Haptic-based Virtual Environment Design and Modeling of Motor Skill Assessment for Brain Injury PatientsRehabilitation

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ABSTRACT

This paper presents a new haptic-based virtual environment system for diagnosis and rehabilitation of Traumatic Brain Injury (TBI) patients. By using the latest technologies, including Virtual Reality (VR), haptic force feedback and telecommunications, the system can work as an alternative to traditional labor intensive and expensive diagnosis and rehabilitation procedures for TBI patients. This paper also introduces a general approach to the design and prototyping of a haptic-based VR system for motor skill assessment and rehabilitation. A numerical model is presented to describe and record the motor skill assessment results and parameterize the rehabilitation training process. The prototype system demonstrates the potential for using advanced information and haptic-based VR technologies to build more effective and intelligent tools for healthcare. The specific techniques developed in this research can be used for motor-skill evaluation in clinical practice.

Keywords:haptic interface, virtual reality, Rey-Osterrieth Complex Figure (ROCF)
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1 INTRODUCTION

In the last decade, virtual reality (VR) has been used in healthcare systems to visualize complex medical data and for surgery planning [4,2,10,]. The application of VR in healthcare has mainly focused on three areas: surgery training, surgery planning and augmented reality for open surgical procedures,endoscopy and radiosurgery [11,15,16,20,38]. In the last few years, researchers have begun to recognize the potential for applying VR and haptics technologies to neuropsychological assessment and rehabilitation [7,24,26]. Haptic devices have been used in, for example, handwriting training and recognition studies [16, 25, 27]. Haptic-based VR, combined with 3D visual rendering, and deformable object modeling, provides a perceptually-complete basis for new applications like this both in industry and research. Figure 1 shows an example lab set up of a desktop haptic device witha 3D stereoscopic visual display used for VR-based surgery simulation [10, 12,13].

Fig. 1:Haptic interface with 3D stereoscopic visual display for surgical cutting training application.

According to projections on the future of psychotherapy, the use of VR and computerized therapies are ranked third and fifth, respectively, out of 38 psychotherapy interventions predicted to increase within the next 10 years [17]. For any motor skillor psychological tests or treatments, VR has advantages, including: supporting a variety of procedures of interventions for psychological distress, the possibility of structuring a large number of controlled stimuli for psychological tests and simultaneously monitoring user responses to test stimuli generated by the VR systems [21].

In the US healthcare system, many patients are currently suffering from Traumatic Brain Injury(TBI). For example, in Veterans Administration (VA) hospitals, soldiers returning from oversea battlefields may have minor TBI due to concussive incidents. More patients suffer from brain injury than any other types of diseases. Other TBI patients have severe conditions, which require surgery, brain scans, neuropsychological tests, even life time rehabilitation treatments. The current diagnosis and rehabilitation therapies for brain injured patients are costly. Professionally trained neuropsychologist and therapists are needed. And the working time on each patient can be long, based on the nature of the assessment procedure and therapy.

For these reasons, we sought to develop a new haptic-based VR system for assessment and rehabilitation of motor skills in TBI patients. By using contemporary computing technologies, including VR, haptic rendering and telecommunications, the new system is expected to serve as an alternative to traditional labor intensive and expensive diagnosis and rehabilitation procedures. This study also introduces a general approach to the design and prototyping of such a haptic-based VR system for motor skill assessment and rehabilitation. Details of the development of the system are presented in the following sections.

2 DIAGNOSIS AND REHABILITATION OF TRAUMATIC BRAIN INJURED PATIENTS

2.1 Overall System Design for Diagnosis and Rehabilitation of TBI Patients

Neuropsychology is an applied science that evaluates how specific activities in the brain are expressed through observable behaviors [9,10]. Traumatic Brain Injury patients typically go through a series of neuropsychological testing to specify impairment level attributable to their injury in various cognitive domains, including attention, memory, executive control, language, constructional praxis and motor functioning[9]. Effective neuropsychological assessment is a prerequisite for the treatment and scientific analysis of any neurologically-based cognitive impairment. The neuropsychological assessment for these patients serves a number of functions including: (1) assisting in determining a diagnosis; (2) provision of normative information on the status of cognitive and functional abilities; (3) assistance in producing guidelines for the design of rehabilitative strategies; and (4) creation of data for the scientific understanding of brain functioning through the examination of different types of brain damage or dysfunction [28].

In this research, the functions of neuropsychological assessment and therapy have been integrated in the prototype system. This integration may benefit treatment therapy in terms of patient progress tracking and support flexible, customized therapy design. It may also save time and money by reducing the information communication costs between diagnosis and rehabilitation processes. Figure 2 shows how the computerized system can reduce repetitive work of neuropsychologists (grey blocks) by automating testing and scoring processes. More importantly, it presents how various data can be organized in a database in order to support accuracy in communication between physicians. In this way, the developed system can be considered as a communication tool. When performed on the VR system, the therapy process is also simplified by use of programmable parameter controls. The results of these processes can be sent to an external server and provide an extension to current Electronic Medical Record (EMR) system content. Physicians can then review these data, along with other important medical information for a patient to prescribe a therapy regimen. The parameters of the system can then be set for a specific patient's therapy regimen.

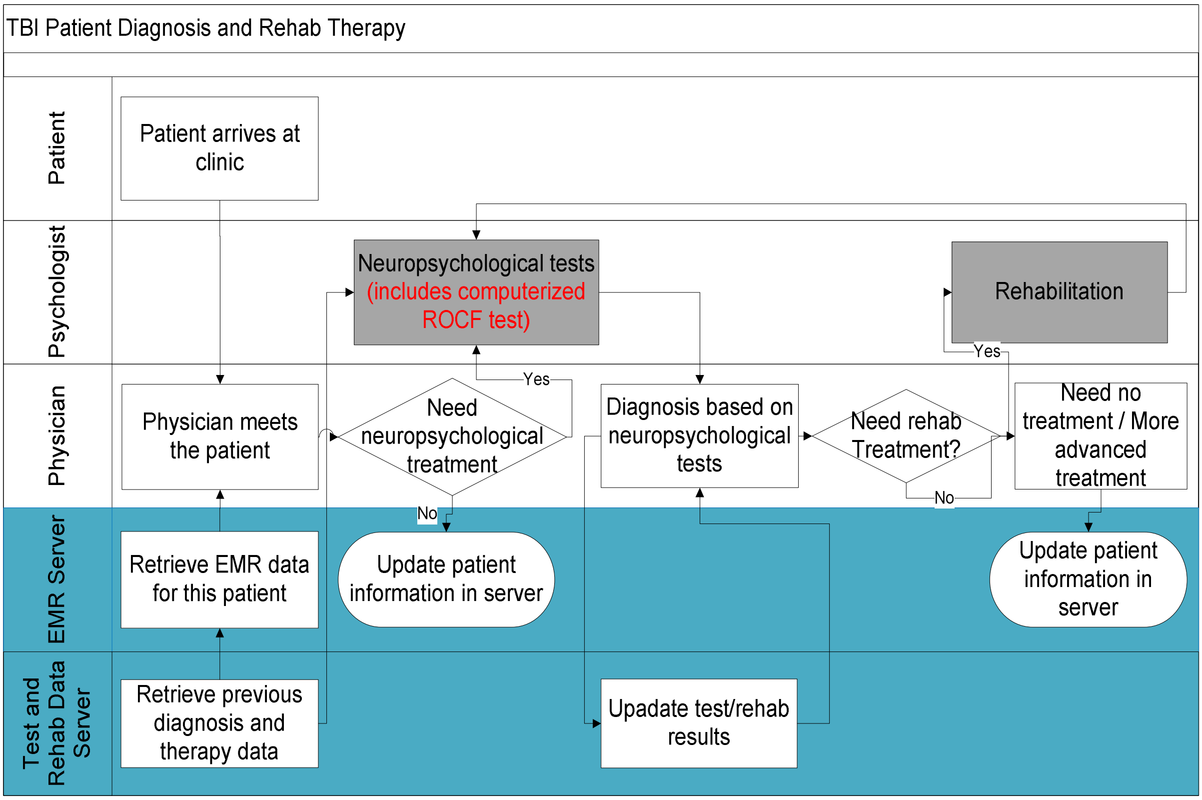


Fig. 2: Data flow for patient diagnosis and rehabilitation therapy using computer-based system.

2.2 Neuropsychological Test and Rey-Osterrieth Complex Figure (ROCF) Test

Neuropsychological assessment (NA) uses psychometric evaluation tools to diagnose dysfunction, and specify cognitive strengths and dysfunction [22]. As shown in Figure 3, the Rey-Osterrieth Complex Figure (ROCF) test is a neuropsychological test that has been used to manually assess various cognitive operations. It is the most commonly used diagnosis tool for TBI patients in hospitals. The ROCF is composed of approximately 34 lines of varying length, plus three dots inside a circle. The determinants of ROCF drawing performance are multifactorial and reflect integrated contributions of many neurocognitive functions. Therefore, varieties of cognitive operations have been measured with ROCF tests, such as perceptual apprehension, attention and control, visual mnestic power, visual and perceptual organization, visual-constructive function and long-term spatial memory, motor functioning and memory, planning and organization, and graphomotor coordination, and results have been presented in the literature[3,5,11,7,8,19]. However, both the administration procedures and scoring systems of the ROCF can be complicated for implementation and are time-consuming [7]. In this study, the ROCF drawing test was computerized for motor skill assessment of TBI patients.

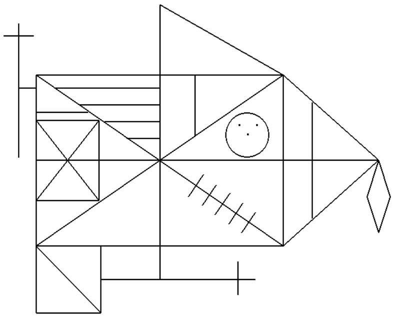


Fig. 3: The Rey-Osterrieth Complex Figure (ROCF) drawing test for brain injury patients.

3 HAPTIC-BASED VR SYSTEM FOR NEUROPSYCHOLOGICAL TESTS OF PATIENTS

The haptic-based VR system was developed to present a virtual form of the ROCF test for brain injury patients. Traditionally, ROCF tests have been performed with pen and paper. The new system was intended to be an example of radical innovation in healthcare applications.

In this study, the target users were TBI patients and cybersickness may be more of an issue for persons with cognitive limitations, in terms of being able to comprehend correspondence among perceptual cues in a VR. Considering the nature of drawing motor skills, a hybrid-design interface was developed for this study, as shown in Figure 4. The hardware system is composed of a desktop SensAble Technology Phantom haptic device on top of the workstation and a Novint Falcon haptic device (in the middle of the supporting frame) for different testing tasks. Figure 4 shows that the image of the ROCF is projected to a rear projection screen. With a 2D display, patient motor skill tests or training may be affected by the lack of depth cues in one dimension, since the motor control actually occurs in 3D. To deal with the depth cue issues, the projection system can be integrated with light shutter glasses in order to present stereoscopic images. However, VR research has revealed that common 3D displays, e.g., head mounted devices or stereoscopic goggles, can cause cybersickness [7]. The actual movement of the stylus of the haptic device to the rear projection screen can also serve as feedback on the other dimension (the depth of the drawing). Patients can actually see and feel the distance control by aligning the stylus (drawing surface) with the screen surface.

For the drawing interface design, the main reason to use a haptic device instead of, for example, a digitizer (tablet) as the input device for this system is that the haptic device has the ability to record a user’s performance in 3D space along with sequential task performance information (timing of user actions), which can provide neuropsychologists with data useful for building a patient model and performing diagnoses. Referring to the task requirements, the 3DOF (degree of freedom) movement and force feedback capabilities of the haptic device are enough for drawing tasks, since the drawing results only depend on a touching point between the pen or stylus and paper.

Fig. 4: Hardware design of ROCF test workstation.

A closeup view of the desktop Phantom haptic device atop the workstation drawing surface (solid rear projection screen) is shown in Figure 5(a). The Novint Falcon device, mounted in the frame, beneath the drawing surface is shown in Figure 5(b). The Falcon was originally developed for video gaming purposes and its performance capabilities are less than those of the Phantom. Characteristics commonly considered desirable for haptic interface devices include:

- Back-drive inertia and friction;
- Minimal constraints on user motion imposed by the device kinematics (i.e., the motion of the device feels free);
- Symmetric inertia, friction, stiffness and resonate frequency properties (thereby regularizing the device so a user does not have to compensate for parasitic forces);
- Balanced range, resolution and bandwidth of position sensing and force reflection; and
- Proper ergonomics that let the human operator focus on task performance when wearing or manipulating the haptic interface (i.e., discomfort, or even pain in use, can distract the user, reducing overall performance).

(a) Desktop Phantom haptic device

(b) Novint Falcon haptic device

Fig. 5: Haptic devices used in the VR system for drawing tests.

The developed haptic-based VR system is used for recording and scoring the patient ROCF drawing tests. Figure 6 shows the data flow in use of this system for patient diagnosis. Details of the haptic force rendering and patient drawing recording and scoring are discussed in the next section.

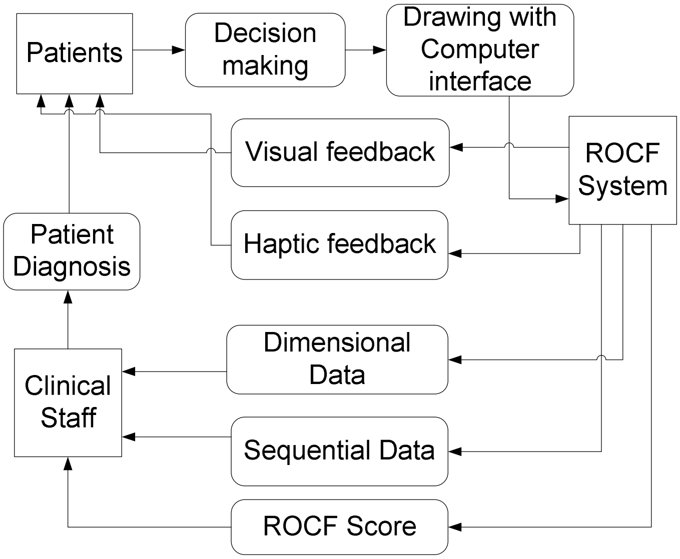


Fig. 6: Automated ROCF system data flow analysis.

4 MODELING OF MOTOR SKILL TESTING VIA THE HAPTIC-BASED VR SYSTEM

To perform a motor skill assessment with the new system, a patient completes the ROCF test with the haptic device, and their performance is evaluated in terms of three responses:

- Physical performance
- Time to completion
- Drawing accuracy and placement (drawing score)

The physical performance of drawing was assessed based on a fuzzy model of handwriting, proposed by Sano and Kishibe [11, 24]. The developed haptic-based VR system was built to record drawing time and to score the ROCF test. Patients are expected to be able to draw the ROCF with the haptic device as if they were using pen and paper. That is, the evaluation of human performance with the new system is expected to be comparable to traditional evaluations using pen and paper across the various response measures.

Figure 7 shows the force model of a simulated drawing application. The force model for the computerized ROCF drawing is not exactly same as for real drawing, when the surface is considered to be hard. For the haptic device, we calculated the normal force Fk, based on the relevant position of the stylus to the defined drawing surface. The hard surface interaction force is modeled as a plane connected to a spring and the spring constant k is applied. The haptic friction force in writing is formulated as follows:

$$F_f = \mu F_k \tag{1}$$

$$F_n = \begin{cases} 0 & if L \geq L_0 \\ k * (L - r) & if L < L_0 \end{cases} \tag{2}$$

where: Ff:is the friction force generated for haptic force feedback

μ: is the coefficient of friction, which is a constant
F_n: is the normal force
K: is the spring constant
L: is the spring length
r: is the spring resting length

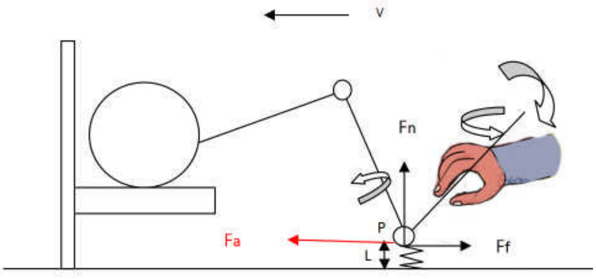


Fig. 7: Force modeling of desktop haptic device for testing applications.

Figure 8 shows the force feedback model for use of the Novint Falcon haptic device. It should be noted that there are three extra rotational degrees of freedom in the control, which are not included in the force modeling. The Phantom Desktop haptic device also provides 3-DOF in force feedback and 6-DOF in movement. Although using the stylus of the Phantom is closer in nature to pen-paper drawing, the greater degrees of freedom, compared with the Falcon haptic device, adds more complexity to the control model. Our experiment results show that users of the Phantom device exhibit some extra muscle activity for rotating, lifting, and tilting the stylus in drawing [12]. And the device may introduce distraction and slow down the testing process.

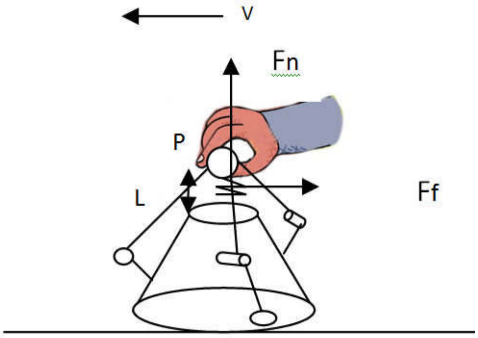


Fig. 8: Force modeling of Falcon haptic device for the testing applications.

Figure 9 presents a flow chart of the motor control process in patient drawing with the developed system. The traditional ROCF diagnosis is only based on the final output, which is a reproduction of Figure 2. For the neuropsychologist using traditional test methods, the control process in Figure 9 can be considered a “black box”. However, they must explain the inter-connections between control functions and different forms of feedback that yield the static drawing results. The new system can effectively support clinicians in the diagnosis tasks. The current system is able to track and record dynamic information on stroke trajectory, changes in trajectory, thickness and force, etc. in real time. The below equations provide a way of modeling the patient drawing behavior based on the force-feedback to users:

$$\{\boldsymbol{M}\} = \{\boldsymbol{P}, \boldsymbol{F}, t\} \tag{3}$$

where M is the quantified motor control model to be recorded in a database and P is the set of control point positions. A control point is defined in 3-D space as:

$$\mathbf{P}=(x,y,z) \tag{4}$$

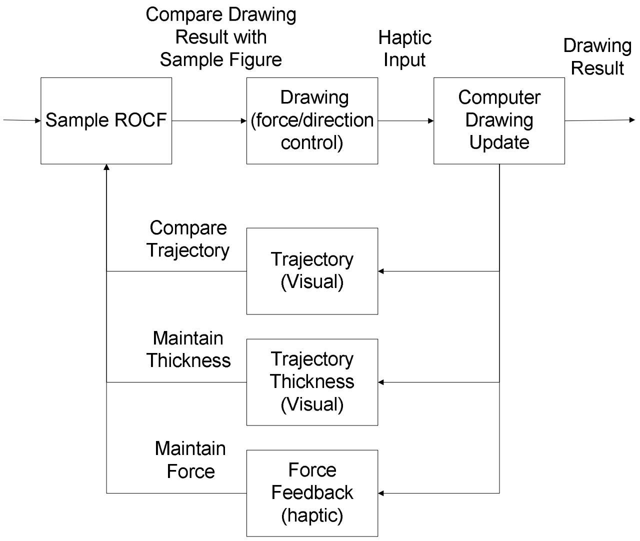


Fig. 9: Motor control model for rehabilitation training.

In Equation (3), the haptic force feedback F can be formulated as follows:

$$\mathbf{F}=(Fn, Fk) \tag{5}$$

In Equation (3), t is the time stamp. By further analyzing the force model, one can generate useful information for specific diagnoses. For example, the sequential data on patient drawing trajectories {S} can be recorded and output for diagnosis purposes, including tremor in the figure reproduction.

$$\{\mathbf{S}\}=\{\boldsymbol{P}, \boldsymbol{P}', t\} = \{\boldsymbol{P}, \boldsymbol{V}, t\} \tag{6}$$

S is the sequential data in Figure 9. The neuropsychologist may query the system for specific sequential information (S1), including the drawing speed V1 and time t1 at which the patient was drawing the area around P1 (x1, y1, z1). {P} is defined as the dimensional data of the drawing. By processing the data set {P}, the system can provide the clinician with drawing scale and deviation information. This may reveal whether the patient has difficulty in drawing certain parts of the ROCF. This extension of the motor control model allows for a more objective and accurate diagnosis. Ultimately, this analysis supports the standard ROCF scoring. As presented in Figure 9, the development of an explicit motor control model and generation of sequential drawing performance information allows for clinician explanation of the control process; that is, it is no longer a ”black box”. Theoretically, the weaknesses in the control loop can be identified. The quantitative results of the system, {S}, {P} and the ROCF score, can be used to set the parameters for the rehabilitation process.

Regarding force feedback assistance for rehabilitation processes, constraints can be placed on either the position {P} or force {F} of the device. Equation (6) shows one possible force-assistance mode for guiding patient drawing in a desired direction during motor skill rehabilitation. The equation describing the guiding force is:

$$\{\boldsymbol{F}_a\} = s * \{\boldsymbol{q}\} \qquad (7)$$

whereFa is a force for directing the drawing on the designed trajectory and s is the strength of the force, which is a constant, set as a system parameter. In Equation (7), the vector q defines the direction along with the trajectory. {q} can be updated from another haptic controlling the unit used by the patient in real time, or recorded or generated from a database. At any time t during the drawing process, the patient will be led by the force Fa(t) in the direction q(t). For the patient training process, Fa(t) is considered as a force dragging the virtual stylus tip to the closest point on the designed trajectory.

$$F_a(t) = \begin{cases} 0 & If|\boldsymbol{d}| = 0 \\ \frac{\boldsymbol{d}}{|\boldsymbol{d}|} * sIf|\boldsymbol{d}| \neq 0 \end{cases} \qquad (8)$$

In Equation (8), s is the force strength constant and d is the vector to the closest point on the designed trajectory. In general, it is anticipated that drawing simulation training would generalize to improved performance in the ROCF test. Related to targeting the weak part of the motor control loop, the training process can be assisted with extra visual feedback or force feedback (see Figure 9). For visual feedback assistance, a desired trajectory in the drawing can be highlighted to guide patient control. If a patient is asked to draw different missing shapes from the ROCF, for example, highlighting of areas or line segments and augmented force-feedback may help in training for visual perception and cognitive planning. The rehabilitation process with the new system can be reinforced through repetitive motor skill training trials.

5 AUTOMATED SCORING OF HAPTIC-BASED ROCF TESTING

One of the prototyping objectives of this study was to develop an automated scoring system for the ROCF test. Clinicians can obtain user drawing files directly from the test workstation, which has been introduced in the previous chapters. A graphical user interface (GUI) has been developed for clinicians to use the system to analyze drawing results. Figure 10 shows an example drawing by a TBI patient during the ROCF drawing testing. Bounding boxes were generated for the purpose of pattern recognition and automated scoring. The lines in drawing are categorized into three groups, horizontal lines, vertical lines and diagonal lines. Possible defects of the freehand drawings were identified by using pattern recognition techniques, and an example is shown in Figure 11. In this study, a list of defect criteria was programmed into the computing software in the new VR system.

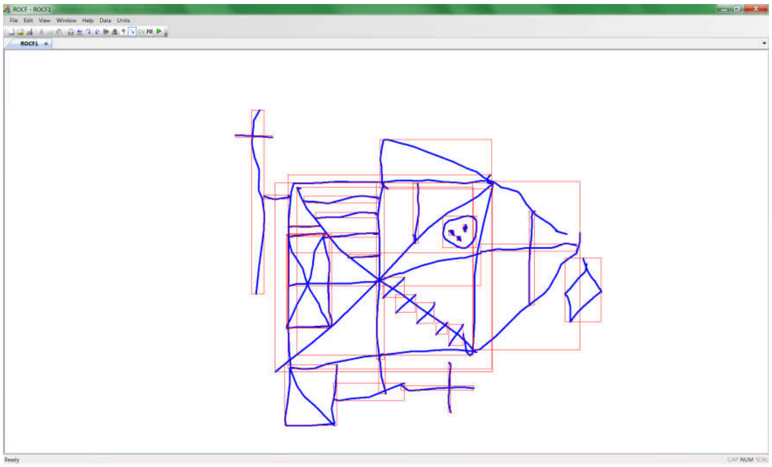


Fig. 10: Bounding box of strokes of TBI Patient's ROCF drawing.

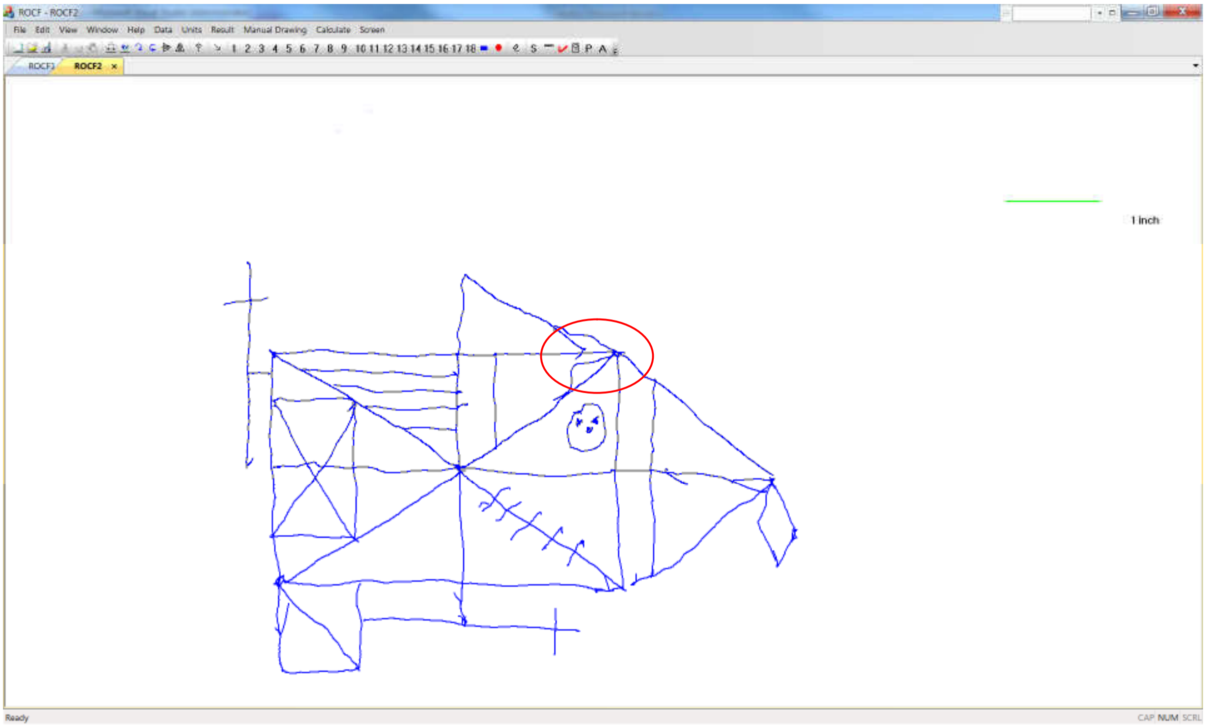
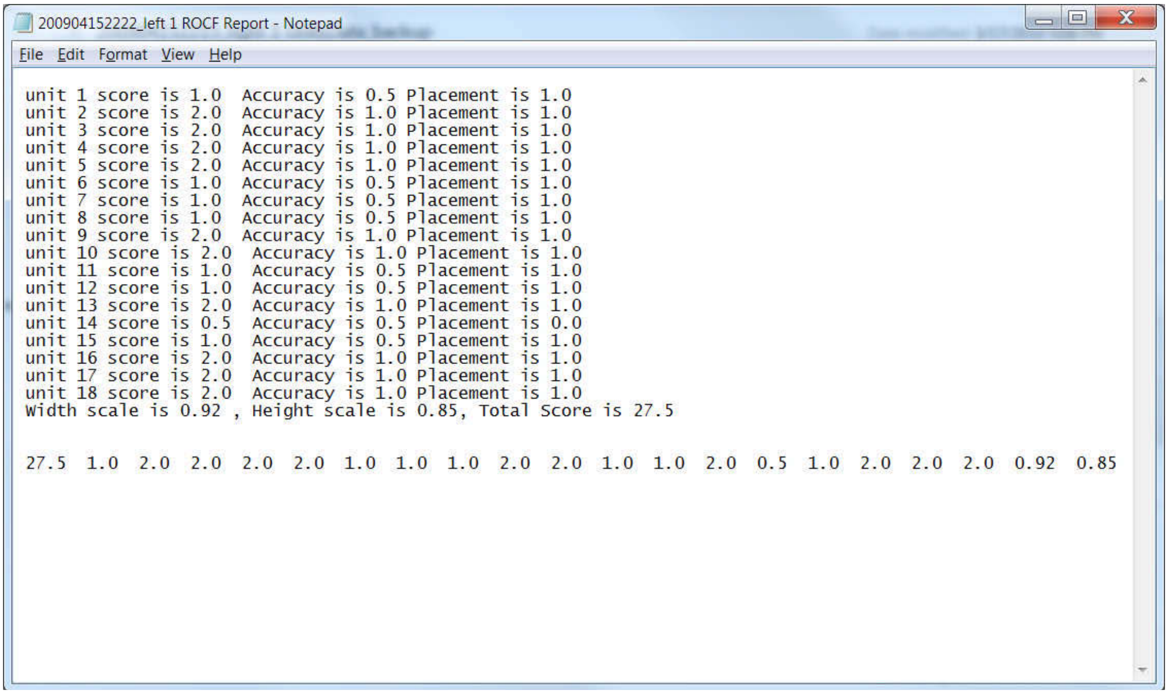


Fig. 11: Example of freehand drawing with defects based on TBI patient testing (overtracing, sketching effects)

The ROCF scoring relies on identification and examination on very detailed features, such as specific corner angles, relations between two specific lines, etc. Individual scores are generated for 18 identifiable features in the drawing and then summed for a total score.This application poses very high accuracy and robustness requirements for drawing recognition and scoring, particularly in use as a diagnosis tool in hospitals. Multiple information resources, including human assistance, are used to guarantee the most effective and accurate drawing recognition and scoring. A list of scoring criteria was also programmed into the system for evaluating drawing results from the ROCF tests.

For each freehand drawing, the system recognizes strokes (line segments) and normalizes them for feature scoring. The system then automatically generates a score report in text format (as an entity to the current EMR system). Figure 12 presents an example of ROCF test results in report format automatically generated by the system.

This part of the study involved developing the interface for clinician use of the automated ROCF test system. The interface allows them to see the drawing result and monitor the computer scoring process. Since patients with actual brain injuries may draw in less organized and recognizable ways, the system must be robust in drawing unit recognition and scoring in the presence of major individual differences. Beyond this, since the target users of the interface are clinicians, it is critical to make the system easy to use and to require only minimal input from them during the automated diagnosis process.



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unit 1 score is 1.0  Accuracy is 0.5 Placement is 1.0
unit 2 score is 2.0  Accuracy is 1.0 Placement is 1.0
unit 3 score is 2.0  Accuracy is 1.0 Placement is 1.0
unit 4 score is 2.0  Accuracy is 1.0 Placement is 1.0
unit 5 score is 2.0  Accuracy is 1.0 Placement is 1.0
unit 6 score is 1.0  Accuracy is 0.5 Placement is 1.0
unit 7 score is 1.0  Accuracy is 0.5 Placement is 1.0
unit 8 score is 1.0  Accuracy is 0.5 Placement is 1.0
unit 9 score is 2.0  Accuracy is 1.0 Placement is 1.0
unit 10 score is 2.0  Accuracy is 1.0 Placement is 1.0
unit 11 score is 1.0  Accuracy is 0.5 Placement is 1.0
unit 12 score is 1.0  Accuracy is 0.5 Placement is 1.0
unit 13 score is 2.0  Accuracy is 1.0 Placement is 1.0
unit 14 score is 0.5  Accuracy is 0.5 Placement is 0.0
unit 15 score is 1.0  Accuracy is 0.5 Placement is 1.0
unit 16 score is 2.0  Accuracy is 1.0 Placement is 1.0
unit 17 score is 2.0  Accuracy is 1.0 Placement is 1.0
unit 18 score is 2.0  Accuracy is 1.0 Placement is 1.0
Width scale is 0.92 , Height scale is 0.85, Total Score is 27.5


27.5  1.0  2.0  2.0  2.0  2.0  1.0  1.0  1.0  2.0  2.0  1.0  1.0  2.0  0.5  1.0  2.0  2.0  2.0  0.92  0.85
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Fig. 12: Example of a score report of a TBI patient's ROCF drawing testing.

6 MOTOR SKILL TRAINING AND REHABILITATION FOR TBI PATIENTS WITH HAPTIC-BASED VR SYSTEM

Motor skill training can be classified into two categories: (1) relearning / rehabilitation motor skills after disease/injuries; and (2) new skill learning, such as surgical training, training in handwriting [9,15,24,28]. In this study, we considered training in figure drawing and the associated fundamental psychomotor behaviors (see Table 1). Figure drawing requires a fine level of accuracy and force control. In general, design of rehabilitation systems to address motor dysfunction focuses on three key features: (1) repetition of activity, (2) feedback, and (3) motivation [4,5]. Repeated practice must be linked to incremental success at some task or goal. This is achieved by trial and error with feedback on performance facilitated via the senses; e.g., visual feedback, force feedback, etc. Motivation to relearn skills is the reason for patients to tolerate extensive practice periods. Feedback has been extensively investigated and there is general agreement that it improves learning rates [18,22,23]. A VR system that can provide patients with repetitive training, while providing feedback and maintaining attractive features may achieve the three key aspects of rehabilitation system design and effectively support neuropsychologists and clinicians. The VR system developed in this study is able to provide different kinds of feedback, including augmented or real-time feedback, and“knowledge of results feedback”. In this way, users can see the task results immediately, and tend to be more motivated to continue performance, as compared to a situation without immediate feedback. The design of the new system interface, haptic device selection, and force modeling were all based on the nature of the motor skills required by the task, promoting the attractiveness of the system.

Tab.1: Motor skill training by ROCF drawing.

Behavior	**Drawing**
Grasp	Prehensile
Direct eye-hand coordination	Tracing
Distant eye-hand coordination	Drawing from a model
Mind-hand coordination	Drawing from memory

Drawing tasks are basic daily life tasks. Practice of the ROCF test is expected to be good for patients with drawing motor limitations. Randomly generated partial figures from the ROCF with certain levels of difficulty for patients to copy is the rehabilitation strategy suggested by neuropsychologists from the Durham (NC) VA hospital. And providing extra force assistance according to the progress of each patient is a unique advantage of using haptic devices in this application.

The results presented in this paper reveal the challenges of developing a VR-based system for motor skill assessment and rehabilitation as well as the advantages and disadvantages of the integration of various haptic devices in the system. For physicians, the new system provides assistance in two ways: (1) diagnosis of test data is more objective and accurate; and (2) communication with neuropsychologists is more effective. Physicians can retrieve data to support their decision making from the EMR system directly. They can also monitor a patient’s progress and adjust the treatment accordingly, on a regular basis. Beyond this, from the medical record management point of view, parameterized/computerized diagnoses and treatment plans are superior to paper records for documentation and organization of a medical records database.

By applying VR technology for neuropsychological assessment and rehabilitation process, neuropsychologists and physicians may be able to work more effectively with reduced workload. The system also allows for customized rehabilitation training to be presented to patients and for updates on the patient progress to be recorded. All of these advantages are expected to accelerate the rehabilitation process.

7 CONCLUSIONS

This paper presents an automated haptic-based VR system for use in healthcare in neuropsychology ROCF tests and rehabilitation therapy on brain injured patients. The system integrates technologies of haptic force rending, pattern recognition in drawing analysis and automated scoring to improve ROCF test efficiency and robustness. Haptic force rendering and analysis techniques were presented for motor skill assessment and rehabilitation. Detailed techniques were developed for generating quick and accurate ROCF test results. The new computer-based system can significantly reduce the workload of neuropsychologists and it can also be used as an open source tool for future research and development activities in TBI patient testing and rehabilitation. This research also demonstrates the potential of engineering efforts in healthcare applications. The techniques presented in this paper may lead to the development of other robust and practical systems for medical diagnosis and rehabilitation in the future.

8 ACKNOWLEDGEMENT

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