ASSESSMENT AND TRAINING IN HOME-BASED TELEREHABILITATION OF ARM MOBILITY IMPAIRMENT

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Abstract: The aging population and limited healthcare capacities call for a change in how rehabilitation care is provided. There is a need to provide more autonomous and scalable care that can be more easily transferred out of the clinic and into home environments. One important barrier to this objective is achieving reliable assessment of motor performance using low-cost technology. Toward this end, an assessment framework and methodology is proposed. The framework uses 4 sequential games to measure aspects of range of motion, range of force, control of motion, and control of force. Parameters derived from the range of motion task are used to define motion requirements in all subsequent assessment games, while parameters derived from the range of force task are used to define subsequent lifting force requirements. A 12-week usability study was conducted in which 9 patients completed the clinical testing phase and 6 therapists and 7 patients completed the questionnaire. Feedback from the questionnaire shows the system is easy to use and integrates well in the clinical setting. The most commonly requested modifications were the inclusion of more games and the incorporation of hand training. Some initial position and force data are shown for one subject and discussion on implications for mobility assessment using the developed device are provided.

Keywords: Arm rehabilitation, Mobility assessment, Reach training, Stroke, Rehabilitation, Home-based telerehabilitation.

Introduction

Home-based telerehabilitation is a growing field that has much to offer healthcare. In many developed countries, the population is aging; people are living longer; and the prevalence of stroke continues to increase dramatically with age. These factors add to a large and growing stroke population, while healthcare resources remain rather stagnant. As a result, there is a need to provide more autonomous and scalable care that can be more easily transferred out of the clinic and into the home. One of the largest challenges in this task is providing a means of low-cost quantitative assessment that can provide clinical relevance for therapists. The assessment must allow transparent supervision and the ability to make informed revisions of prescribed training plans during post-acute stroke care.

Stroke is the most common source of long-term disability in Spain and throughout developed countries worldwide. European statistics as a whole report that nearly 1 million people experience a first or recurrent stroke each year (Hesse et al. 2005). Improved medical treatment during acute stroke care has resulted in lower rates of mortality, and yet residual arm impairments persist long-term with only 14-16% of the hemiparetic survivors recovering complete or near complete motor function (Nakayama et al., 1994).

A variety of methods are used in post-stroke rehabilitation including constraint-induced movement therapy and progressive resistance training, as well as techniques aimed at patients with less mobility such as bilateral movement training, and mirror therapy (Oujamaa et al., 2009; Fasoli et al., 2004; Stevens & Stoykov, 2004). For patients with more mobility, constraint-induced therapy is a widely-used approach aimed at combating learned non-use of the impaired limb, but has the limitation that patients must have a minimum level of movement and control in order to use it (Dobkin, 2005) and therefore may only be applicable in as few as 10 percent of patients (Grotta, 2004). Progressive resistance training is another widely-used approach and one which can be supported through web-based interfaces and robotic technologies.

Performing progressive resistance training exercises have been shown to increase both strength and function in a number of studies (Patten et al., 2004). Patten and colleagues summarize nine studies that show evidence that training as little as 3-4 times per week for 6-12 weeks is enough to yield functional improvements. Dobkin (2005) reports significantly better outcomes in task-oriented practice for patients who are able to engage in 16 or more additional hours per week as opposed to those who only spend a few additional hours. Although this supports the "more is better" approach, it has further been suggested that the process and quality of care are likely to be as important as total hours of therapy (Quinn et al., 2009). Patients improve more, for example, when they actively participate in training tasks rather than play a passive role.

Still, the amount of professionally-supported rehabilitation training provided to the average patient falls short of the ideal. A Dutch report published in 2008 (Peerenboom et al., 2008) reported that the average treatment time for stroke patients in skilled nursing facilities was about 4.5 hours per week. Only about half of this time, just over 2 hours per week, was spent in physical therapy.

In an era where rehabilitation services are diminishing under the weight of growing demands and fewer therapists, robotically assisted rehabilitation and home-based rehabilitation have become a major focus of much research. Robotics offer precision and repeatability of movements, quantitative measures, and data that can be used for assessment of movement quality. For these and other reasons, robot mediated therapy for upper limb rehabilitation continues gaining momentum as a very promising technique. Results of clinical trials with robots such as the MIT-Manus (R&D prototype) and the InMotion3.0 (commercialized version of the MIT-Manus) have demonstrated that robotically assisted rehabilitation is safe, accepted by patients, and comparable with conventional therapy (Krebs et al., 1999; Lo et al., 2010). The MIT-Manus, under development since the late 1980´s and later commercialized as the InMotion3.0, was one of the earliest systems for robot assisted rehabilitation. Like many research prototypes, its primary focus was on assessment and training in the clinical setting. Only in more recent years have

several groups begun to launch systems for home use to address the real unmet needs in the healthcare system.

Home-based telerehabilitation offers a way of increasing duration and intensity of post-stroke training. Unfortunately, most platforms for home-based rehabilitation are developed with a specific set of rehabilitation tools or devices in mind, and therefore have limited extendibility to other tools and devices. Another criticism that can be made is that most telerehabilitation software is developed from an engineering perspective with minimal requirements derived from the wide spectrum of stakeholders. Because of this, combined with the inherent difficulty of altering existing policies and practices in medicine, progress in clinically-supported telerehabilitation technologies has been slow.

Despite the pace, home-based technologies are making significant advances as the need becomes more recognized. Some of the more notable advances in the history of game-based telerehabilitation have been made by Cogan et al. (1977) with the introduction of Pong to the world of rehabilitation, Reinkinsmeyer et al. (2001) with Java Therapy, Ellsworth and colleagues (Johnson & Winters, 2004) with TheraJoy, Feng and Winters (2005) with UniTherapy, and Lum et al. (2005) with AutoCITE. Following these and other preliminary research studies, a large increase in telerehabilitation efforts have been seen, particularly over the last 3 years. Recent commercial players in the field include Telefonica ([20]), MediTouch ([21]), HomeTelemed ([22]), Tyromotion ([23]), Hocoma ([24]), and others ([25-30]) (see Appendix 1). Even with the players involved, commercial success is limited; new technologies are still needed that can support patients while training at home and simultaneously lessen the load on the therapist. The solution lies in the development of a system that can be easily integrated with current practice and that supports a smooth and early transition of patients to the home environment, with a special focus on minimizing initial and recurrent costs.

In this work, an assessment methodology for a new home-based telerehabilitation system for post-stroke arm rehabilitation is presented. Together with a set of games for mobility assessment and training, results of

a usability study with the ArmAssist system are presented, and some preliminary assessment data and discussion are provided.

Background and Previous Work

Telerehabilitation System Overview

A telerehabilitation system called the ArmAssist (Figure 1) has been under development at TECNALIA for the past five years. It combines a portable device for arm support with web-based therapy management software and a set of games for assessment and training. The training concept is based on well-known research on gravity-induced discoordination in the shoulder and elbow and its effect on the active range of motion of the arm [Beer, Dewald, & Rymer, 2000; Dewald & Bear, 2001; Bear et al., 2004; Ellis et al., 2005].

The combined system is designed to allow the initiation of arm training in the clinical setting, under the direct supervision of a therapist, and the continuation of training at home, thereby increasing both duration and intensity of training. The system components and functionality have been previously described in publications (Zabaleta et al., 2011; Perry et al., 2012; Rodriguez-de-Pablo et al., 2012) and a short summary can be found in Appendix 2.

Telerehabilitation and Assessment Software

In addition to the hardware to support arm reach training, a modular telerehabilitation platform was developed. It was designed to support the phases of therapy planning, execution, and assessment. Details of the functionalities supported in the platform are further described in [Perry et al., 2011a; Arcas Ruiz-Ruano et al., 2012].

In the development of game interfaces, a distinction was made between games for assessment and games for training. Assessment games were short tasks (1-2 minutes) that involved a targeted movement with defined parameters, while training games spanned longer timeframes (5-15 minutes) and provided more entertaining or challenging environments to fill the majority of training time and maintain user engagement. The training games were developed following fundamental training methodologies recommended

by the therapists including movements that should be encouraged and discouraged. Encouraged movements were those that worked against the abnormal muscle synergies in the upper limb (Brunnström, 1970), forcing the user to train reach extension movements that were difficult to control because of abnormal patterns of muscular contraction. The movements generally require simultaneous abduction of the shoulder and extension of the elbow. Arm movements that require the opposite movement, (i.e., flexion of the elbow with adduction of the shoulder), should be supported against gravity and/or allowed to move freely, if not assisted. This is recommended in order to minimize the potential of eliciting undesired spastic reflexes. Assessment games were designed to provide the clinician with an objective assessment of the range of movement, vertical support force, and the patient's ability to perform trajectories and supported reach extension movements. Training games, on the other hand, were composed of more complex tasks and exercises. They included integrated cognitive and motor components of higher complexities in order to better motivate and engage the subject; they incorporated aspects such as: problem resolution with jigsaw puzzles, card games, and sorting tasks; memory recall tasks with classic memory games; and language skills with word completion tasks. Further details about the Telerehabilitation platform and games developed for training can be found in Appendix 3.

Figure 1. The ArmAssist telerehabilitation system is composed of the ArmAssist base module, extended arm reach support, a web-based telerehabilitation (TR) platform, and a 21-inch touchscreen display.
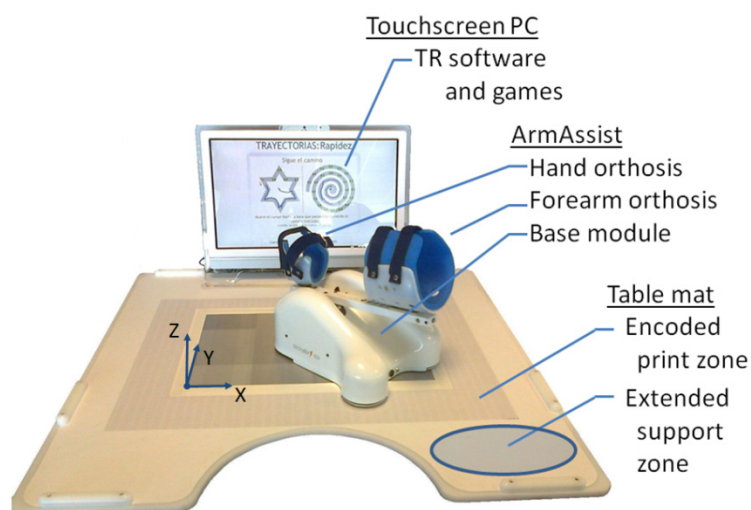
Initial levels of the assessment games are shown in Figure 2. The set of assessment games were designed to measure: 1) Range of motion, involving multi-directional reach extension from a central point (Fig. 2a); 2) Range of Force, involving support arm weight in the vertical direction (Fig. 2b); 3) Control of motion, involving a trajectory following task (Fig. 2c); and 4) Control of force, involving a sustained vertical support force while performing a reach extension task (Fig. 2d). Each game is described in detail in Appendix 4.

Figure 2. ArmAssist games for assessment: (a) range-of-motion, (b) range-of-force, (c) control-of-motion, and (d) control-of-force.

(a)

(b)

(c)

(d)
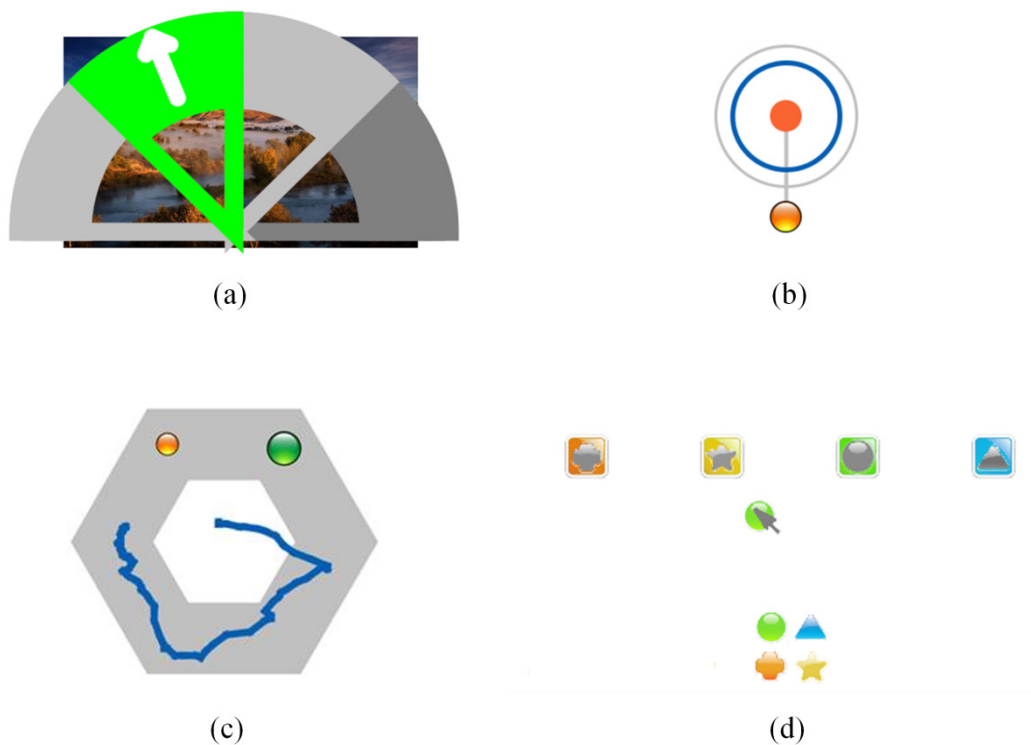
Methods

Usability Testing Protocol

Usability testing of the passive (non-motorized) ArmAssist prototype was carried out at two rehabilitation centers. A 12-week clinical pilot test was conducted according to the timeline shown in Figure 3. The protocol involved a period of 3-4 weeks training in the clinic with direct supervision from the therapists, an 8-9 week training at home, and a transition period in

between during which the system was setup in the patient's home. The transition period allowed for differences between various in-patient stays and coordination with local research personnel to support the setup process. The target amount of ArmAssist training during the study was 30 minutes per day, 5 days per week.

The evaluation of patients' progress using standard clinical scales were planned to take place at fixed stages of the process: on admission, on discharge from in-patient training, on discharge from home training, and 3 months after the home training discharge. In-patient training started when therapists decided that each patient had sufficient trunk and shoulder stability to use the ArmAssist device. The measures for this were not standardized between the centers. The time that each patient spent at the hospital varied depending on his/her condition. Performing the home-training phase at the patient home was not possible in some cases, due to the nature and duration of in-patients at one of the centers. As a result, the degree of supervision during the "home training" phase varied with each center and therapist, and was not strictly enforced.

Feedback was collected from seven patients and six therapists through written questionnaires while other patients contributed only through recorded movement data of 2D position and vertical force. Questionnaire feedback was collected voluntarily from patients and therapists via a series of structured interviews and Likert-based evaluation questions. The administered questionnaires presented 16 questions to each patient and 19 questions to each therapist. Questions included aspects of system features, system usability, and recommendations from the user to improve the system. The specific questions can be found in Appendix 5.1. 2D planar position and vertical support/lifting force data during assessment tasks were recorded throughout the clinical and home training phases for later analysis. Of the participating patients, nine completed the clinical testing phase. Range of motion and range of force data from two of these patients is provided in the results section.

Mobility Assessment Games and Measures

General performance indicators were stored for all games in each session. During assessment games, full force and trajectory information were also stored in order to allow a more detailed post-processing analysis. In case of lost network coverage, the platform was equipped with an offline training and data storage mode so that data could be stored locally on the hard-drive and synchronized periodically with a central server.

Strict overall times and intermediate countdowns in the case of inactivity were employed in all the assessment games to ensure that assessments were carried out efficiently.

Figure 3. Testing timeline for usability evaluation of the ArmAssist telerehabilitation system.
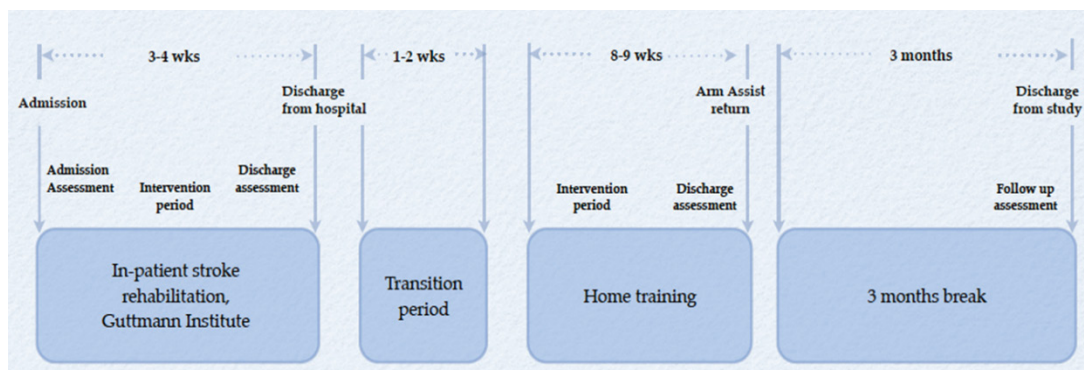

Level Structure

The game level structure implemented had three level aspects: motion level (L_{ROM}), force level (L_{ROF}), and task level (L_{TG}). The motion level, L_{ROM}, was set by the range-of-motion assessment game and altered the range of motion of all successive games (assessment and training) for the session. For this reason, the range-of-motion assessment was always performed first. The force level, L_{ROF}, set by the range-of-force assessment game was also used to alter all successive games. The range-of-motion game did not involve a force level assignment as the objective was to measure range of movement in the fully-supported condition.

There were 5 difficulty levels for each level component (i.e., L_{ROM}, L_{ROF}, L_{TG}) to allow adjustment of the assessment environment to best fit the patient´s

capabilities. Each game was scored based on a combination of evaluated features. In this experiment, the game levels were adapted automatically based on performance. The motion and force levels were adjusted by the range-of-motion and range-of-force games, respectively, and the task level was adapted based on the previous performance(s) in each respective game. The adaptation method adopted was the following: a game score of 100 percent or two consecutive scores of at least 80 percent prompted a level increase. The game levels involved in defining the difficulty of each task are illustrated in Figure 4a. Examples of the initial and final game levels for the assessment games are shown in Figure 4b

Figure 4. (a) Sequential relationships of assessment measures and level structure. (b) Assessment game level increases from initial level to final difficulty level for each of the assessment games. Note that the force level in the range of force game (bottom-right) can be adapted without changing the visual layout of the task.

(a)


(b)
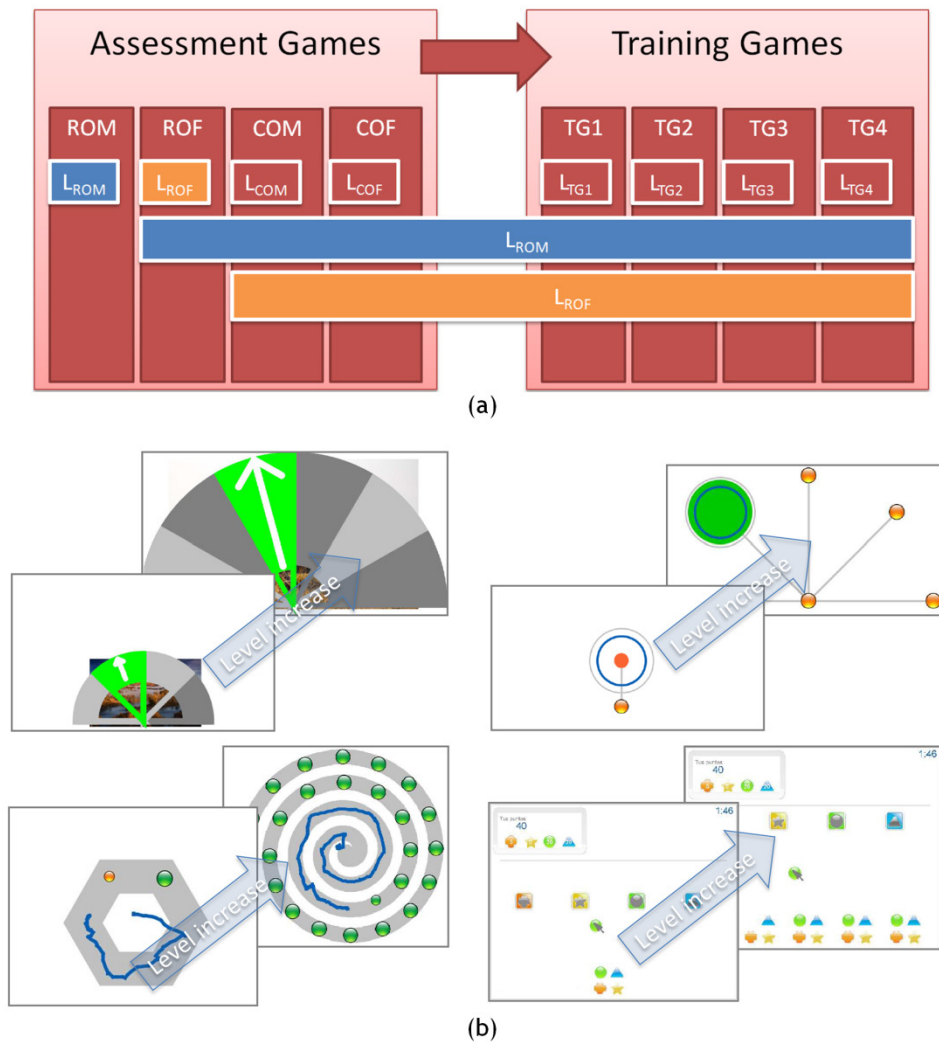
Results

Usability Feedback

Six therapists and seven patients provided feedback through the evaluation questionnaire. The feedback gathered from patients and clinicians was overall very positive. The system was found easy to use, and was generally well accepted. The games provided a clear increase in motivation when patients started using the system and the therapists felt the tasks were well aligned with the techniques they typically used for training. Through the questionnaire, therapists expressed that they felt the system would be useful for the kinds of patients that they see, that the patients would benefit from the training, and that the training would produce an improvement in the patient condition. One of the criticisms common to both therapists and patients concerned the need for a wider selection of training games and for an increased number of levels within the same game. This and other feedback related to the usage and user perspectives of the telerehabilitation platform and games are being integrated into the system to improve its features and usability. Further details about the questions and responses for both patient and therapist questionnaires can be found in Appendix 5.

Pilot Assessment Data

A qualitative evaluation of the data progressions reveals characteristics of the reach movements related to range of motion, directional control, smoothness, and limb support capacity. It should be acknowledged that to show these characteristic trends quantitatively along with their respective magnitudes and significance, further analyses and computation of metrics are needed. For the purpose of illustration and discussion, initial results of range of motion and range of force assessments from two stroke subjects are presented in Figures 5 and 6. The subjects were training at two different rehabilitation centers in Spain. Although 9 subjects completed the clinical training phase, only two subjects from one center continued the protocol at home due to various reasons unrelated with system performance. Due to the

nature of one center, it was not possible to support a truly home-based training, and so when possible, patients continued training in the clinic under reduced supervision.

Figure 5. Pilot result of planar movement and vertical support force for stroke Subject A. Polar plots of range of motion ((a)-(d)) and range of force ((e)-(h)) assessment show movement data in the horizontal plane, and boxplots of arm support ((i)-(l)) show force applied to the device at the target locations illustrated in polar plots (e)-(h). Color coding in subplots (e)-(l) show correspondence between locations and magnitudes of vertical force data. Data shown in each column were recorded during the same session (session dates provided at the top of each column).
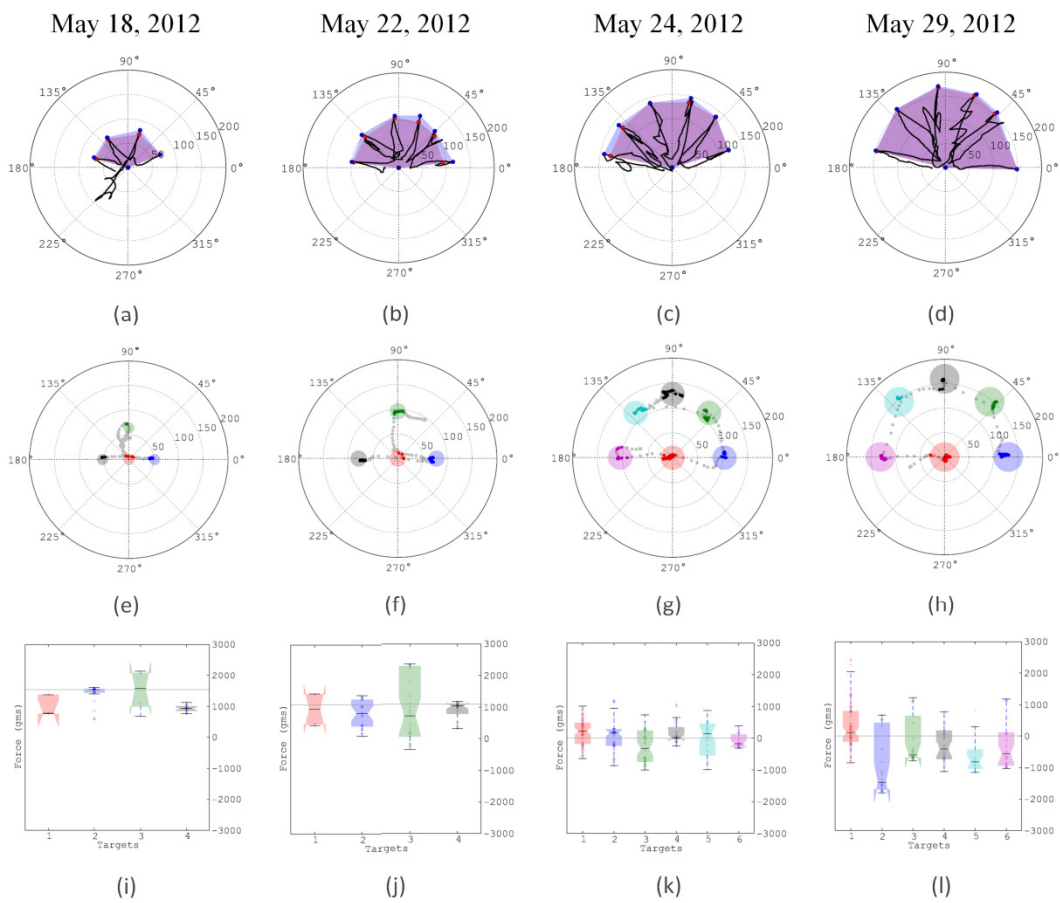
In both Figures 5 and 6, subplots (a)-(d) show four polar plots of planar movement trajectories and work areas during the range of motion assessment. Subplots (e)-(h) show polar plots of planar movement trajectories and locations of selected force measurements near the targets. Colored data points in subplots (e)-(h) show the locations of the force data that have been included in the boxplots of subplots (i)-(l). Subplots (i)-(l) show boxplots of the vertical force measures that are achieved near the targets where the velocity is low (i.e., less than 10 percent of the peak velocity). Grey data points in subplots (e)-(h) indicate trajectory points where the velocity was higher than 10 percent of the peak velocity or where the distance to the target was more than 25 percent of the average distance between central and peripheral targets. This area is shown in subplots e-h as colored areas surrounding each target location. These were not visible during the assessment game. Data shown in each column were recorded during the same session and the session date is provided at the top of each column.

In the range of motion assessment data for Subject A, shown in Figure 5, both target work area (red shaded region) and performed work area (blue shaded region) increase over the sessions. The planar location of vertical force assessments in Figures 5(e)-(h) (colored circles) progressively shift more distal while the target vertical force threshold (grey line, Figures 5(i)-(l)) which shows the target level of unloading (i.e., reduced resting weight on the device) lowers on the graph, and the patient's ability to unload the arm is maintained or increased at progressively more distal targets.

Similar trends can be seen in the data of Subject B, shown in Figure 6. Although the work areas in Figures 6(c) and 6(d) were nearly the same, improvements in directional control and force measures are seen. More direct trajectory paths and smaller groupings of endpoint positions during the lift tasks indicate the patient exhibits a higher level of control. Comparing vertical unloading forces in Figures 6(i) and 6(l), although the magnitudes and variations are similar, the progression shows that an improvement in sustained support in extended reach positions was achieved.

In Figure 6(g), two targets on the left were not reached within the allotted time and the assessment algorithm moved the targets 50 percent closer to the central target where they were then successfully reached.

During the usability study, the actual time spent in assessment and training by the patients fell short of the desired 30 minutes per day, averaging 14 minutes and ranging from 6.7 to 40.8 minutes per day.

Figure 6. Pilot results of planar movement and vertical support force for stroke Subject B. See Figure 5 caption for subplot details.
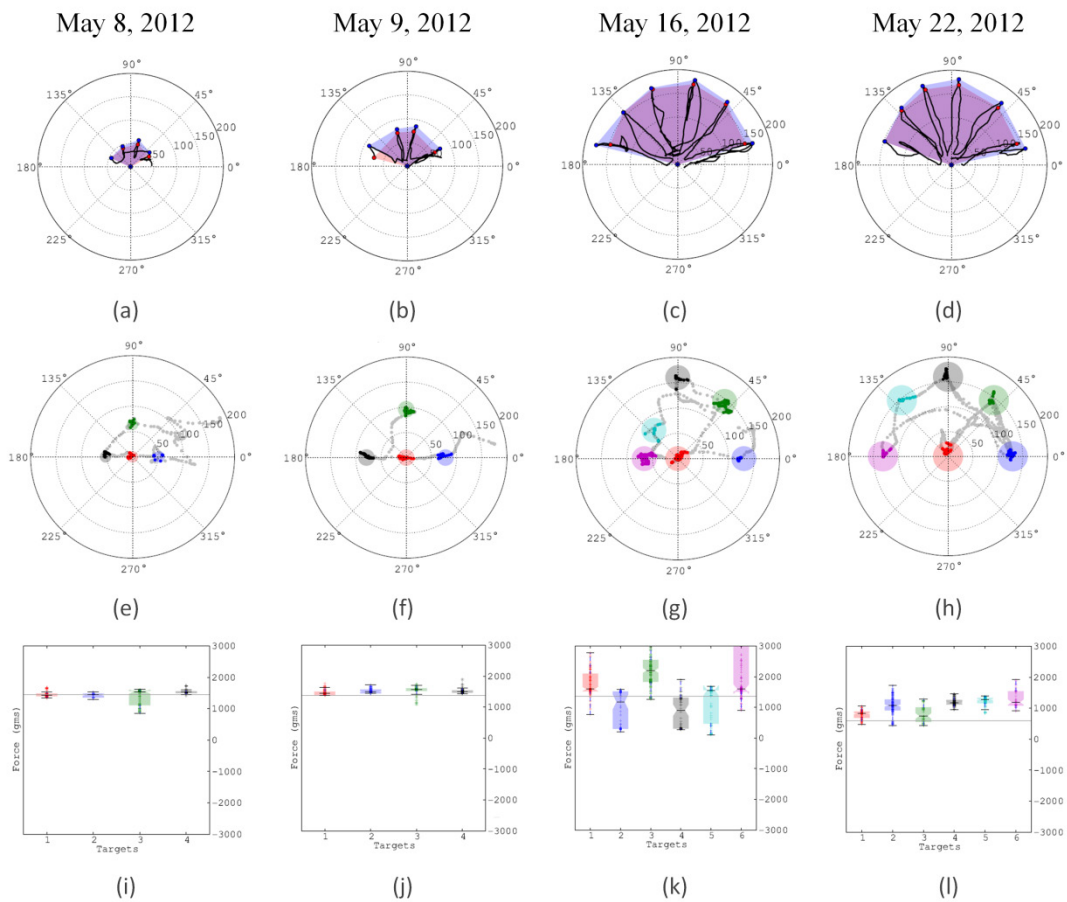
Discussion

Training Motivation

Although patients were clearly motivated at the start by the game interaction and feedback, the set of games and levels available played a significant factor in decreasing motivation as the patients trained for longer durations. When asked at the beginning of training about patient motivation using the system, therapists were nearly unanimous in their belief that the system increased motivation. When asked at the end of the study whether the patients were motivated to train longer with the system, the responses were a bit more neutral but maintained a clear tendency toward agreement that the system increased motivation (see Appendix 5.2). At the same time, therapists and patients consistently made requests for a wider variety of games, both to increase the number and expand into new genres. As a result, although the strength of motivation reported was more neutral after the 2-3 months of training than at the start, the results indicate that motivation is increased by the system and that the system´s maximum potential for motivation was not reached.

Assessment Metrics

In this paper, various assessment games and training adaptation methods have been proposed and qualitative observations on assessment data have been made, but little focus has been placed on metrics. These qualitative observations can theoretically be confirmed with the computation of quantitative metrics, providing a more objective evaluation of patient mobility performance. Although the selection and comparison of optimal mobility metrics has not been presented here, this work is in progress and will be the focus of a future publication. It should be noted that the optimal methods and metrics to use for mobility assessment is a current and ongoing debate (Lambercy et al., 2012). For range of motion, the metrics of interest were those that represented the extent of extension movements away from the torso, and therefore can be represented by an array of linear measures, or as a single measure of area. For control of motion, the metric of interest

was the smoothness with which positional changes are achieved to reach a known target that requires extension of the arm. For range of force, the metric of interest is the maximal level of self-support against gravity that the user can achieve. This does not imply a movement of the arm or an active application of force by the device, but rather the passive measurement of the weight of the user´s arm resting on the device. This was done at known and predetermined locations within the user´s active range of motion. For control of force, the metric of interest was smoothness of the force signal as well as the error with respect to the desired force.

In the measure of range, an important element to monitor is posture in order to ensure a proper measure of movement. If compensatory movements can be avoided, the important aspect in range of movements is not *when*, but *whether* a target can be reached. The element of time will be accounted for in the later measures of control, as a lack of control will naturally lead to sub-optimal movement trajectories that require a larger execution time. Postural changes during compensatory movement are a common occurrence during arm rehabilitation. Although a greater level of compensation may be allowed during training, for a proper assessment, postural compensation must be handled either through the use of physical or mechanical restraints or visual monitoring and corrective feedback.

Game Levels

Five game levels were defined by the number and radius of sectors in the 2D planar workspace with the goal of: a) allowing patient-specific adaptation in order to maximize visual resolution of movement feedback to the user, b) improving the match between ability and task challenge within the assessment, and c) reducing the potential for demotivation as a result of the size or complexity of the displayed, and/or potentially unused, workspace. Through combination, the 5 levels produce up to 25 game levels in the range of force game and up to 125 levels in games specified by L_{ROM}, L_{ROF}, and L_{TG} levels. The number of levels that will be played by any one patient, however, will vary with their ability level and the speed at which they progress through each individual assessment level. While this could offer benefits for patients whose compensatory movements are prevented or

corrected during assessment, in many clinics this was not the case. Assessments were done with minimal correction on posture allowing patient to advance through the assessment levels at a potentially faster rate than otherwise would be expected. This consequently makes it more difficult to compare patient results between sessions over the duration of training until level 5 is reached and the assessment task remains constant. As a result, it is recommendable to present range tasks in a standardized single-level format. The results of the range-of-motion can (and should) then be used to normalize the range-of-force assessment, and the outcome of both range-of-motion and range-of-force should be used to normalize the control-of-motion and control-of-force assessments, and all successive training games to the patient. This automatic game normalization should be carried out with the purpose of optimizing the presentation of tasks in the appropriate position and force workspaces in order to both challenge and motivate the patient to advance.

Training Time

It was noted during the study that the actual time spent in training varied substantially between patients and sessions. This is thought to be due in large part to the method in which training assignments were made and the nature of the game lengths to be highly dependent on the ability and speed of the user. Game durations were not fixed, nor were estimated lengths provided to the therapists to know approximately how much training time they had assigned to the patient. These results lead to a need for a better control on the length of assigned training tasks, for example, by repeating assigned games until a predefined time period has expired.

Future work

Building from the initial pilot testing results showing qualitative improvement with training, further work on comparison of alternative assessment metrics will help to provide clinicians with objective measures on which to base training revisions. Optimization of these metrics, and comparison to standardized clinical scales in order to best characterize mobility deficits within the stroke population, will provide valuable

measures of patient progress that can be performed independently and monitored remotely. For the patient, improved quantitative characterization of deficits is expected to improve automatic level adaptation within the training games in order to optimally match the user´s ability with the task challenge. Proper adaptation of the task challenge such that the risk of boredom (being under-challenged) and frustration (being over-challenged) are minimized, is expected to increase aspects of user engagement and motivation.

Conclusion

The telerehabilitation system and training adaptation structure described in this paper has been developed and evaluated with therapists and patients in both in-clinic and at-home settings in order to maximize usability with the end users. A set of games for mobility assessment and training were developed following therapist recommendations that games should train coordinated movements that go against the abnormal muscle synergies, and avoid movements that can reinforce flexor muscles. Through appropriate game design and selection of task parameters, tasks and task difficulty can be adapted for each training session in telerehabilitation training at home. In their current versions, the range-of-motion, range-of-force, control-of-motion, and control-of-force assessments are performed by uncovering a picture, lifting (or unloading) the arm at one or several positions, tracing a path trajectory, and by picking and placing objects from proximal to distal locations.

It is believed that the quality of arm mobility in planar reach movements can be adequately characterized by measures of planar position and vertical force. Qualitatively, the mobility data measurement recorded by the non-motorized ArmAssist, consisting of 2D position and 1D vertical force, are able to represent improvements in mobility performance over time. The visual progressions with increased training duration show noticeable improvements in both directional control and general smoothness during arm reach and lift tasks. However, demonstration of long-term efficacy of the intervention in

home use requires further study of mobility metrics and stricter adherence to the home testing protocol.

Overall, initial feedback from patients and clinicians has been highly positive. Some decline in motivation and participation was observed with some patients due to the low number of training games and levels developed for the purpose of system evaluation. It is recognized that a high number of training games is needed in order to maintain patient engagement and motivation in long-term high intensity training. These findings promote the need for a larger array of task-specific games and training exercises to both improve the variety of training activities available and to increase the level of sustained user engagement and active participation.

Acknowledgements

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APPENDIX

APPENDIX 1. Growth of telerehabilitation

Over the past 50 years, the number of software systems for home-based rehabilitation has remained relatively small with a sharp increase in related research in the last decade. The promising benefits of rehabilitation systems for home use are attracting universities, research institutions, and companies alike. Companies showing interest in the field are primarily new startups, but examples of well-established companies such as Telefonica, can also be found. A short list of research and commercial activities in Telerehabilitation are illustrated in Table 1.

In a first attempt to produce more enjoyable and motivational games for rehabilitation, Cogan et al. (1977) modified the commercial game Pong into a task interface played with a joystick for rehabilitation of hemiparetic patients. In 2001, Reinkensmeyer et al. (2001) introduced a novel web-based

force feedback telerehabilitation application called "Java Therapy". Building on previous ideas, Ellsworth and colleagues created TheraJoy (Johnson & Winters, 2004), a telerehabilitation environment that uses a modified force-feedback joystick to complete games and tracking tasks created with the custom software UniTherapy (Feng & Winters, 2005), a computer-assisted neurorehabilitation tool for teleassessment and telerehabilitation of arm function. In 2005, Lum et al. performed some novel experiments with the AutoCITE device ([23]) for providing guidance in the performance of various Constraint Induced Movement tasks. The system was used to simulate the effect of telerehabilitation by separating the patient and therapist in different rooms. Results indicated the AutoCITE could be used to provide Constraint Induced Movement therapy with a 75% reduction in Therapist time.

Table 1. Summary list of devices and platforms for telerehabilitation, showing the approximate year of development, whether upper limbs (UL) or lower limbs (LL) are targeted, and the company or research group involved.

Rehab Device Name	Year	Targeted Joints	Company (Location) / Researcher (University)	Compatible TR Platform
T-WREX*	*2001*	*UL: shoulder, elbow*	*Renkinsmeyer (Univ. California, Irvine)*	*Java Therapy*[14]*
TheraDrive*	*2004*	*UL: wrist*	*Winters (Marquette U.)*	*TheraJoy* [15]*
AutoCITE	*2005*	*UL: wrist*	*Lum (Catholic University of America)*	*(Simulated platform)* [17, 18]*
(IMU-based device)	*2009*	*LL: hip, knee*	*Telefonica (Spain)*	*RehabiTIC [19]*
HandTutor, ArmTutor, LegTutor	*2010*	*UL: wrist, fingers, UL: shoulder,elbow, LL: hip, knee*	*MediTouch (Natanja, Isreal)*	*MediTutor [20]*
Curictus VRS	*2010*	*UL: shoulder, elbow,wrist*	*Curictus (Gothenburg, Sweden)*	*Curictus Analytics* [24]*

Rehab Device Name	Year	Targeted Joints	Company (Location) / Researcher (University)	Compatible TR Platform
ReJoyce	*2010*	*UL: shoulder, elbow, wrist, fingers*	*HomeTelemed (Edmonton, Alberta)*	*(video-conference software) [21]*
Pablo, Pablo®Plus	*2011*	*UL: shoulder, elbow, wrist*	*Tyromotion (Graz, Austria)*	*(Assessment and Therapy) [22]*
ArmeoBoom	*2011*	*UL: shoulder, elbow*	*Hocoma (Switzerland)*	*Armeocontrol [23]*
*ArmAssist** (Others)*	*2011*	*UL: shoulder, elbow UL*	*Tecnalia (San Sebastian, Spain)*	*TeleREHA** [25]*
(Various devices)	*2012*	*UL / LL*	*Play4Health.com (Palma de Mallorca, Spain)*	*Platform P4H [26]*
(Kinect-based device)	*2012*	*UL / LL*	*Principe Felipe (Valencia, Spain)*	*Neuro@Home* [27]*
Gloreha	*2012*	*UL: fingers*	*Indrogenet (Brescia, Italy)*	*? [28]*
(Kinect-based device)	*2012*	*UL / LL*	*VirtualWare (Basauri, Spain)*	*VirtualRehab [29]*

In the case of Telefonica, a well-known provider of telecommunication services, a platform called RehabiTIC has been developed to guide patient movements based on movements acquired from wearable sensors (Olivares, 2011). Six systems are under development through small startups, and two through more established companies (Hocoma in Switzerland and Tyromotion in Austria). Two systems are based on movements acquired from a Kinect sensor while games are used for guidance and correction ([27], [29]), while the majority use proprietary devices in the training of movement. One of the six startups, Curictus (Gothenburg, Sweden), was acquired by the JSM Group in 2010 and, as a later result of difficulty entering the market, decided to close the project. Subsequently, the code was made available to the public

for others to use and further develop ([24]). The list in Table 1 is not a comprehensive overview of the current telerehabilitation work, but provides insight on the recent rate of growth.

## APPENDIX 2. ArmAssist Hardware for arm reach support

The ArmAssist system is equipped with 5 integrated sensors and 4 degrees of freedom (dof). Together, the sensors and freedoms allow measures of supported movement in a large semi-planar workspace. The hardware is designed for left and right use, employing lateral symmetry in components such as the base module, table mat, and monitor placement. Non-symmetrical components like the orthoses can be rapidly disconnected and replaced with a single button press (Perry et al., 2012).

Wireless Mobile Base Module

The internal structure of the wireless mobile base unit is composed of an aluminum structural frame, an integrated pcb, a 1-dof force sensor, and a quick-connect forearm assembly. The structural frame is an assembly of custom aluminum brackets designed to house three omni-directional wheels, the force sensor, and connect the various other components that make up the assembly. The 1-dof force sensor has been integrated as the connecting element between the structural frame and the forearm assembly, measuring all user interaction forces in the vertical direction. This vertical support measure is a fundamental component of the system and the primary measure that enables progressive load training.

Global Position Detection Table Mat

Figure 7. The global position detection mat is printed with 16 zones (a), each containing a distinct repeated pattern (b).

(a)   (b)
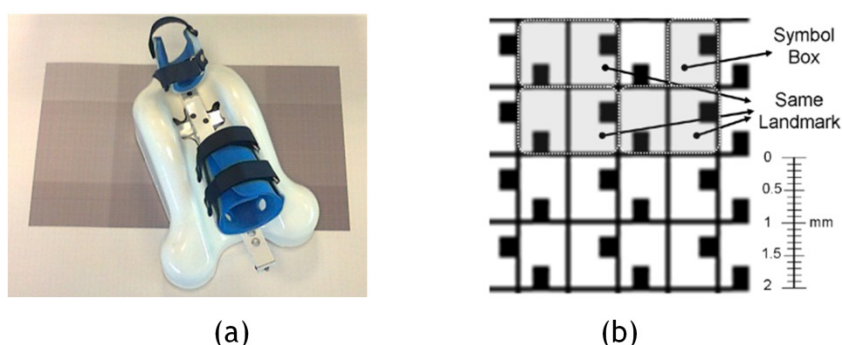
The global position detection mat is composed of a high density polyethylene sheet with a high resolution laminated print mounted to the top. The sheet extends the planar support surface provided by a standard table in the lateral zones. A semi-circular cutout allows patient to sit close to the table while allowing the mat to wrap around the torso, providing support to the mobile base module in the lateral regions when the patient is at rest. Further details of the global position detection mat and the optically-based encoding method utilized has been previously published (Zabaleta et al., 2011).

In summary, the laminated print is encoded with a central grid composed of 16 zones (Fig. 7a) that are each made up of a repeated 2-symbol pattern (Fig. 7b). The pattern is then captured by a camera and sent to the PC for image processing and the position within the current zone is estimated. The accuracy of the estimation can be affected by image print quality and camera resolution. For laser print quality and an ADNS-3080 mouse sensor (Avago Technologies, 30x30 pixel count), the system planar (x-y) resolution that can be achieved is on the order of +/-1 cm in position and +/-2.6 degrees in orientation (Perry et al., 2012).

APPENDIX 3. TeleREHA platform and training game development

TeleREHA Online vs. Offline Platforms

It was evident during early system testing that gaining access to a reliable internet signal in many hospital settings is currently unrealistic. As a result, both online and offline versions of the software were developed. For the online version, Java was used as the primary language for the system server development. The Spring framework was used in a 3-layer model, including Hibernate with MySQL as the database layer, and Primefaces for the presentation layer. For the video communications, a red5 media server was used. In the case of the offline platform, a 2-layer model using Java Server Pages and XML as storage repository was used, avoiding the installation of a locally-running database. Ajax was used for results synchronization with the centralized server. In both online and offline platforms, Tomcat 6.0 was used for the application server.

In the development of serious games for assessment and training, the same technology was used in both TeleREHA online and offline versions. 2D games, described in (Rodriguez-de-Pablo et al., 2012), were developed with Java 2D, whereas 3D games were built with Java Monkey Engine 2. Games were deployed on the web browser using Java Web Start, and results were stored in XML files for transfer to the centralized server.

Serious Game Development

Throughout the game design and implementation process, ergonomic and user interface design standards were closely observed. Design criteria considered included aspects that were deemed necessary for proper administration of game-based training such as consistency between games, suitability toward visual or cognitive impairments, clarity of instructions and feedback, and robustness. A detailed description of the aspects of serious games that were considered fundamental are described in (Rodriguez-de-Pablo et al., 2012).

Four games for assessment and five games for training were developed. Assessment games measured multi-directional range of motion from a central point, vertical force support capacity, trajectory-following ability, and controlled lift and reach ability, involving a combined control of planar movements with a simultaneous vertical support force. Difficulty levels within the assessment games were configured with varying rules. Parameters related to range were increased linearly, both for force and motion targets within each sector, whereas increasing difficulty parameters related to control were less defined. The control of motion game, for example, increased in workspace according to the range of motion assessment, but simultaneously increased nonlinearly in complexity by adding additional targets to fill the workspace.

A first implementation of the lift and reach control-of-force assessment game, called Drag and Drop, was developed and later determined to involve too much time and cognitive involvement for a rapid assessment. The drag and drop game has since been removed as an assessment game and instead added to the set of training games, and a new lift and reach game has been

developed to better assess the user´s level of force control in a fast and simple manner.

Games for training included Memory, a Puzzle, Solitaire, Word Completion, and the Drag and Drop game. The complexity of each game was designed to be adaptable over a range of difficulty levels to better match the ability of the user.

APPENDIX 4. Assessment game descriptions

The Discover the Picture assessment game (Fig. 2a) evaluated the range of movement in different directions of the transverse plane. In the game, a picture was uncovered by erasing the sectors with a reach extension movement of the arm. The direction of the movement and the sector in which the movement should be made was indicated by a white arrow on a green background. The user had to make a controlled movement without excessive velocity in order for the range to be counted. Lateral deviations from the sector prompted the user to return to the sector at the last value of range achieved before an additional range of movement could be obtained. Five game levels were defined by the number and radius of sectors.

The Range of Vertical Force game (Fig. 2b) assessed the arm support/lifting capacity in different positions of the plane by placing the cursor over a circular target and lifting the arm. As the arm was unloaded from the device, the size of the target was increased in proportion to the lifting force in order to reach the diameter of a peripheral ring which indicated the target unloading level. The different levels were configured by the number of target positions and the percentage of arm weight to be lifted to get the maximum score at each location.

The Trajectory game (Fig. 2c) monitored the ability to perform a controlled movement along a trajectory signaled by a discrete path of circular targets. The various levels were defined by the number of circular targets, the trajectory difficulty (hexagon, star, or spiral) and the path width. In the first level, the user must trace the path of a hexagon, whereas in more advanced

levels the user traced a spiral (clockwise for right-arm patients, counter-clockwise for left).

The Force Control game (Fig. 2d) involved a sustained support force while performing an extension reach movement. A set of objects are located proximally on the screen and a set of targets with similar color and shape to the object to which they corresponded were located distally on the screen. The user was instructed to partially unload the weight of the arm from the device and maintain it in order to lift the objects from proximal locations and carry them to the distal targets. Once the target was reached while still carrying the object, the object was removed from the display.

APPENDIX 5. Questionnaires and questionnaire results

APPENDIX 5.1 Questionnaires

Six therapists and seven patients answered the evaluation questionnaire administered (16 questions for the patients, 19 questions for the therapists). The questions were over the same topics for both groups except for 3 additional questions (12, 18, and 19) on the therapist questionnaire related to the appropriateness of the system for patients and the feedback of patient results; these questions were omitted from the patient questionnaires. For each statement in the questionnaire, subjects were asked to show their level of agreement or disagreement according to a standard 7-point Likert scale measuring the level of agreement (1-strongly disagree, 7-strongly agree).

Statements included in the questionnaires that required Likert-based valuations were the following (*note that* questions 12, 18, and 19 were submitted only to the therapists*, and that* question 13 was submitted only to the patients):

   Q1.   It has been easy to learn how to use the system, both the hardware and the software.

   Q2.   I think I will often need the support of a technical person to be able to use this system.

Q3.   Using this system, I need to spend a lot of time in non-training activities (system setup, login, game selection/loading, etc.).

Q4.   I can remember with no problem how to use the system effectively every time I work with it.

Q5.   It took a long time to be able to use the system without problems.

Q6.   I think that I will benefit from using this system / I think that patients will benefit from using the system.

Q7.   Using this system I am motivated to train longer / I think the system will motivate the patient to train longer.

Q8.   I think that this system is uncomfortable to use.

Q9.   I enjoyed training with this system / I think the patients enjoy training with the system.

Q10. I would recommend other people to use this system.

Q11. I think that the system must be improved.

Q12. I think that a tele-rehabilitation system would not be beneficial for the kind of patients I treat.

Q13. I had internet connection problems while using the system.

Q14. I feel uncomfortable using a system like this, because I have no experience in using a pc.

Q15. I don't think using this system will make any change to my condition / I don't think using this system will make any change to the patient's condition.

Q16. I feel that the games are inadequate for the training.

Q17. I am familiar with this kind of technology.

Q18. The outcome results of the training are sufficient and clearly presented.

Q19. I don't need to use the outcome feedback of the system to see if the patient has improved.

In addition to the likert-based scoring on the statements above, patients and therapists were asked to comment on the aspects they liked most and least about the system, and also to leave any additional comments they had to improve the experience with the system.
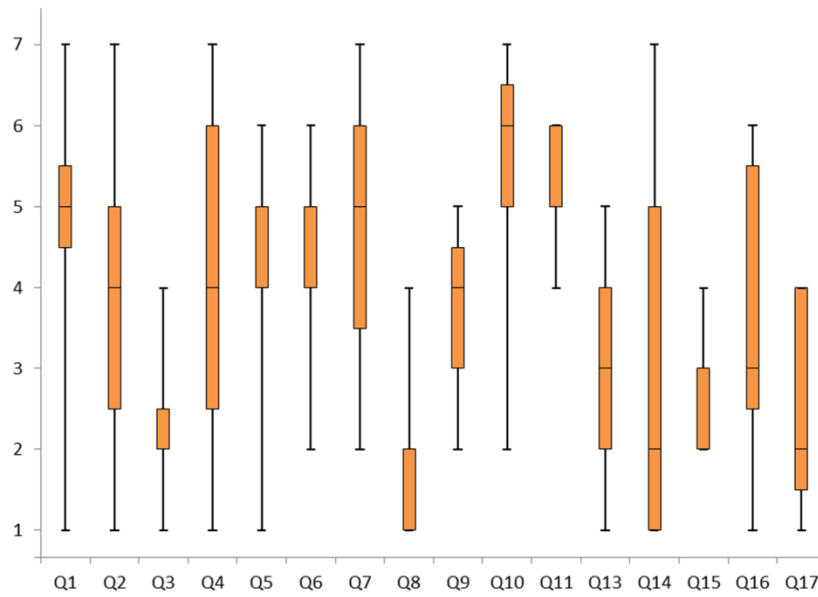
APPENDIX 5.2 Questionnaire Results

Figure 8. Patient Questionnaire Results

Figure 9. Therapist Questionnaire Results