Development and Testing of a Low-Cost Diagnostic Tool for Upper Limb Dysfunction

Pravin Nair[1], **Chetan Jadhav**[2], **Venkat Krovi**[3]
[1] pknair@buffalo.edu, [2] cjadhav@buffalo.edu, [3] vkrovi@eng.buffalo.edu (Contact Author)
Department of Mechanical and Aerospace Engineering, State University of New York at Buffalo, Buffalo, NY

Abstract

The overall goal of our research is to create a low-cost, home-based diagnostic and rehabilitation tool (see video) to assist the rapid functional recovery of people with Upper Limb (UL) dysfunction (due to muscular dystrophy and stroke) – the diagnostic aspect of which is discussed in this paper. Viewed in the broader context of robot-assisted neurorehabilitation, the proposed framework takes advantage of manipulation of an instrumented manipulandum along prescribed movement patterns to create a sensitive, quantitative, computer-based assessment/diagnostic tool. Specifically, in this paper, we discuss various aspects of an implementation using a COTS force-feedback driving wheel, interfaced to a PC to create a Virtual Driving Environment (VDE). Coupled with the exercise/movement protocols (structured as driving exercises along paths of varying complexity), this results in creation of a low-cost, user-friendly and immersive personal-movement trainer that is well suited for deployment in patients' homes. Our initial analysis of data collected from 5 healthy subjects indicates that the tool has adequate sensitivity/resolution to distinguish even between healthy subjects and shows considerable promise for diagnosis in diseased population (which is currently underway).

1. Introduction

It is estimated that in the U.S. alone, each year, there are over 750,000 people who experience a new or recurrent stroke, leading to motor disability and upper limb (UL) dysfunction [1]. There is considerable evidence which directly links functional recovery to the duration, frequency, regularity and intensity of the rehabilitation therapy [2-7]. Many of these studies have confirmed that significant improvement is possible by following a dedicated therapeutic regimen (even several years after the initial incident).

However, there are many issues pertaining to the successful implementation of such a rehabilitation therapy regimen. One very important issue is the early and accurate diagnosis of the disease coupled with careful characterization of the level of functional impairment. Significant variation of functional impairment can be seen not only between different patients in patient populations (due to demographic or age-related differences), but also within the same patient over time due to recovery or degeneration [8-10]. Current functional assessment methods involve clinician/therapist based evaluation of physiological characteristics like dexterity, speed, coordination, range of motion, strength and endurance, using *subjective* or *semi-quantitative* tests (such as the Rivermead motor assessment score [11] and Fugl-Meyer [12] index). There is a clear need for quantitative methods which can bring forth desirable characteristics such as specificity (to distinguish between different diagnoses), sensitivity/resolution (for finer gradation), and repeatability/stability (observer-, spatial- and temporal-invariance). While quantitative methods are commonly used in engineering applications for these reasons, they may tend to be dependent on the particular measure chosen. Therefore, care must be taken to select a measure which is invariant and yet offers adequate insight and resolution into the underlying measured process.

Another important issue remains that of overall economic viability and logistics of deployment. Unfortunately, while the number of patients with such UL dysfunction has increased, the resources for rehabilitation therapy available for them have reduced. The problem is particularly acute for those people living in rural or remote locations, where regular visits by a therapist over a period of time become infeasible.

In recent years, several research groups have been examining the development of low-cost, portable force-feedback devices (henceforth referred to as *robotic therapy devices*) to quantify the rehabilitation process. Most of such devices have tended to be specialized/custom-built devices intended for specialized rehabilitation therapies. For example, the Rutgers Master II force feedback glove [13-15] is an example of one such device that was used extensively for hand movement therapy. Many such devices, including the MIT MANUS device developed by Hogan and co-workers [2-4], have also seen great success in clinical neurorehabilitation trials.

While many of the therapies require specialized devices (as seen above), we believe that there is a class of problems where low cost commercial-off-the-shelf *(COTS) therapy devices*, coupled with rehabilitation therapy protocols, can serve a vital role in creating a low-cost, home-based, rehabilitation therapy environment. Commercially available force feedback devices, primarily used for gaming applications, can not only sense a person's movement, but can also apply forces during movement. Similar to existing robotic therapy devices, such devices can serve as interfaces to stimulate the sense of touch and movement, as well as to create customizable patterns of active/passive motion and force assists to user motions. Unlike larger robotic devices, however, the use of such COTS therapy devices opens up the possibility of widespread use as a truly inexpensive personal-movement trainer.

We focus our attention on the development of such a low-cost Virtual Driving Environment (VDE) comprising a COTS force-feedback wheel and a series of exercises/protocols (developed with a driving scenario in mind) for assessment of UL dysfunction. (At a later stage we wish to enhance this to include a therapeutic component thereby aiding in UL motor rehabilitation). The VDE paradigm explored over here, offers a promising and cost-effective method for objective/quantitative assessment of UL performance while performing both unilateral and bimanual sensorimotor tasks in the context of one higher activities of daily living (AsDL). By networking it to rehabilitation centers through the Internet, such a device could provide a means for patients to access a personalized program of therapeutic exercises, customized by a rehabilitation expert. Furthermore, networked access could provide a means for the rehabilitation expert to track the user's sensorimotor performance while the user stays at home. Thus, such a system of low-cost, home-based hardware, coupled with a customizable regimen of motion- and force-based hand movement therapy can help make telerehabilitation services a viable proposition.

2. Literature Review

Beginning in the late 1990's several researchers [2-4, 13-16] examined the application of robotic devices and automation technology to assist, enhance, quantify, and document neurorehabilitation. Hogan and co-workers [3] discussed the development and implementation of a robotic therapy device called the MIT MANUS, and demonstrated the positive influence on the recovery process. Specifically, they augmented the standard rehabilitation treatments on stroke patients by the MIT MANUS and examined improvements in functional motor recovery in two sets of trials, three years apart [2, 4]. In addition to significant improvements in motor recovery for the treatment groups in both trials, they also established the viability of use of such robotic devices as a standardized sensitive measurement tool that could track disease progress over time.

Burdea and his co-workers examined many aspects surrounding the development, implementation and clinical testing of a home-based/PC-based orthopedic rehabilitation system [13-16]. In [13], they introduce the use of the Rutgers Master II (RM II) haptic device to serve as an instrumented interface to sample hand positions and provide suitable resistive forces. In [14], they enhance the system by including an alternative input device (cyber glove) and by setting up a set of immersive virtual environment (VE) based exercise protocols for hand movement studies. In [15], they extended the above therapeutic studies to detailed clinical trials with post-stroke patients in the chronic phase, as well as extending this concept for home-based ankle rehabilitation [16]. One of the important benefits noted in all the above [13-16] include the ability to install the therapeutic systems in user homes and remotely monitor their progress via the internet which we will also pursue. However, we note that in the above cases, they used specialized devices which limit ubiquitous access to such systems.

In contrast, Reinkensmeyer *et al.* [17] examine the use of truly low cost, mass-produced COTS force-feedback devices (commonly used for gaming applications) for rehabilitation therapy applications. A modified COTS force-feedback joystick (Microsoft Sidewinder), with an arm support was coupled to a target tracking scenario to serve as an exercise protocol, implemented as a downloadable web-based, Java applet game. While they examine the use of artificial assistive forces (generated via the force feedback joystick) to favorably assist arm movements, they do not explicitly exploit the quantitative measurement capabilities to create a diagnostic tool.

Bardorfer *et al.* [18] exploit the sensitive instrumented user interface provided by a haptic device, coupled with tailored user-immersive protocols in a VE to aid the diagnostic process. A PHANTOM haptic interface was coupled with exercise protocols involving motion of the pointer through labyrinths of varying complexities for functional studies of the UL in patients with certain class of neurological diseases. In particular, they examine the development of numerous quantitative measures of performance (and therefore, extent of the disease) based on the copious raw data collected. While using a COTS system, the choice of the PHANTOM haptic device as the instrumented interface nevertheless raises the overall cost of the system.

3. Our Approach

Therefore, we would like to examine the development of an inexpensive, portable and home-based set-up of a diagnostic (and at a later stage, therapeutic) tool. The overall development and implementation of this tool involves the merger of hardware and software elements with the set of exercise protocols within the framework shown in Figure 1.

Specifically, we would like to emphasize the use of a low cost COTS device (Microsoft Sidewinder force-feedback driving wheel) which easily interfaces with a standard PC, without explicit data acquisition cards, but with USB interfaces, making it suitable for home-based usage. In its current form, the software component comprising the diagnostic module (containing the exercise protocols) is implemented with MATLAB and several toolboxes, in order to simplify the data collection, display and analysis process. (However, at the deployment stage, we anticipate creation of a stand-alone PC-based executable).

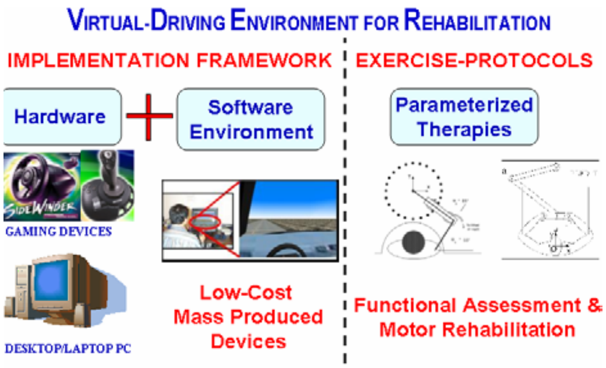


Figure 1: *Overall framework depicting hardware and software elements of the implementation, coupled with the parameterized therapies.*

We will discuss the visualization and the programming components within the software element separately. The visualization component or the VDE consists of two modalities of visual feedback in that the user operates primarily in a 3-D VRML environment, but has the option of working in a 2-D Graphical User Interface (GUI). The 3-D environment is preferable in that a wide variety of objects can be added in the VE thus enhancing user immersivity.

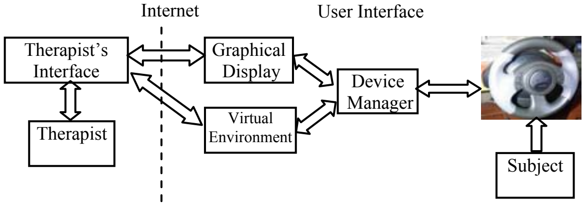


Figure 2: *Functional interaction of the visualization, programming and data acquisition components.*

A simple method for creating 3-D scenes that we adopted is to create them in a CAD environment and then export them to VRML. 2-D graphs are created using the programming features of MATLAB. From a programming perspective, the tool is required to collect data from the user through the wheel, process the collected data and then display/output the processed data back to the user.

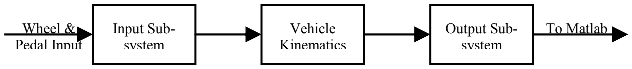


Figure 3: *Sub-system based decomposition facilitates modularity of implementation.*

We have adopted a subsystem approach treating the overall system as composed of an input-, output- and a coupling subsystem [8] as shown in Figure 3. In our case, the wheel and pedals providing analog input captured at a rate of 1000 Hz using the MATLAB Data Acquisition (DAQ) toolbox, forms our input sub-system. The output sub-system is the driver interface comprising a 2-D GUI (or 3-D VRML environment), which is implemented using the GUI capabilities of MATLAB (or the Virtual Reality toolbox). The vehicle kinematics/dynamics forms the coupling subsystem between the input and output subsystems, and is modeled using Simulink. In the preliminary stages, we have considered only the kinematics, but the process can be easily extended to model the dynamics. The user is considered to be driving a differential-drive vehicle which can be modeled using the knife-edge model as shown in Figure 4.

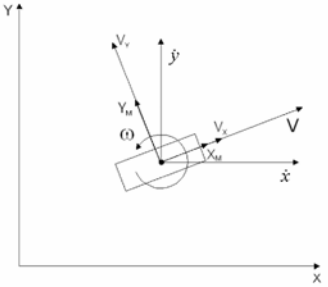


Figure 4: *Knife edge kinematic model of a differentially driven wheeled vehicle.*

The configuration may be represented by the vector: $q = [x, y, \phi]^T$ and the wheel is assumed to be capable of rolling with a velocity V_x in the body-fixed x-direction and rotating with an angular velocity ω. However, due to non-holonomic constraints, the wheel is not permitted to have a velocity V_y in the body-fixed y-direction. Therefore, the motion of the origin of the body-fixed reference frame can be expressed with respect to the inertial frame as:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} \cos\phi & 0 \\ \sin\phi & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} V \\ \omega \end{bmatrix} \tag{1}$$

Numerical integration of the above equations is used to determine the instantaneous position of the vehicle that is compatible with the non-holonomic constraints imposed by the condition of no slip in the body-fixed y-direction. In our implementation, the wheel provides angular velocity ω and one of the pedals provides the forward velocity V. The Simulink block diagram for this scenario is shown in Figure 5. The visualization interface is updated at every time instant to provide a visual feedback to the subject and the simulation stops once the subject reaches the goal. The time history of the virtual vehicle's motions is recorded along with the time history of the subjects' inputs. The Error Value Parameter (EVP) is calculated as the difference between the subject-generated path and the nominal path, at each time instant.

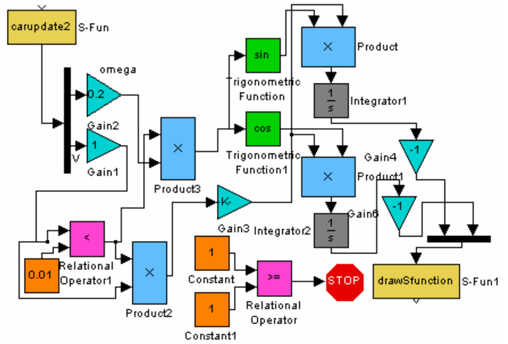


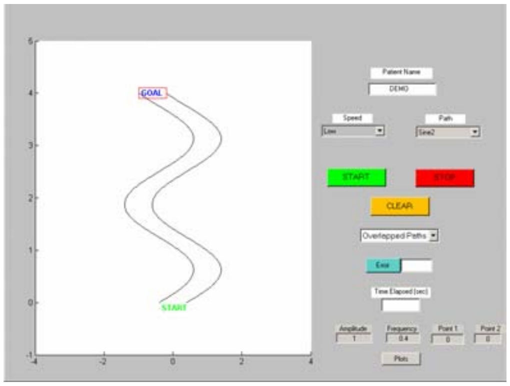
Figure 5: *Simulink Block diagram of the system implemented.*

4. Diagnosis module

Our initial implementation of the diagnosis module emphasizes a comprehensive parametric sweep-based testing (which we will refer to as the *static testing phase*). A GUI, such as the one shown in Figure 6, presents the subject with a test-suite of paths of varying complexity, from a database library of paths, in a sequential manner. The use of such a database library permits the inclusion of models of existing roads (perhaps from a GIS database) to serve as the testing sample as shown in Figure 7 (a).

However, we will focus our attention on the creation and use of a *library of parametrically generated paths*, specifically sinusoidal and labyrinthine maze-style paths, as shown in Figure 7 (b). The sinusoidal paths can be parametrically generated by specifying the amplitude and frequency, while the labyrinthine mazes could be generated by specifying the mean value of free straight line path and/or the number of turns between a desired start and finish location. The motivating reason for the selection of sinusoidal and labyrinthine mazes is that more complex paths can be expressed in terms of these parametric basis functions (sinusoids/ step-functions) with additional analysis (Fourier/wavelet decompositions), without tremendously increasing the computational burden.

Such a parameterized set of paths offers a low-order parameterization of the infinite dimensional set of exercises, permitting a therapist to easily control the complexity of the proposed exercise/diagnosis regimen. Furthermore, we envisage creation of a test-suite using the Design of Experiments (DOE) methodology that progressively/interactively varies the complexity of the tests. This mitigates the need to explicitly present the user with the complete test-suite, thereby speeding up the diagnosis process. Additionally, this can also facilitate creation of a finer resolution of tests to enhance the differential diagnosis process.



Patient Name: DEMO
Speed: Low
Path: Sine2
Amplitude: 1
Frequency: 0.4
Point 1: 0
Point 2: 0

Figure 6: *Example of a 2D GUI which allows conduct of the experiment and provides immediate relevant statistical feedback.*

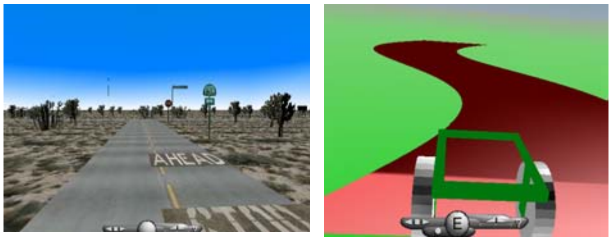


Figure 7: *Examples of 3D visual interfaces for our Virtual Driving Environment (a) with realistic roads from a database; (b) with simple parametrically generated paths.*

4.1 Testing Procedure

For the static testing phase, 3 sinusoidal paths of increasing amplitude and frequency, and 3 labyrinthine paths of increasing complexity were chosen. Subjects were required to guide the "vehicle" along these paths, remaining as close as possible to the center line, with 3 preset forward speeds. For the preliminary testing, the test group consisted of 5 male subjects in the 25-30 year age group. The subjects considered were of normal health, had similar driving backgrounds and did not vary significantly in height and weight. This testing was intended to be the precursor to the clinical testing stage.

After discussions with an exercise physiologist, shoulder and elbow flexion angles (θ_1 and θ_2, as shown in Figure 8(a)) were measured with a manual goniometer and fixed approximately at 45^0 and 60^0, respectively. The height of the chair and the distance from the wheel was adjusted to maintain a fixed offset (D_1 and D_2, in Figure 8(a)). The subjects were asked to grip the steering wheel in the 9-3-clock position, with their thumbs aligned along the grooves provided on the wheel. The set-up photo is shown in Figure 8(b). The tests were conducted on each subject at a stretch without any rest breaks, since all the tests were of a short duration.

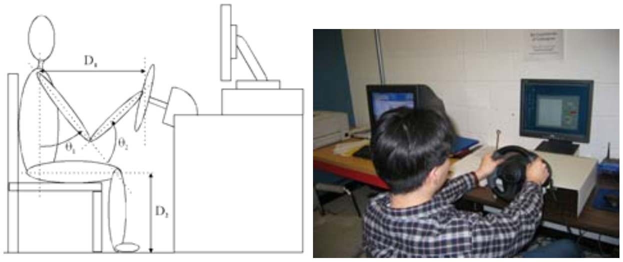


Figure 8: *Experimental Test Setup: (a) Schematic with relevant parameters; (b) Photograph taken during testing.*

5. Results

The EVP is a dimensionless quantity computed as the difference between the desired path and the subject generated path at each time instant, normalized by the amplitude of the desired path. The time history of the EVP (and statistical measures based on this time history) serves as our principal assessment measure. We can consider simple statistical measures (such as mean/standard-deviation/kurtosis) or perform additional analysis (by way of Fourier Decomposition/Principal Component Analysis) to extract measures of increasing complexity.

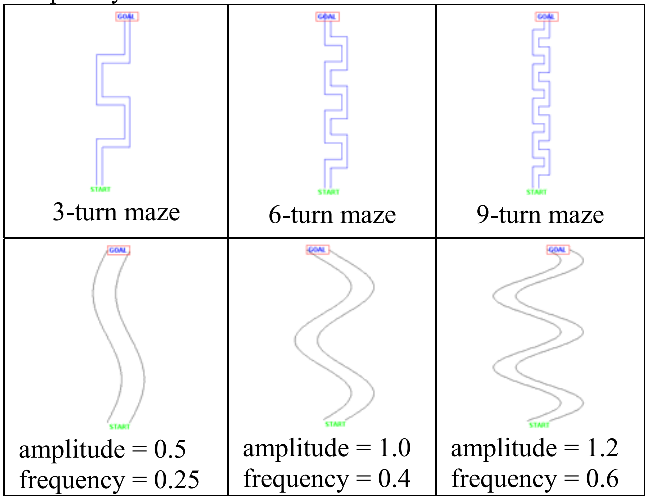


Figure 9: *Parametric library of labyrinthine maze-style paths and sinusoidal paths.*

For this paper, however, we present primarily a qualitative and simple quantitative analysis of the time history. Figure 9 shows the parametric library of sinusoidal and labyrinthine maze-style paths. Figure 10 is a plot of the EVP v/s time for all subjects traversing the 'Sine1' path at the 'Low' speed. Statistical analyses were carried out for various combinations; for example, the mean path deviation of the various subjects is tabulated in Table 1. The time bar-plot for 'Sine1' at all the 3 speeds is also shown in Figure 11.

Qualitatively speaking, we see from the time plots that even within a small group of healthy subjects there is a significant variation in the EVP which shows that our setup is sensitive enough to record these variations. We anticipate that these differences will be further exaggerated in population with UL dysfunction, permitting us to distinguish between various individuals as well as classes of functional impairment. Such a distinction based upon the type and extent of functional impairment can then be detected at an earlier stage, thereby prompting the therapist to take steps to arrest the disease progress (or rehabilitation).

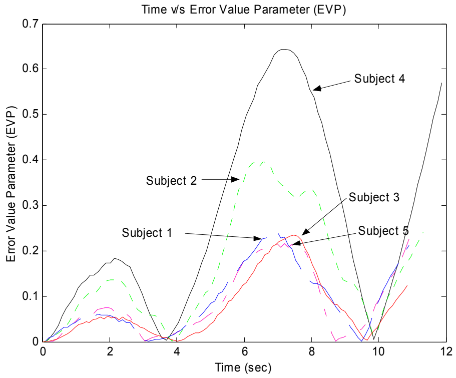


Figure 10: *Plot showing the EVP plotted against the time value collected from the subjects for 'Sine1' at 'Low' speed.*

By comparing the data obtained from the time bar-plot and the corresponding mean deviation data from table no.1, we can see that the subjects deviating the most from the nominal path usually take more time to complete the task. Thus, even a relatively simple measure such as mean time to completion can serve as a good measure of performance.

We have initially considered only the mean deviation between the subject-generated curve and nominal path, but other error measures such as the ratio of subject velocity to the nominal velocity required to traverse a particular path can also be considered. This ratio can be used as a measure of the subject's ability to optimize the path [18].

Speed	**Path**			**Subject**	**Ranking**
	Sine1	Sine2	Sine3		
Low	12.06	33.36	46.32	1	
	17.13	31.68	51.80	2	
	14.52	23.32	42.56	3	
	19.92	*29.84*	*50.88*	*4*	*Poorest*
	10.41	**18.50**	**44.39**	**5**	**Best**
Medium	**13.66**	**22.33**	**50.29**	**1**	**Best**
	19.72	*38.49*	*46.90*	*2*	*Poorest*
	19.64	31.35	49.50	3	
	15.76	29.08	51.74	4	
	17.37	28.18	47.26	5	
High	14.42	25.78	47.20	1	
	15.43	33.28	49.20	2	
	15.10	39.68	45.06	3	
	19.05	*28.79*	*52.48*	*4*	*Poorest*
	14.17	**25.80**	**47.46**	**5**	**Best**

Table 1: *Mean deviation values for the subjects at all the 3 speeds for the 3 sinusoidal paths.*

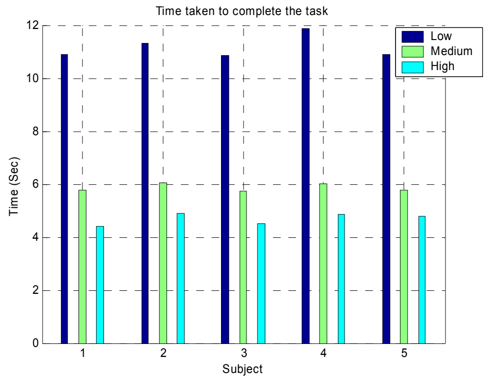


Figure 11: *Graph showing time taken by the subjects to traverse the path 'Sine1' at all speeds.*

6. Summary

In this paper, we have discussed the development, implementation and the initial testing of a low-cost, Upper Limb (UL) dysfunction diagnostic tool developed by using a COTS gaming force-feedback wheel with a parameterized set of movement protocols. Preliminary tests were conducted on 5 healthy subjects and the results obtained there from display the potential of our set-up as a diagnostic tool. Our approach emphasizing a computer-based, quantitative measurement of user capabilities, coupled with automation of the conduct and extraction of performance measures, shows considerable promise for improving the speed, resolution and quality of diagnosis. Preliminary clinical testing with patients with UL disabilities is currently underway.

7. Acknowledgment

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