide range rotation of the shoulder and extension of arm. Orientation of the target and distance between hand and target are the most important variables used to manipulate difficulty.

3.2.6 *Coordinated Torso and Limb Movements*

The "Ball Shooting" and "Social Interaction" tasks were developed for coordinated torso and limb movement, as shown in Figures 13-16. The user's torso and limb movement are detected through a modern visual sensing system that requires no markers or sensors attached to the user see Figures 14 and 16. Through the captured video from multiple cameras, 3D visual hull data can be reconstructed in real time. Aa advanced posture recognition technique is applied so that user's posture can be recognized in real time. Either an HMD, autostereoscopic display or shutter glass can be used to perceive the 3D stereo effect.

The task, "Ball Shooting", requires the user to move their torso and arm simultaneously to reach a ball shooting from the wall. Since the ball is moving dynamically, a synchronized movement of the torso and limb is required for successful task perfomance. Speed, start position and target position of the ball (vector path) are critical variables for manipulating the difficulty level of the task. Further, since there is nothing attached to the user, they can move in a more naturalistic, unencumbered fashion.

The task, "Social Interaction", requires user to interact with the virtual actor using some specified postures. These specified postures are designed to be relevant in daily life.

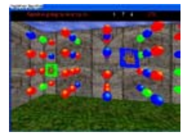

Figure 11. Object Reaching **Figure 12. Arm and shoulder operation**

Figure 13. Ball Shooting **Figure 14. Torso and limb movement**

Figure 15. Social Interaction **Figure 16. Posture recognition**

3.3 Data Acquisition and Performance Index

3.3.1 *Isolated Finger Movement*

In both tasks, time history of fingertip position (x,y,z) is recorded such that the trajectory of the finger can be reconstructed for further analysis. Reaction time is measured to evaluate movement efficiency. Number of collisions with the ball array or tube wall is counted to evaluate the fluid coordination of finger movement.

3.3.2 *Coordinated Thumb and Index Movement*

Time history of force exerted on the target cube is recorded to evaluate the continuity or discontinuity of force output. Also, time history of the two fingertip positions are recorded to reflect the synchronization between thumb and index fingers. Reaction time is measured to evaluate movement efficiency.

3.3.3 *Coordinated Single Hand Movement*

Successful grasping is an index to evaluate performance on this task along with reaction time to evaluate movement efficiency. Time history of the orientation (rx, ry, rz) for each joint on the hand is recorded to provide the information needed to reconstruct a kinematics model for movement analysis.

3.3.4 *Wrist/Forearm Movement*

Twist range is the main index to indicate user's wrist capability (i.e. supination/pronation). This can be tested through various settings of the rotation angle about the arm axis. The length of real movement path is calculated so that it can be compared with the shortest length of path as an index of efficiency. Reaction time is measured as an index of speed. Time history in 6DOF space is recorded to reconstruct the trajectory of wrist/forearm movement.

3.3.5 *Coordinated Arm and Shoulder Movement*

Extension range across different orientations is used to quantify the user's arm and shoulder movement capability. It can be tested through various settings of the target position distributed in 3D space. Time history in 6DOF space for each tracker is recorded to reconstruct the trajectory of coordinated arm and shoulder movement for movement analysis.

3.3.6 *Coordinated Torso and Limb Movements*

Extension range, movement speed and efficiency are the main indexes to evaluate coordinated torso and limb activity. With the "Ball Shooting" task, extension range can be tested through the various setting of ball speed and trajectory. Movement speed and efficiency can also be derived from 3D visual hull data. Further, complicated synchronization between torso and limb movement can be evaluated through various posture settings in the "Social Interaction" task.

4. CLINICAL PILOT TEST

Pilot test, using the "Spatial Rotation" and "Space Tube" tasks, has been conducted on two volunteer stroke patients who are currently receiving therapy from a neurorehabilitation center at the University of Southern California (USC) (see Figure 17). Based on survey questionnaire data, both patients and therapists are reporting moderate to high levels of satisfaction with our initial VHS-based tasks and this user-centered feedback is incorporated into our iterative design cycle to evolve the systems.

Figure 17. User-Centered Pilot Testing

5. DISCUSSION AND FUTURE WORK

5.1 System Features

1) Patient and Therapist User-Centered Design: Both of these user group are providing key feedback to evolve our system design for the needs of stroke patients.

2) Game-Like Tasks Design: Tasks are built within a game format and include various sound and visual effects. This provide necessary performance feedback for rehabilitation purposes and can serve as a perceptual guide to help users achieve success. Actual performance measures are converted into scores or credits that motivate patients to practice repeatedly.

3) Communicative Interaction Design: The Patient-User can communicate with the therapist and from a remote site computer. All conversation can be recorded and stored into database in real time through "Audio-Peer" technology developed at our center. While the patient operates the task from a remote site, the therapist can view performance in real time on the screen and also provide appropriate feedback when needed. Speech recognition is also used to help patients operate the interface.

4) 3D Stereoscopic Perception: Perception of 3D stereo is a crucial factor to simulate ecological real-world factors in a virtual environment. The task simulation of partial or whole body movement accompanied with 3D stereo effects may also enhance the sense of "presence" in these virtual environments.

5) Force Feedback Perception and Measurement: Force feedback effects can help user to feel the "touch" of virtual object. Further, quantitative reaction force output design can require the user to exert variable force on virtual objects through specific wrist, arm or elbow movement. Also, force and torque history can be measured and recorded. That is a key way to detect, test and/or quantify the user's level of impairment.

6) User Body Motion Tracking: Impairment levels of the users can be detected not only from measurement of force output but also from analysis of kinematics models. Body motion tracking is also a key method to develop kinematics model.

7) Kinematics Based Analysis Model: Most movement patterns require the coordination between several elements of the body. Information of single elements in isolation is typically not sufficient for diagnostic purposes. Through the analysis of kinematics models more relevant information can be captured to detect impairments relevant to real world functioning.

8) Artificial Intelligence (AI) Originated Diagnostics System: Tremendous amounts of data, such as force, torque, position and orientation, are collected at a high sampling rate. How to mine important information for correct diagnostics is the key toward a successful system. Modern AI techniques, such as fuzzy logic, neural network or data mining, can be applied to develop a reliable diagnostics system.

5.2 Future Work

AI-based diagnostic models still need to be built to advance the development of the system. Large-scale clinical trials will have to be conducted so that the functionality of the system can be verified and/or improved. More VHS based tasks are also being developed to maximize the systems capacity to comprehensively address the complex and unique needs of individual patients.

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