A Low-Cost Framework for Individualized Interactive Telerehabilitation

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Abstract—**In this paper we examine the issues pertaining to development of a low-cost telerehabilitation framework for upper-limb dysfunction, that is suitable for deployment in patients' homes. We use the example of a Virtual Driving Environment (VDE) to present the overall architecture and discuss issues of: (i) quantitative data-acquisition using commercial-off-the-shelf gaming devices; (ii) model-based parametric data transmission/playback; and (iii) parametric biomechanical identification and data reduction; to support individualization within the telerehabilitation regimen.**

Keywords—**upper-limb dysfunction, customization, tele-rehabilitation, robotic-therapy devices, immersive environment**

I. INTRODUCTION

The overall goal of our research efforts is to develop the architecture and the algorithms of an inexpensive telerehabilitation framework that extends the individualized interactive nature of traditional rehabilitation therapies to the patients' homes. The intended audiences are patients with upper-limb dysfunction, secondary to a cardiovascular accident (stroke) or physical injury.

As a precursor to the presentation of the framework, we consider some of the conflicting requirements for a successful deployment of *any* rehabilitation regimen. On one hand, there is considerable evidence which directly links functional recovery to the duration, frequency, regularity and intensity of the rehabilitation therapy [2, 3]. In this light, home-based rehabilitation programs have gained importance and relevance due to the considerable flexibility afforded in tailoring the scheduling, intensity and duration of the rehabilitation regimen. On the other hand, patient studies have shown that newer techniques such as constraint-induced therapy can bring about significant speedups in restoring functional use [4]. However, such neuro-rehabilitation approaches require intensive and supervised diagnostic and therapeutic procedures, administered by a clinician working with a single patient at a time which limits applicability to clinical settings.

Such labor-intensive procedures are a primary application field for robotics and has resulted in development and deployment of robot-assisted-therapy devices ("rehabilitators") that physically-interact with patients in order to assist in movement therapy [5]. Such robotic devices now takes the role of a therapist in guiding the patient through the intensive, repetitive practice of functional movement and several other studies have documented their successes [6]. However, even with such robotic-therapy devices, the significant costs and other associated logistics limit deployments to hospital settings.

Thus, it is in the final stages of bringing these advances over to the home-based rehabilitation arena that things have faltered due to a combination of: (i) the lack of readily-available and affordable specialized equipment; and (ii) the lack of specialized/individualized therapies for each patient. Our research efforts, in developing this telerehabilitation framework, focus on overcoming some of these limitations.

In this paper, we use the example of a Virtual Driving Environment (VDE), shown in Fig. 1, to present the overall architecture of the telerehabilitation framework for the following reasons. First, it serves as an illustrative example to help us integrate the multiple facets of our research within a common overall framework for individualized telerehabilitation. At the same time it also allows us to identify the issues with development, implementation and deployment of a flexible, reconfigurable, inexpensive, portable rehabilitation tool suitable for setup in patients' homes and outpatient clinics. Finally, the development of such a rehabilitation tool in the context of driving, one higher activities of daily living (AsDL), can serve to enhance the motivation and compliance aspects of a therapeutic regimen. However, we would like to specifically note that this VDE is intended to serve as a *network-based tool for assessment and rehabilitation of Upper Limb* (UL) *motor dysfunction* and not necessarily as a "driving-simulator" [7] for human-factor assessment.

II. ARCHITECTURE

The VDE shown in Fig. 1 consists of a Patient Interface (ultimately intended to be home-based) and a Therapist Interface (ultimately intended to be at a remote central hospital location) that are connected through the Internet. The Patient Interface (shown on the left side of the figure) serves both as the data-acquisition framework as well as the exercise deployment framework. It consists of an immersive virtual environment with which the patient can interact using a variety of commercial-off-the-shelf force-feedback kinesthetic interface devices. We focused however on selecting and validating the use of the low-cost mass-produced devices and simplified PC-interfaces (USB-based

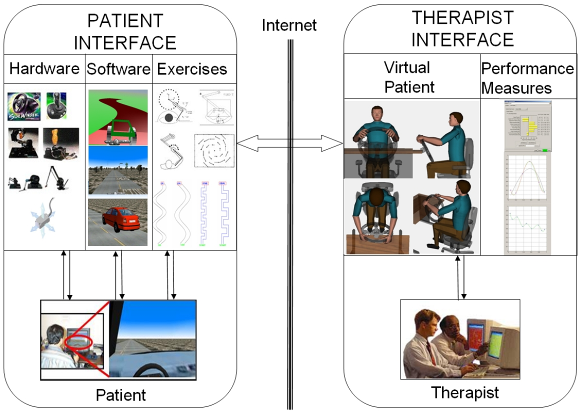


Fig. 1. Virtual Driving Environments for Telerehabilitation.

vs. explicit data acquisition) making it suitable for home-based usage. Other unobtrusively mounted sensors (such as MEMS rate gyro mounted in a jacket) are also used to redundantly capture the users' upper-limb motions. In the longer term, we propose to include touch- and force-sensing film to monitor the hand contacts and inexpensive force torque sensors to measure the bilateral forces.

A variety of exercise scenarios, implemented in the form of immersive driving activities, form the software component that is deployed on the patient's home-computer. The virtual environment reads these quantitative user-inputs (motions and forces) from the force-feedback interface device (and other sensors) and generates the motions and forces to be fed back to the user and updates of the virtual environment according to an appropriate kinesthetic dynamic-interaction (haptic) model [8]. A variable level-of-detail implementation is envisaged to facilitate mixing and matching the various levels of modeling and simulation fidelities – both for visualization (simple 2D GUI to detailed 3D environments) and haptic dynamic simulation (kinematic vs. dynamic vehicle models). Such a 3D interactive environment can function in a standalone manner – in this from it resembles any game that would be available on the market.

However, it is the addition of the parametric diagnostic and therapeutic modules, which sets the stage for creation of the individualized interactive therapeutic framework. As the patient interacts with the 3D environment, the diagnostic module uses the quantitative patient information captured (e.g. the pertinent user motions and force histories) in the biomechanical identification process and for development of performance measures (e.g. ranges of motion, measures of strength). A library of exercise routines created as specific parameterized driving scenarios (e.g. roads of increasing curvature, sharp turns etc.) serve as templates to generate the desired exercise therapeutic regimen. We would like to emphasize the parametric nature of the diagnosis and the subsequent therapy (discussed later in this paper), which form the cornerstone of our efforts.

From the therapist's point of view, this telerehabilitation system facilitates effective visualization and quantification of the patients' motions and associated pathologies as the patient follows a prescribed exercise regimen. Synthetic models of the human user consist of articulated rigid body models that reflect the geometry and the kinematics of the user. We use JACK [9], a software package for human body simulation to develop the therapist interface. These digital human models consist of parametric articulated rigid body models (69 scalable articulated parts, 138 degrees of freedom and 70 joints) that reflect the geometry and the kinematics of the user [10]. This JACK model will form the virtual prototype ("the avatar") of the patient with which the therapist interacts within this virtual environment. Each such digital model will be customized to reflect the specific performance characteristics of each individual patient (ranges of motions and strength), as determined by our biomechanical identification efforts (discussed later). The remotely collected data can be used to replay the patients driving (exercise) session on the digital human model and reviewed from various viewpoints. Further, the interface can also provide the therapist with additional computed, postprocessed information (such as graphs of computed ranges of motion, comfort indices etc.) to aid the assessment process. The therapist can now appropriately modify the therapeutic regimen and download a new therapeutic regimen back to the patients' machine.

III. Research And Develoement Issues

Our overall research goal is to support individualized interactive therapeutic regimen within the telerehabilitation framework. The three aspects of the telerehabilitation framework on which we focus our attention include: (i) sensory data-acquisition using inexpensive gaming devices to facilitate quantitative analysis; (ii) model-based parametric information transmission/playback to facilitate evaluation and diagnosis; and (iii) parametric biomechanical identification to assist in data reduction and development of performance metrics.

A. *Quantitative (but Inexpensive) Data Acquisition*

The suitable selection of the therapeutic equipment is critical – they need to 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. On one hand, highly sophisticated force feedback devices with multiple degrees of freedom are available. Bardorfer *et al.* [1] use once such device (PHANTOM) in the context of diagnosis of upper-limb dysfunction. However, the cost associated with such equipment is prohibitive for home-based use. On the other hand, numerous truly low cost, mass-produced commercial-of-the-shelf force-feedback computer-interface-devices (commonly used for gaming applications) are also available. Fig. 2 shows the examples of use of both classes of devices for rehabilitation applications.

Reinkensmeyer et al. [11] examine the use of one such devices for rehabilitation therapy applications. 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 facilitate diagnosis. We believe that there is a class of problems where coupling low cost COTS therapy devices with rehabilitation therapy protocols

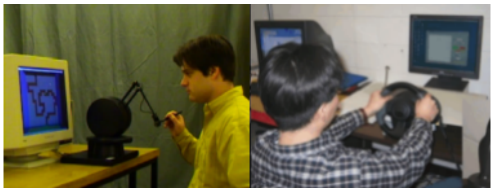
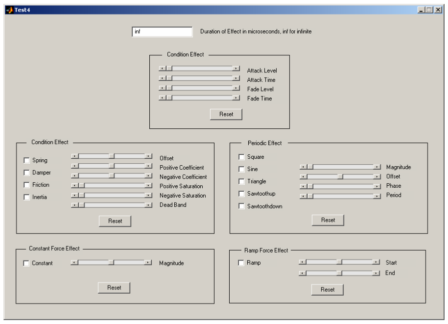

(a) (b)

Fig. 2. Two Approaches: (a) Use of Specialized FFB devices [1], (b) Use of COTS FFB devices [9]



inf Duration of Effect in microseconds, inf for infinite

Fig. 4. Matlab GUI Calling Various Types of DirectX FFB Effects

and diagnosis, opens up the possibility of widespread deployment as home-based personal-movement trainers.

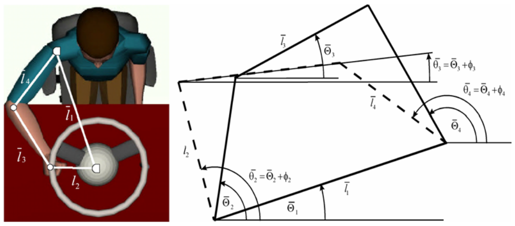
From a software perspective, we prototype the overall interactive environment within a Matlab/Simulink environment, leveraging various toolboxes to accelerate the initial implementation, prior to using the automatic compilation to generate a Windows executable. It is worthwhile to note that COTS gaming devices are relatively easy to control from a PC Windows environment (without the requirements for specialized software interfaces of robotic therapy devices). For example, we take advantage of the extensive DirectX libraries [12] of force feedback (FFB) effects, which can be composed to create an entire assistive/resistive exercise regimen. Fig. 4 depicts one such interface we have developed for composing DirectX FFB effects from within MATLAB/Simulink.

B. *Model-based parametric information transmission/playback*

In recent years, leveraging the power of internet, real-time transmission of video has come to supplement audio and data transmission for telemedicine applications in general and telerehabilitation, in particular. Many groups [13, 14] are evaluating the effectiveness of this technology for conducting assistive technology assessments remotely. The real-time video component of video teleconferencing provides a visual and explicit exchange of information during this process with significant consumer (both patient as well as therapists) acceptance.

However, multiple camera views may be necessary for therapist to recognize patient's activity patterns increasing infrastructure (cameras, network-bandwidth) requirements. Quantitative assessment of patient's performance is difficult with standard videoconferencing infrastructure and thus such systems are unable to leverage the available computational infrastructure to assist the diagnosis. In recent times, a few research groups are beginning to augment video information with collected quantitative physiological information [15]. However, these approaches are principally for cardiac, respiratory and diabetes management and are not being explored in the telerehabilitation context.

Fig. 5. Implementation of network-connected patient/therapist interfaces



(a) (b)

Fig. 6. (a) Formation of a closed kinematic Loop in the transversal plane; and (b) calibration of parameters

In our telerehabilitation system, we stream selected sets of parametric information (joint angles, steering wheel angle) across the internet instead of full motion video thereby significantly reducing bandwidth requirements. Fig. 5 shows the implementation of internet connection subsystem. The data acquired from the patients' arm movements are replicated by digital JACK model on the therapists' computer. The benefit of such a model-based approach is that the therapist can interact (viewed from different viewpoints, playback captured motions and proposed exercises) with the digital patient model in ways not possible simply with video conferencing approaches.

C. *Parametric biomechanical identification*

Further, we also propose to use the ongoing and continuous streaming measurements to facilitate: (i) parametric estimation of the patients' biomechanical parameters (arm-lengths, ranges of joint motion, etc.); and (ii) invariant and quantitative performance measures to quantify the changes in functional performance (improvement/degeneration).

Data reduction of the collected sensor information will be critical for good performance in limited-bandwidth networks. We focus on data reduction techniques that will also have a ready physiological interpretation. Specifically, we adapt methods from online parameter estimation to identify adequate model parameters from the patient's musculoskeletal system and use these to develop a custom biomechanical model, representative of the virtual patient. Some of our early efforts for identification of the kinematic parameters of the upper arm, as depicted in Fig. 6, building on the literature on online kinematic calibration [16] is reported in Jadhav and Krovi [17]. The end goal is a system that is capable of adaptively estimating these parameters based solely on the streaming measurements without requiring expensive and explicit calibration.

We also emphasize the use of a library of parametrically generated exercises – e.g. sinusoidal paths can be specified using amplitude and frequency and labyrinthine mazes could be the mean value of free straight-line path and/or the

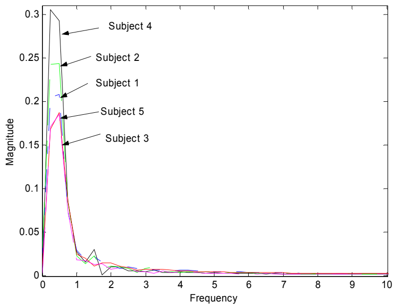


Fig. 7. Principal Component Analysis of data collected from subjects driving at “low” speed along a sinusoidal path of “given amplitude”.

number of turns between a desired start and finish location. Such a parameterized set of paths offers a low-order parameterization of the infinite dimensional set of exercises, and would permit a therapist to easily control the complexity of the proposed exercise/diagnosis regimen.

Finally, our efforts in developing invariant and quantitative performance measures also leverage the parametric nature of this library of exercises. The principal reason for the selection parametric basis functions (sinusoidal/step function) for all generated paths is the ability to perform additional analysis (Fourier/Wavelet decomposition), without increasing computational burden. Some aspects of development of such performance measures were explored in the context of the VDE [8]. For example, the results of the principal component analysis performed on motion data collected from five healthy subjects, shown in Fig. 7, indicates that the COTS gaming devices possess adequate sensitivity/resolution to distinguish even between healthy subjects.

IV. CONCLUSION

In this paper, we presented a brief overview of our efforts at developing a framework for low-cost individualized telerehabilitation suitable for home-based deployment. We use the example of a Virtual Driving Environment to present the overall architecture of the telerehabilitation framework and motivate some of research and development issues. Initial indicators suggest that COTS gaming devices possess adequate fidelity for use as diagnostic tools and for providing controlled motions/forces with minimal modifications or developmental efforts. In-depth testing with sample patient populations would be critical prior to deployment of this framework and is currently being pursued.

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