An Interactive Framework for Personalized Computer-Assisted Neurorehabilitation

Xin Feng *Student Member, IEEE* and Jack M. Winters, *Member, IEEE*

Abstract—**This paper presents the implementation of a framework for computer-assisted neurorehabilitation that intends to address the need for more personalized healthcare technologies. This framework, called UniTherapy, is applied to home neurorehabilitation for individuals with stroke-induced disability. It supports interactive upper limb assessment and therapy that makes use of mass-marketed force-reflecting joysticks and wheels, as well as some customized therapeutic devices. A novel service-oriented technical infrastructure is presented which includes a rich menu of performance assessment capabilities and support features that include telerehabilitation links, protocol design, and data analysis tools. Example results are presented that demonstrate its potential as a sensor-based assessment tool. User feedback is summarized.**

Index Terms—**Computer-Assisted Motivating Rehabilitation (CAMR), Personalized Medicine, Telerehabilitation, User Interfaces**

I. BACKGROUND

The vision of a more personalized, consumer-oriented healthcare system is gradually emerging. While not evolving as quickly as envisioned by a consensus workshop on *homecare technologies of the future* that met in 1999 [1, 2], one possible reason relates to the challenges associated with addressing the top recommendation of this workshop: the need for better tools for intelligent management of information and interfaces [3]. One aspect of this challenge relates to the evolution of "intelligent" frameworks that enable effective co-participation by stakeholders through a process that is more personalized and convenient. Recognition of such factors has motivated a number of technical approaches [4-6]. However, for applications such as home rehabilitation, critical to the success of such frameworks is that they need to support embedded assessment tools that achieve and document desired outcomes as well as interfaces that are accessible and usable, preferably personalizable for each of the co-participants (e.g., home client, remote practitioner) based on their roles, preferences and abilities. This paper presents one such approach, targeting a specific societal need for more effective tools for personalized neurorehabilitation and, in particular, stroke rehabilitation.

Most of the estimated 5.4 million survivors of stroke in the U.S. [7] have been discharged from hospital care and are viewed as "chronic" by the healthcare system. Most live with upper-limb hemiplegic impairment and disability. Mounting scientific evidence has shown that many of these individuals could benefit significantly from intervention programs that encourage goal-directed use of their impaired extremity [8]. Yet over the past decade, the duration of reimbursed therapy has decreased due to economic pressures on healthcare systems, especially in the U.S. The change especially impacts neurorehabilitation, as the reimbursement model of 2-3 visits per week typically is insufficient to improve the intervention outcomes. Consequently there is a need for new approaches that are cost-effective while also providing a greater amount of therapy. This pressing need has generated considerable research on novel approaches such as robotic-assisted therapy and generated evidence that shows that significant improvements in function are possible even years after the initial stroke [9, 10]. While proven to be effective for patients meeting certain inclusion criteria, high costs and mechanical sophistication appear to inhibit the likelihood of large-scale implementation, and the number of persons with stroke who actually benefit from these new interventions remains small. As alternatives, web-based therapy [11], virtual reality [12, 13] and motor imagery [14] have been studied as training tools in stroke rehabilitation.

A recent conceptual model breaks down the science of rehabilitation into three areas: rehabilitative recovery dynamics, human-technology interface design, and behavioral modification and motivation [15]. Ideally, all of those areas in the rehabilitation process could be personalized: a) the therapeutic intervention protocol, b) the plan for timely and relevant assessments, and c) the user interface. In terms of the first of these, scientific evidence suggests that the form of the intervention should be varied, with some tasks customized to target the individual subject's motor deficit [16].

In terms of assessment, goal-directed tasks with the

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X. Feng is a biomedical engineering doctoral student at Marquette University, Milwaukee, WI 53233 USA. (E-mail: xinfeng@mu.edu).

J.M. Winters is a professor of biomedical engineering and John P. Raynor Distinguished Chair at Marquette University, Milwaukee, WI 53233 USA. (E-mail: jack.winters@mu.edu).

affected limb in stroke subjects are typically characterized by an abnormal pattern of muscle activation and a decreased range of motion, movement speed, smoothness and coordination [17]. Related to this, there is a need for sensor-based performance metrics that are more objective and sensitive to functional changes than many of the current clinical scales. This becomes especially important for applications in home neurorehabilitation, which is characterized by less frequent supervision by clinical experts.

In terms of the user interface, with the eventual target of rehabilitation being to optimize beneficial rehabilitative change, one of the key challenges in the telerehabilitation field is the need for interfaces that are more consumer-centered and support user preferences [18]. It is suggested the personalizable interfaces can also impact motivation. Indeed this paper falls under the collection of approaches that have been called Computer-Assisted Motivating Rehabilitation (CAMR) by Bach-y-Rita [19]. Here the focus is on motivating games where movements become subconscious, and patients participate in tasks of interest that have been crafted to use regions of the arm workspace. Improvements often appear to extend beyond the specific movements that are being practiced [19, 20].

Finally, there is a great potential for home rehabilitation to work when an appropriate support system is also available. Using a prospective randomized method, Bach-y-Rita and colleagues have shown that for those early stroke patients, home rehabilitation was effective both in terms of functional recovery and cost analysis [19]. The results suggested that patients and their families were less stressed and generally happier when rehabilitation could be provided at home in a familiar and supportive environment.

In summary, it is suggested that instead of using a similar approach for all individual clients, a framework is needed that supports a rich menu of therapeutic options which can be used to generate personalized protocols with customized intervention and interface settings. To be used at home, the framework must also be low cost and support remote clinical expert supervision.

This paper presents the implementation of a consumer-centered alternative therapeutic strategy for neurorehabilitative therapy: a modular framework called UniTherapy that supports a rich menu of diverse forms of assessment and therapy, designed especially for use in the home environment. It builds on:

- Microsoft's DirectX technology [21] which supports mass-marketed windows gaming devices including force-feedback joysticks and wheels.
- Scientific insights from robotic "assist" and "resist" therapy.
- Emerging interface standards that target the cost-sensitive consumer electronics industry and emerging approaches for customizing interfaces to the user's role, preferences, capabilities, and therapeutic program objectives. For instance, the new ANSI INCITS 389-393:2005 suite of User Interface Socket / Universal Remote Console (UI-Socket/URC) standards [22] and the Universal Plug and Play (UPnP) standard [23] have been supported in the framework to enable users' own preferred interfaces to operate with the home client version.
- State-of-the-art telecommunication and software platform capabilities that support location-independent tools for assessment of the client's functional abilities and their degree of adherence to an exercise protocol.

Example results are reported, with a special focus on (a) the use of assessment tools that have the potential to be sensitive to the change in the client's functional ability and (b) initial user feedback on the usability of the framework.

II. METHODOLOGY

This section presents the conceptual model and implementation details for the personalized framework including the service-oriented technical infrastructure and the consumer-oriented design strategy that is sensitive to various user roles and abilities.

A. Analysis of User Needs in the Rehabilitation Process

The design of a personalized neurorehabilitation framework starts with understanding the needs, roles and interactive sequences of each user involved in the neurorehabilitation process. As shown in the sequences diagram (see Fig. 1), three roles are defined, with an access mode associated with each role:

- *Therapy Designer (TD)*: A user in this role has full access to the interactive UniTherapy framework. The TD creates a personalized intervention protocol (i.e., a sequence of therapeutic exercise tasks) for a specific home client. Structural refinement of a protocol also requires the user to be in TD mode.
- *Home Client (HC)*: The HC, often in the role of patient if still receiving clinical services, can run and navigate through a menu of prescribed intervention sessions using a personalized access interface. The HC also has optional access to their own progress and history with the assumption that positive feedback will enhance their motivation.
- *Telepractitioner (TP)*: The TP can remotely load and manage an intervention protocol for an HC. This includes privileges to change settings within a protocol, for instance changing the difficulty of a goal-directed assessment task based on remotely assessing progress of the HC over the past week. For interactive tasks in the intervention session, the TP can remotely supervise and interact with the HC with a telerehabilitation link. This includes the ability to remotely generate "assistive" or "resistive" forces on the HC's device.

The tasks within an intervention protocol can be classified into two categories: self-managed tasks (which the HCs complete without remote involvement) and interactive tasks (which include interaction between an HC and a TP). While the relative use of these two approaches is a user choice that may change over the course of an iterative rehabilitative process and a session may include some of both, the practical reality is that the framework must be usable enough that the majority of time is spent in self-managed tasks.

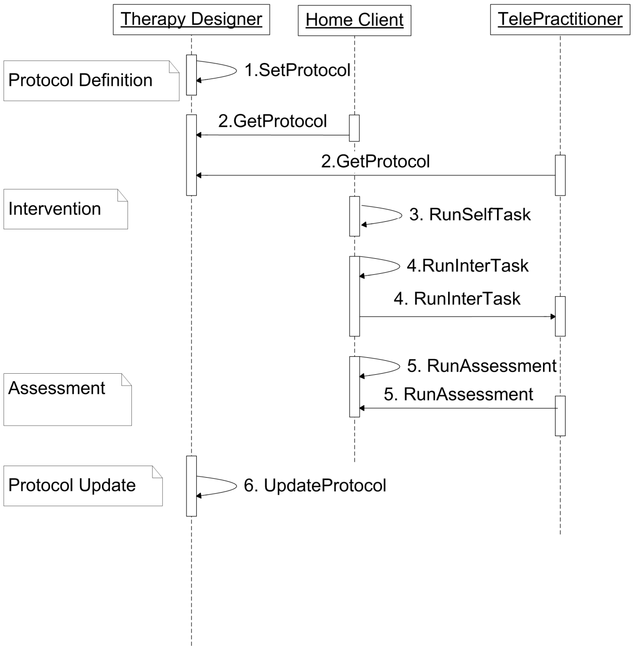


Fig. 1. The sequence diagram of the home neurorehabilitation framework that defines the roles and the interaction sequence, where time proceeds downward. Note that this interaction sequence is designed to be an iterative process when actually implemented.

B. Supported Devices for Therapy and Assessment

The next requirement for wide-range applications of home neurorehabilitation is that the framework should support devices of computer-assisted assessment and therapy that are low-cost and readily available. Potentially, all input devices supported by Microsoft DirectX technology can be used within the UniTherapy framework. For instance, the framework now supports force-feedback joysticks, force-feedback driving wheels, various pointing devices (e.g. mouse, trackball) and windows keyboards. Certain therapeutic and assessment tools are customized for devices with different degrees of freedom (DOF) (e.g. driving wheel – 1 DOF; joystick – 2 DOF). Most of these hardware devices are readily available in low-cost; for instance, both conventional force-feedback joysticks and wheels can be purchased for well under $100.

When using force-feedback devices, the TD can interactively program force effects such as forces associated with virtual mechanical elements (e.g., spring, damper, and inertia), task-related “assist” or “resist” forces, or force effects for system identification studies (e.g. spasticity evaluation). These are implemented by using the Microsoft DirectX Software Development Kit (SDK).

One of the tenets behind the name “UniTherapy” is that this framework should support universal interfaces that help break down access barriers and can be used for performance assessment and interventions. One implemented example is the support for simple voice commands (e.g., “left”, “right”, “up”, “down”, and “stop”) in tracking tasks. Although simple for now, this suggests the potential for this framework to be used in other areas of rehabilitation practice such as speech therapy.

C. Service-Oriented Infrastructure

Certain advantages favor exposing a framework as a service rather than a stand-alone application, such as platform independence, higher reusability, and support for customized User Interface (UI) and Web services [24]. As shown in Fig. 2, the personalized neurorehabilitation framework is designed and implemented as a six layer service-oriented infrastructure. Each layer communicates only with the adjacent layer:

Service Layer: The user directly communicates with the Service Layer. Functionality in the Service Layer is organized by modular “managers” with corresponding consoles, with only the TD having full access to these interactive managers. For instance, the TD can use the *Assessment Manager* to design assessment tasks and then save the task settings by using the *Protocol Manager*. Data from assessment tasks can then be analyzed by using the *Data Analysis Manager*. The details of these implemented managers will be discussed in sections D-F.

Personalized Agent Layer: Functionality between the Service Layer and Description Layer support both personalized protocol design (including assessment and therapy tasks) and personalized UI generation based on user role, preferences and capabilities. As an example, the *Task Builder* will generate personalized assessment and therapy tasks which are designed by a TD using the *Assessment Manager* and the *Therapy Manager*.

Description Layer: This abstract layer provides standard descriptions for upper layers to get access to but hide implementation details, thus supporting current and anticipated future system extensions (e.g., support for novel therapeutic devices). These descriptions are for therapeutic devices, data structures, protocol structures and so on. An important component of description layer is a suite of UI-Socket/URC standard-compliant documents which can be used for personalized UI generation (see also Section H).

Development Library Layer: This layer includes development frameworks, toolkits and libraries that are used by the upper layers. The Microsoft .NET Framework, Mathwork’s MATLAB library, the Microsoft DirectX SDK and the Universal Plug and Play (UPnP) SDK are current examples.

Network Layer: This layer involves standard network communication protocols such as TCP/IP.

Physical Layer: This layer includes support for therapeutic devices (e.g. force-reflecting joysticks, driving wheels), network devices, and human computer interfaces.

A number of functions within the Service Layer and

Personalized Agent Layer have been encapsulated into a components library that can be distributed as a SDK. The primary software development environment is the Microsoft Visual Studio .NET.

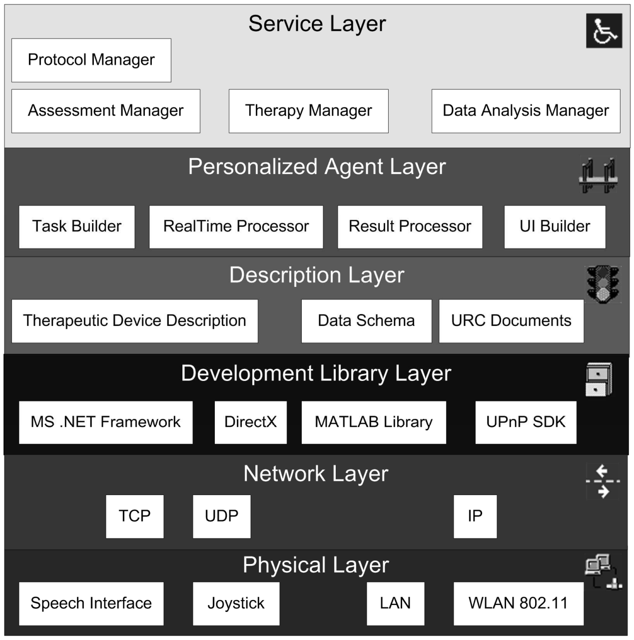


Fig. 2. The personalized rehabilitation framework is designed and implemented with six modular layers. The boxes included in each layer are example components that have already been implemented or used in the system. IP: Internet Protocol; LAN: Local Area Network; MS .NET: Microsoft .NET; TCP: Transmission Control Protocol; UDP: User Datagram Protocol; UI: User Interface; UPnP: Universal Plug & Play; URC: Universal Remote Console; WLAN 802.11: Wireless Local Area Network 802.11.

D. Personalized Assessment Capabilities and Features

Computer-based performance assessments can provide timely evaluations of human performance in support of an iterative therapeutic optimization process, can potentially serve as a key motivational tool, and can provide metrics that potentially have higher sensitivity to subtle changes in HC function than traditional clinical assessment scales.

The collected assessment data (e.g., position, timestamp, applied force) along with context information (e.g., patient ID, collection date) are recorded into XML files with the structure defined by XML Schema. The Data Analysis Manager supports a suite of performance metrics (with different classes of metrics associated with different types of assessment tasks) and also supports presentation of results in different forms (e.g., graph, image, text report), as appropriate for the task.

The Assessment Manager includes four toolboxes: Range of Capacity (ROC), Tracking, System Identification and Conventional Forms.

1) Range of Capacity (ROC) Toolbox

The HCs ROC is measured so that the system can map between a given input device workspace range and the user capability range. This mapping is based on an ROC task that prompts the HC to draw a rectangle as big as they can and then reach as far as they can on the screen; the data are fitted into a rectangle which is used as the patient's estimated ROC, with the fitting parameters still adjustable by using controls in the ROC toolbox. A five-parameter fitting algorithm then is used to perform a 2D-transformation and re-map the device workspace to the user-capability space (or vice versa):

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{pmatrix} S_x & 0 \\ 0 & S_y \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} t_x \\ t_y \end{bmatrix} \tag{1}$$

where x and y are actual user position, S_x and S_y are scale transform parameters, θ is a rotation transform parameter, t_x and t_y are translation parameters, and x' and y' are positions mapped to the device workspace. This mapping helps ensure that HC can reach most of the space for subsequent tasks.

2) Tracking Toolbox

Tracking tasks have been widely used in the practice of neurorehabilitation and are aimed at assessing various performance capabilities. The Tracking Toolbox supports two categories of tracking tasks: discrete tracking (point-to-point target acquisition) and continuous tracking (pursuit/preview tracking).

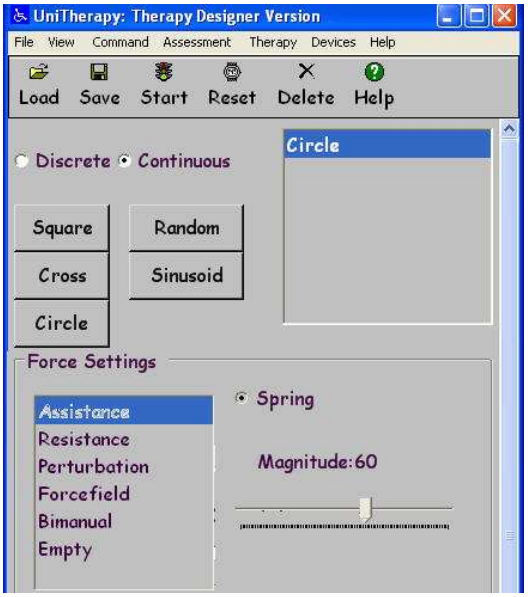
By using the Tracking Toolbox shown in Fig. 3, the TD can design the tracking task by selecting basic spatial patterns (e.g. Rectangle, Cross, Circle, Sinusoid Random) with predefined force field settings (e.g. assistance, resistance, perturbation) and then customize the task settings (e.g. amount of preview, task duration), the spatial pattern settings (e.g. range of the pattern) or the force field settings (e.g. force magnitude). By overlapping two or more patterns in a time series, more complex patterns such as pseudo-random patterns (e.g. three sinusoidal patterns with different frequencies) can be created.

3) System Identification Toolbox

It has been common in neurorehabilitation research to use system identification tools to help understand nonlinear and time-varying human systems [26, 27]. The System Identification toolbox is used to apply predefined force perturbations (e.g. Impulse, Step, Sinusoid, and Noise) to the subject and then measure their response given a certain instruction (e.g., "hold," "relax"). The force perturbations are implemented by or derived through DirectX SDK. The TD can design system identification tasks by selecting one or more force effects and then customize task level settings (e.g. instruction, task duration) or force level settings (e.g. force magnitude, force direction).

4) Conventional Forms Toolbox

Motivated by previous work that evaluated the effectiveness of using remote functional assessment tools [28], a number of classic neurorehabilitation assessments (e.g. Barthel Index [29], Wolf Motor Function Test [30]) have been integrated into the Conventional Forms Toolbox. Currently consisting of eight questionnaire assessment instruments, this toolbox complements the sensor-based assessment capabilities described in this section. A given questionnaire can be filled out either directly by the HC or through remote interaction between the HC and the TP via a teleconference link.



○ Discrete ● Continuous

Circle

Assistance

● Spring

Magnitude:60

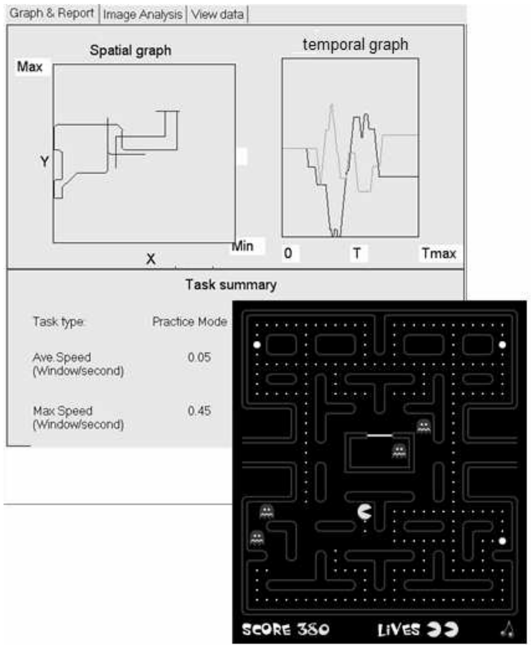
Fig. 3. A partial screenshot of the Tracking Toolbox. As shown here, the TD can design a continuous tracking task by selecting the “Circle” pattern and a spring force field with 60% maximum force magnitude under “Assistance”. A designer window (not shown in this figure) interactively displays an X-Y spatial diagram and an X-T/Y-T temporal diagram to support “What You See Is What You Get (WYSIWYG)” features in the task design time [25].

E. *Motivating Therapy*

Third-party computer game programs can be integrated into the framework as add-ins. Therapy Manager allows the TD to add/remove third-party programs and change sequences. A collection of simple arcade games (e.g., several card and poker games, smart driver, Pong, and Pacman) are current examples of motivation therapy tools (see Fig. 4). The framework can sample the joystick port signals without affecting the performance of most games. Under the “Reduction Data” mode, a few generic kinematics metrics (e.g. Range of Intensity (ROI), speed bins) can be retrieved to estimate factors such as “duration” and “intensity” instead of recording a large amount of movement data when the game context is unknown. The reduced metrics can be presented in different forms (e.g., graph, report and image). For example, ROI can be viewed as an 8-bit gray-scale image that reflects regions within the workspace where the HC stayed longer, with the intensity of each pixel calculated by

$$v = ROI[x, y] * 255 * 2^n / count , \qquad (2)$$

where v is the intensity of the pixel, $ROI[x, y]$ is the count of data points passing the point coordinate $[x, y]$, n is the adjustable parameter in the range [-10, 10], and *count* is the total number of data sampling points. Interactive image processing tools include point operations (e.g. brightness, contrast), convolution (e.g. sharpen, smooth) and edge processing (e.g. Kirsh, Prewitt, Sobel) are integrated into the framework.



Task type: Practice Mode

Ave Speed (Window/second) 0.05

Max Speed (Window/second) 0.45

Fig. 4. Example motivating therapy session involving use of third-party game software: kinematics data (e.g. position, speed) (upper-left) were collected at 33 Hz when an HC was playing “Pacman” (lower-right).

F. *Protocol Design & Management*

The Protocol Manager (PM) enables a user signed in as TD to design an ordered sequence of tasks into a protocol file (XML file) with the structure defined by XML Schema; the HC and optionally the TP can then download the protocol file and load it at runtime. The protocol file is located and loaded at runtime using a Unique Resource Identifier (URI).

To assist novice users, an interactive task design wizard has been implemented to design assessment tasks by answering natural language questions in an interactive dialogue form (e.g., “How fast will the target move?”). Most of the answers are given in 1 to 5 scales, where 1 represents lowest/shortest/least and 5 for highest/longest/most with appropriate default settings. This provides an alternative way for naïve users to design assessment tasks without requiring much previous knowledge regarding framework use.

While in a research study the protocol is normally fixed, the TD can update personalized protocols for a given HC according to the outcome of timely assessments. In addition, we are currently working with physical therapy experts to create a suite of “template” protocols for a few typical populations (e.g. chronic stroke patients, cerebral palsy children) that may share common classes of tasks. These templates then provide a start and can be adjusted to the given HC’s personalized aims.

G. *Telerehabilitation Link*

The communication link between the HC and the TP, supported with the TCP/IP network protocol, can be used both for dynamic “assist” and “resist” modes where the input of the TP’s device (e.g. mouse, joystick) is used as control signal to control the forces on the HC’s therapeutic devices and for cooperative communication between these users. While local input and control signals are always sampled at 33 Hz, with the telerehabilitation link the control signal of the TP (which is the input of the TP'device) is transferred to the patient side is at a reduced rate of 5 Hz due to the lack of guaranteed quality-of-service across the Internet. Both the HC and the TP can view the HC's performance data in real-time. The telerehabilitation link can be used in one of four different modes:

Telesupervision (Telepresence): Using Instant Messaging (IM) technology, the TP can supervise the HC to perform the goal-directed task remotely by audio/video.

Teleassessment: The TP can view the HC's performance data in goal-directed tasks in real-time and view assessment metrics afterwards.

Teleintervention: The TP can remotely interact with the HC in the intervention session by providing assistive or resistive forces to the force-feedback device the HC is using based on the task type and observation of the HC's performance.

Telecooperation: While not yet the focus of any ongoing study, instead of an HC-TP connection there can be an HC-HC connection, thus enabling two HCs to cooperatively accomplish a goal-directed task with team work or compete in a computer game together, where performance data collected by the framework are viewable on either side.

H. Personalized Neurorehabilitation Appliance in the Home

The goal of bringing this framework into a patient's home gives added significance to addressing the need for more consumer-centered, personalizable interfaces. The default HC version is designed and implemented as a multi-modal application with a simple UI which resembles media player [31]. Similar to the process of loading a CD into a CD player, descriptive information such as "protocol title", "task information", and "status" will display for an HC who can then navigate through the protocol list and select specific tasks. Simple voice commands (e.g., "start", "stop", "next", "previous", "repeat") are supported in the HC version. Windows accessibility features are implemented and ready to be used for a screen-reader application.

Alternatively, the HC version also supports UI-Socket/URC standards [22] which facilitate full-function operation of a device or service (called a Target in the UI-Socket/URC standard) through intermediate interfaces or an intelligent agent (the URC) as though they are using a remote console. As shown in Fig. 5, the UI-Socket/URC standards compliance documents in the Target device/service provide information about the Target's socket and describe methods in which a Target can be used to provide descriptive information for any URC ranging from desktop PC to PocketPC to smart wearable computers. This information is intended to be sufficient to dynamically construct a device-independent user interface on the URC with multi-modal interfaces [33]. Most importantly, the interface can be personalized based on information about the user's role, preferences and abilities, which are stored in a separate user accessibility resource file [34].

Our approach is to treat the UniTherapy framework as a target appliance (device) and thus provide UI-Socket/URC standard-compliant documents which are intended to be sufficient for a URC to construct a full-function custom-tailored user interface. A URC prototype running on the PocketPC is implemented and can successfully operate as a remote console consistent with the UPnP Remote UI standard [23].

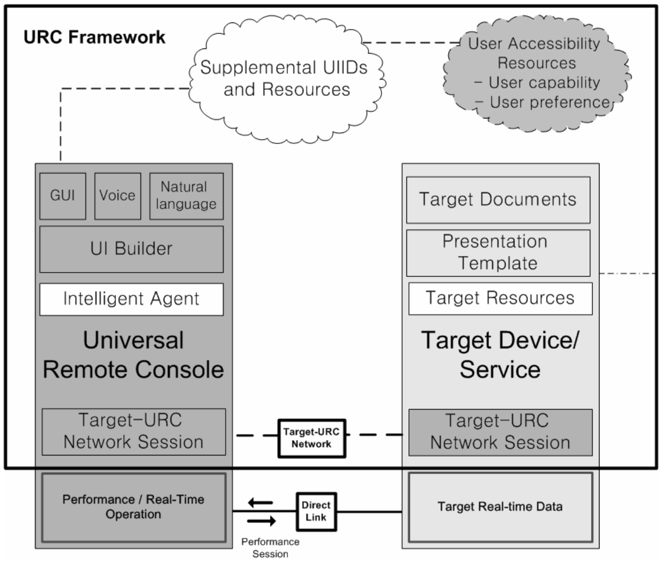


Fig. 5. The overall framework for the UI-Socket/URC standard is described within the black frame. The UI builder in URC generates the HC interface based on the information in the target's socket, which is described by four types of UI-Socket/URC-standard compliant XML documents (target description, UI socket, presentation template, and resource property sheets) and external resources related to user preferences and capabilities. Outside the framework is an optional non-standards-compliant performance session which runs as a Direct Link between URC and the target [32].

III. EXAMPLE RESULTS AND DISCUSSION

A. Research Projects Using the Framework

Several research projects [35-38] have used this framework as their research platform, each with different research aims. These studies have included the collection of both usability and performance data. A byproduct of these studies has been data that can be used to help evaluate various aspects of the framework. This section extracts relevant results from one of these studies, with a focus on answering two questions associated with the sensor-based assessment capabilities of the framework: **1)** whether performance metrics derived from goal-directed assessment tasks are sensitive to the functional level of subjects, and **2)** how task settings (device position, force settings, task configuration) influence the performance of human subjects in goal-directed tasks and should be detected by performance metrics.

This pilot study involved eight chronic stroke subjects with varying degrees of hemiparesis and eight able-bodied subjects as controls. For stroke subjects, the experiment included the upper extremity motor control portion of the Fugl-Meyer (UE FM) [39] assessment test as a tool to assess level of motor impairment, with a maximum score of 66 corresponding to normal arm function. The stroke subjects clustered into "low function" (n=4, UE-FM: 38.2 ± 17.9) and "high function" (n=4, UE-FM: 65.8 ± 0.5) groups. Stroke subjects were first assessed by the ROC task. All subjects then performed a suite of tracking and system identification tasks using conventional force-feedback joysticks and larger remodeled "TheraJoy" joysticks [35], each targeting different upper-extremity arm workspaces. These goal-directed performance tasks were designed using toolboxes ((e.g., Range of Capacity Toolbox, Tracking Toolbox, and System Identification Toolbox) in the Assessment Manager, and managed using the Protocol Manager (see Fig. 2). They also completed a computer game (solitaire) using only the conventional joystick, and participated in a teletherapy session with a remote practitioner who loaded a predefined protocol and observed subjects performing tasks remotely. In addition to performance data collected by the framework, video data were collected using the Mobile Usability Lab (MU-Lab) [40] for usability analysis purposes, and EMG data was collected on eight shoulder and arm muscles. Usability surveys were given at the end to determine the prospective use of the system in the subject's home and their impression of the UniTherapy software and joysticks. All subjects gave informed consent.

Representative results from the ROC task and the continuous circle tracking task will be presented here. For the latter task, subjects were asked to use the joystick to keep the cursor within a moving target square box which moves in a circle pattern within 80% of the device workspace range at a moderately low rate of 12 seconds/circle. The task was first completed under no force settings and then repeated once under spring assistance force field generated by

$$F_{x,y} = k * (s_{x,y} - t_{x,y}) \,, \qquad (2)$$

where $F_{x,y}$ represents the assistance force parallel to the x and y axes, k represents the spring coefficient, $s_{x,y}$ represents the subject (x, y) position, and $t_{x,y}$ represents the target (x, y) position.

B. Data Analysis and Results

A suite of performance metrics was developed and implemented using the Data Analysis Manager (see Fig. 2) with the aim to examine accuracy, smoothness, quickness and stability [41]. The key is to find tasks with metrics that are sensitive to functional changes in the HC, as these would be useful for personalized assessment. Two of these, ROC Area and Percentage Time on Target (PTT), are presented here:

ROC Area: the human subjects' ROC space area. ROC Area reflects effective ROC when using the input device.

PTT: the percentage of time the human subject stayed within the target. PTT reflects both overall performance ***accuracy*** and ***stability***.

Stroke subjects' ROC Area were calculated and presented in graph form along with their UE-FM score. Pearson correlations were used to calculate the correlation between ROC Area and UE-FM score. Mean and standard deviation values of PTT were calculated and are presented in graph form for controls (n=8), the high functioning group (n=4) and the low functioning stroke group (n=4) under no force and assistance settings. A two-way repeated-measure ANOVA test is used with the Bonferroni test for post-hoc analysis.

Figure 6 shows the ROC Area metric by stroke subjects group for the remodeled joystick. Note that there is a strong correlation between ROC Area and UE-FM score. This suggests that the ROC Area metric is sensitive to the impairment level of the stroke subjects.

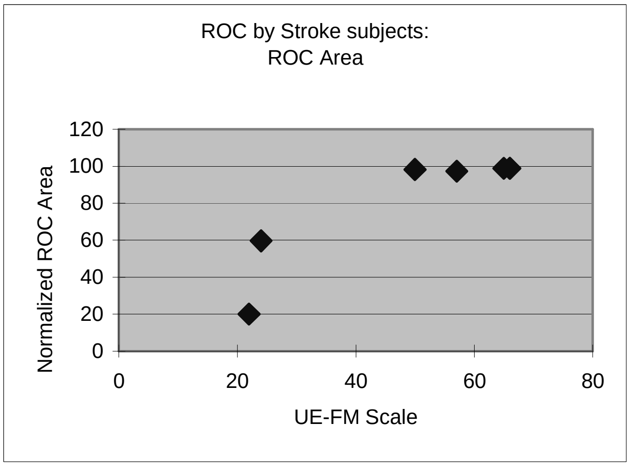


Fig. 6 ROC Area by stroke subjects using the remodeled "TheraJoy" joystick. The ROC Area is normalized to the remodeled joystick's workspace. The correlation r = 0.90 (p< 0.01). 7 of 8 stroke subjects finished the ROC task. Two subjects' data point overlapped at UE-FM=66 and ROC Area = 99%.

Figure 7 shows the Percentage Time on Target (PTT) metric for the continuous circle tracking tasks for control, high function and low function stroke groups under both no force and assistance settings. Note that there is a significant difference between high function and low function stroke group as well as between no force and assistance settings.

C. User Feedback

Questions regarding usability of the UniTherapy framework were included in a survey. For instance, 5 out of 8 control subjects and 7 out of 8 stroke subjects strongly agreed or agreed that "these tasks (performed in the experiment) captured some form of my daily activity." Most subjects were satisfied with the technology, operability and comfort of the system. Most of the stroke subjects indicated that they enjoyed using the computer games with conventional joysticks and were motivated to play in order to increase their game score; they also responded positively to the questions asking if they would use the system frequently and if they would use the system in their home.

Control subjects also provided insightful comments. For example, control subject 1013, a pediatric occupational therapist, showed interest to use this platform in her daily practice and commented: "…Different shapes & characters of cartoons (for fun feedback) would be engaging for a pediatric population." We are using such comments to refine our system.

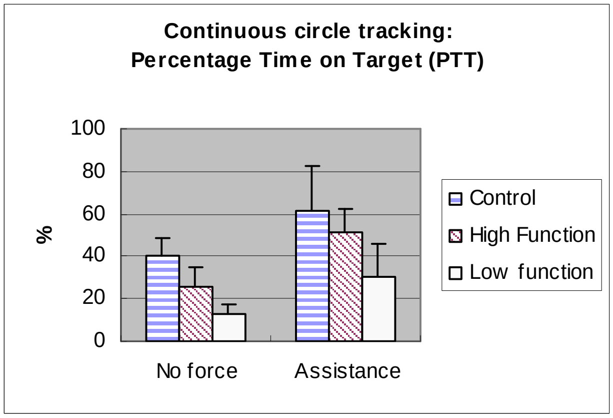


Fig. 7 PTT for continuous circle tracking under no force and assistance settings with a conventional force feedback joystick sorted by the control, the high functioning and the low functioning stroke groups. The results show 1) there is a strong trend in the difference between the control and the high functioning stroke groups ($p = 0.149$); 2) there is a significant difference between the high functioning and low functioning stroke groups ($p < 0.05$); and 3) there is a significant difference between no force and assistance settings ($p < 0.001$).

D. Discussion

Our results support the potential benefit of the personalized framework for stroke rehabilitation in the home. As illustrated in the earlier examples, we have been able to confirm the usefulness of assessment metrics in distinguishing between subjects on different functional levels. These results were consistent with the other published data [42, 43].

Results also suggest that particular assessment metrics can distinguish between motor performances levels in the same subject under different task settings. For instance, with continuous circle tracking, PTT detected differences in accuracy and stability between no force and assistance settings across both groups: subjects performed significantly better under assistance than no force settings.

The example with force assistance was specifically selected because it suggests that the force generated by a conventional force feedback joystick (a small and safe unit available at local electronics stores) could provide significant assistance to home patients and has great potential in stroke rehabilitation practice.

IV. CONCLUSION

In summary, an interactive framework for personalized computer-assisted neurorehabilitation has been implemented with a consumer-centered design approach. A diverse menu of assessment and therapy capabilities is available; these can be used together with other services including a protocol manager and a data analysis tool with a telerehabilitation link. Special attention is paid to the usability and accessibility issues of the tools used by HCs. While targeted primarily for neurorehabilitation, it is suggested that the conceptual framework and structural approach is well-suited for use in other areas of biomedicine.

We validated the potential of the concept via several research projects. The example results presented here support the basic usability of this personalized neurorehabilitation framework for a diversity of goal-directed performance tasks and also demonstrate assessment metrics that are sensitive to functional level of the human subjects and agree with other published data.

An important contribution is the proactive support of existing and emerging standards such as UI-Socket/URC and UPnP. Because of UI-Socket/URC standard compliance, the HCs could use their own preferred interfaces for navigating through protocols without any loss in functionality within the framework. A larger longitudinal study is still needed to evaluate the framework in the home and to determine how well these results can be generalized.

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Xin Feng (S’05) received the B. S. and M. S. degrees from the Tsinghua University, Beijing, China.

He is currently a doctoral student in the Biomedical Engineering Department at Marquette University, Milwaukee, Wisconsin. His primary research interests include home neurorehabilitaiton, human performance analysis, and universal access.

Jack M. Winters received his bachelor’s and doctoral degrees in bioengineering from the Universities of California at San Diego and Berkeley, respectively. He has been a faculty member in biomedical engineering programs for 20 years and is currently a professor at Marquette University. His areas of research include movement biomechanics, neurorehabilitation, and telerehabilitation, and he is the PI and Director on the Rehabilitation Engineering Research Center on Accessible Medical Instrumentation.