Improving the match between ability and challenge: toward a framework for automatic level adaptation in game-based assessment and training

Joel C. Perry, Sivakumar Balasubramanian, Cristina Rodriguez-de-Pablo, and Thierry Keller
Rehabilitation Technologies Department
TECNALIA Health Division
Donostia-San Sebastian, (Guipuzcoa) Spain
{joel.perry, sivakumar.balasubramanian, cristina.rodriguez, and thierry.keller}@tecnalia.com

Abstract— 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. For the purpose of impairment assessment, it is further proposed that a complete picture of mobility performance can be represented through the assessment of metrics representative of each of four capacities: 1) Range of motion, 2) Range of force, 3) Control of motion, and 4) Control of force. In this paper, a set of games for mobility assessment is presented and initial plots of motion profiles and several computed metrics are shown for one patient in the performance of range of motion and control of motion assessments. Assessment plots are shown for four of seven training sessions and metrics are computed at each of the seven sessions to show the progression over the course of the 2-week clinical pilot study with the ArmAssist.

Keywords—Mobility assessment; serious games; stroke rehabilitation; home-based training; assessment metrics;

I. INTRODUCTION

Assessment of arm mobility after stroke continues to be a primarily clinically-based process despite a steadily increasing stroke population and a growing awareness for a needed shift toward at-home solutions. Improved medical treatment during acute stroke care has resulted in lower rates of mortality, and yet residual arm impairments tend to persist long-term with only 14-16% of the hemiparetic survivors recovering complete or nearly complete motor function [1]. Studies have shown that patients who perform progressive resistance exercises as little as 3-4 times per week for 6-12 weeks can improve both in strength and function [2], and also that patients improve more when they actively participate in training tasks rather than play a passive role.

Still the amount of rehabilitation training provided to the average patient falls short of the amount that research would suggest is beneficial for motor improvement. The reasons can be summarized by two key factors: first, the high costs associated with in-hospital rehabilitation, and second, increasing economic pressure on already scarce supplies of physical and occupational therapists. The result is a growing tendency to reduce the amount of time given to patients and the duration of stroke rehabilitation programs overall. These trends further promote the need for home-based training and assessment tools that allow remote supervision of the rehabilitation cycle outside of the strictly clinical setting.

The development and introduction of serious games and training platforms for neurorehabilitation are helping to improve motor learning in stroke, traumatic brain injury, and other neuromuscular impairment. Games allow repeatable scenarios and task conditions in order to compare performance measures over the duration of a training program. A number of devices and telerehabilitation platforms for upper limb rehabilitation offer the ability to train specific movements at high intensities and longer durations. However, maintaining patient interest and preventing abandonment remains challenging.

In order to address these challenges, it is believed that advances in assessment techniques can improve game level adaptation, leading to increased motivation, more appropriate performance feedback, and faster rates of recovery. At the same time, it is believed that these advances can also provide better tools for the therapist in order to allow more effective monitoring and revision of therapy. It is further believed that the quality of arm mobility in planar reach movements can be adequately characterized by measures of planar position and vertical force. For the purposes of impairment assessment, it is proposed that a complete picture of mobility performance can be represented through the assessment of metrics representative of each of the following four capacities: 1) Range of motion, 2) Range of force, 3) Control of motion, and 4) Control of force.

In this paper, a set of assessment games are presented and some preliminary mobility measurements of range of motion and control of motion from the games are shown at four points in the training of a single stroke patient. Measures of movement and control are recorded by a non-motorized ArmAssist prototype system [3]. Some background on games and telerehabilitation systems is presented in section II. An assessment methodology and four assessment games developed for arm reach assessment are presented in section III, and plots from a stroke subject during usability testing with the ArmAssist system are shown in section IV.

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TABLE I. TELEREHABILITATION DEVICES AND PLATFORMS

Year	Telerehabilitation Hardware and Software Systems		
	Rehab Device Name / (type)	***TR Platform Name / (features)***	***Company/University***
2001	T-Wrex[a]	Java Therapy[a]	U. California, Irvine
2004	TheraDrive	TheraJoy	Marquette U.
2005	AutoCITE	(Simulated platform)	Catholic U. of Amer
2009	(IMU-based)	RehabiTIC	Telefonica (Spain)
2010	HandTutor, ArmTutor,	MediTutor	MediTouch (Natanja, Isreal)
2010	Curictus VRS	Curictus Analytics[a]	Curictus (Gothenburg, Sweden)
2010	ReJoyce	(video-conferencing)	HomeTelemed (Edmonton, Alberta)
2011	Pablo, Pablo®Plus	(Assessment and Therapy)	Tyromotion (Graz, Austria)
2011	ArmeoBoom	Armeocontrol	Hocoma (Switzerland)
2011	ArmAssist[b] (Others)	TeleREHA[b]	Tecnalia (San Sebastian, Spain)
2012	(Various devices)	Platform P4H	Play4Health.com (Palma de Mallorca, Spain)
2012	(Kinect-based)	Neuro@Home[a]	Principe Felipe (Valencia, Spain)
2012	(Kinect-based)	VirtualRehab	VirtualWare (Basauri, Spain)

a. *Not commercially available

b. **Anticipated commercial release in 2013 through ReHub Investments (Zanturzi, Spain).

II. BACKGROUND

A. *Serious Games in Rehabilitation*

The use of games to increase motivation in patient training began as early as 1977 with the first use of the game Pong with hemiparetic stroke patients [4]. Following these and other preliminary research studies, a large increase in telerehabilitation efforts have been seen, particularly over the last 3 years (Table I), and yet very few game-based technologies have been successfully integrated into mainstream stroke care, and even fewer are available for remote use at home. Presumably, deficits of the latter are significantly affected by a current lack in semi-autonomous assessment methodologies to appropriately match the difficulty level of training games to the respective ability level of the patient.

B. *Telerehabilitation Training*

The telerehabilitation training cycle is a cyclic and iterative process that takes place across various timeframes. Described as the Plexas cycle, the process is composed of phases of therapy planning, task execution, and performance assessment, where each phase consists of defined inputs and outputs (Fig. 1a). The input-output relationships between phases allow for continuous iteration around the cycle at various levels with more interior levels being repeated at higher rates of frequency. The Plexas cycle is shown in Fig. 1b with training iteration levels grouped by *task*, *session*, and *therapy*, where a *task* is considered an individual training exercise, a *session* is composed of one or more repeated tasks, and a *therapy* is composed of one or more repeated sessions.

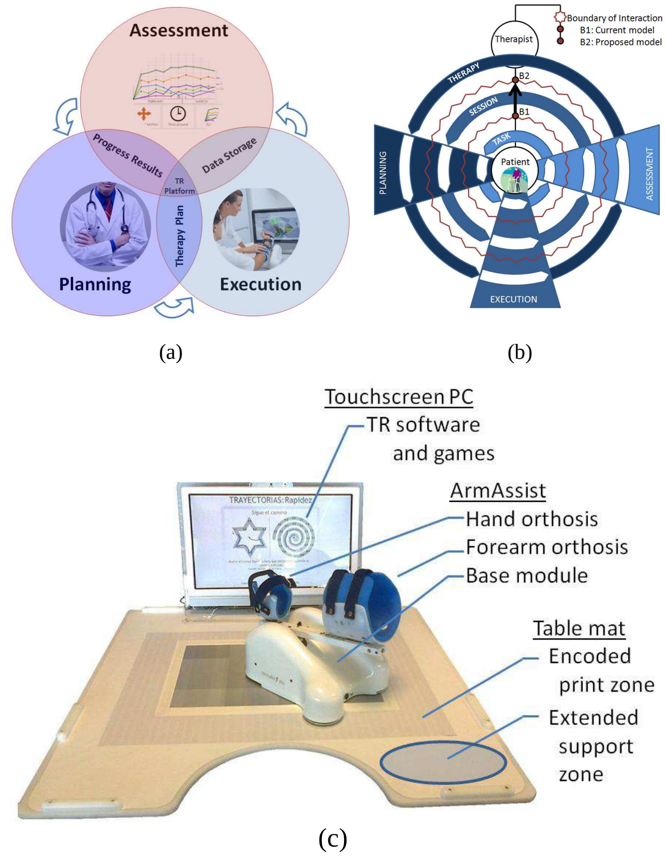

Figure 1. The Planning-Execution-Assessment (Plexas) rehabilitation cycle (a) consist of repeated executions of tasks over a number of training sessions within a given therapy plan. The task-session-therapy levels (b) can be supported by telerehabilitation technologies such as the ArmAssist system (c) in order to shift the boundary of responsibility (b) and provide the patient with greater autonomy.

Under this model, the assigned therapy can be revised by the therapist at any time and can furthermore be modified selectively at any of the *task*, *session*, or *therapy* levels.

Before the availability of robotically-assisted rehabilitation, all three task-session-therapy (TST) levels were assessed, planned, and executed in the presence of the therapist. The therapist was needed for manual movement assistance in tasks, for modifying the task difficulty, and later in selecting new tasks as functional mobility of the patient improved. The therapist was at least partially responsible for the patient´s understanding and completion of training at all levels and phases of the Plexas cycle. Robotically-assisted rehabilitation technologies shift this responsibility more toward the side of the patient, allowing the patient more autonomy of practice, and freeing the therapist from the burden of in-person guidance at the task and session levels.

C. *ArmAssist Arm Rehabilitation System*

The ArmAssist system described in [3, 5] was used in this work to collect absolute position data [6] from stroke patients during arm reach tasks as specified by a set of assessment and training games [7]. The ArmAssist (Fig. 1c) is composed of a low-friction rolling base module on top of an encoded mat that rests on a table surface and games are displayed with a 21.5" touchscreen pc with integrated training software.

III. METHODS

A. Assessment Games and Metrics

In the assessment of mobility performance, human movement can be characterized by measures of positional changes and interaction forces that occur between the body and the environment. All other measures can be derived from these. For this reason, assessment of movement performance is naturally based on two measures, force and position, while measurement components of range and control are derived from these. As a result, it is proposed that in order to provide a complete picture of mobility performance with regard neurorehabilitation training goals, the assessment games must provide data which can be used to compute a metric representative of capacities in terms of ranges and levels of control of both motion and force.

As shown in Fig. 2, it is proposed that the fundamental parameters to assess mobility can be represented by four metrics each extracted from a game-based assessment task. It is further proposed that the order of execution of the assessment games should be approached in the following sequence: 1) Range of motion (RoM), 2) Range of force (RoF), 3) Control of motion (CoM), and 4) Control of force (CoF). In this way, the range of motion can be used to adapt all successive assessment and training games to the user´s capability. Likewise, performance of the range of force game, determined next, allows all successive games to be adapted to the adequate requirements of force. These two adaptations should tailor all additional games for the session (assessment and training) in order to provide the user with ability-appropriate workspaces and gravity supporting tasks (Fig. 3).

It should be noted that the optimal methods and metrics to use for mobility assessment is a current and ongoing debate [8]. The metrics that have been selected for the present study are presented as follows:

Range of Motion – For range of motion, the metrics of interest are those that represent the extent of extension movements away from the torso, and can be represented a measure of the workspace area.

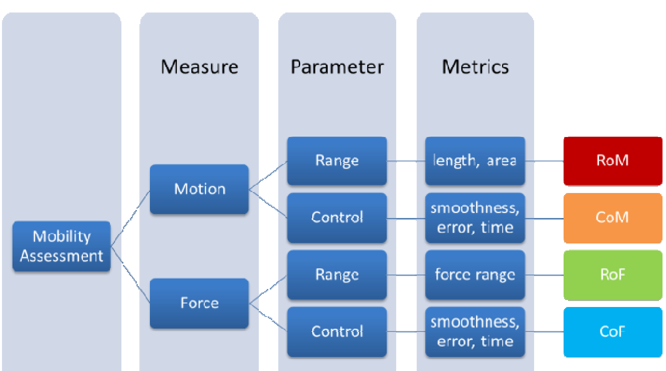

Figure 2. Basic measures, parameters, and metrics for mobility assessment.

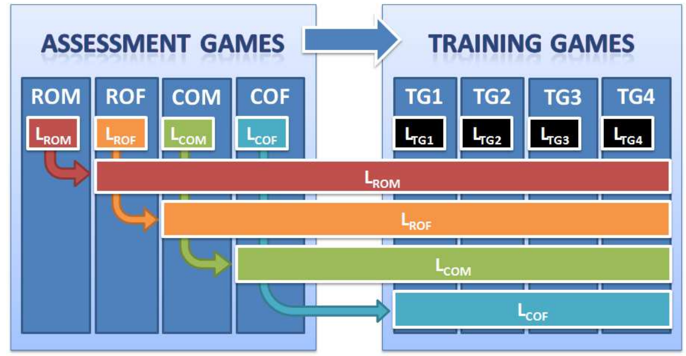

Figure 3. Sequential relationships of assessment measures and level structure.

Range of Force – For range of force, we are interested in the maximal upward (unloading) force that the user can apply to support the weight of his or her arm. This does not imply an active force from the device, but rather a lifting by the user to lessen the amount of arm weight that rests on the ArmAssist device. This should be done at known and predetermined locations within the user´s active range of motion.

Control of Motion – For control of motion, the user must perform reach movements within his workspace to desired targets. The metrics of interest are smoothness, error (distance from desired target), and completion time of the task.

Control of Force – For control of force, the metric of interest is smoothness of the force signal as well as its magnitude or error from the desired magnitude.

Note that in Figure 2, time is considered a metric for measures of control but not for measures of range. 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 measure of control, as a lack of control will naturally lead to sub-optimal movement trajectories that require a larger execution time. In the measure of range, the important element to monitor is posture to ensure a proper measure of movement. This can be done either by a trained observer, a restraint harness, or a dedicated system for postural detection. In the current implementation, a trained observer (the therapist) is utilized.

B. Games for Assessment

The assessment games developed for this work were designed to measure: *range of motion* by performing multi-directional reach extension from a central point; *range of force* by measuring the amount of arm weight resting on the device in the vertical direction as the user tries to lift the arm; *control of motion* by performing a trajectory-following task; and *control of force* by performing a reach extension task while maintaining a target level of self-supported arm weight. In this paper, the assessment of *range of motion* and *control of motion* are the focus and thus only the metrics corresponding to these measures are presented below.

The *Discover the Picture* assessment game (Fig. 4a) evaluates the range of movement in different directions of the transverse plane. In the game, a picture is discovered by erasing the sectors with a reach extension movement of the arm. The direction of the movement and the sector in which

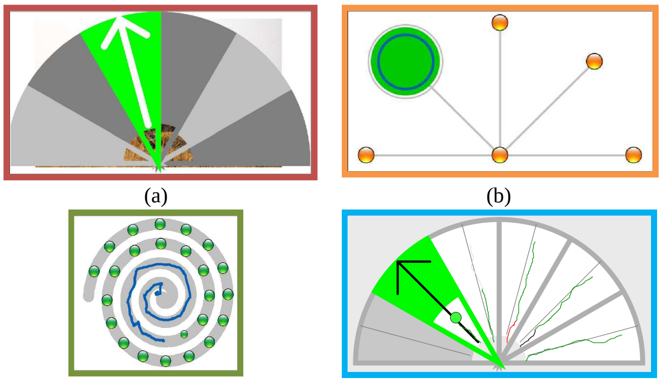

Figure 4. Assessment games to measure (a) range of motion, (b) range of force, (c) control of motion, and (d) control of force.

the movement should be made is indicated by a white arrow on a green background. The user must make a controlled movement without excessive velocity in order for the range to count. Lateral deviations from the sector prompt the user to return to the sector at the last value of range achieved before additional range of movement can be obtained. Game levels are defined by the number and radius of sectors. Four different movement performance measures were calculated for this assessment game:

(i) **Workspace area** covered by the target locations (red region in Fig. 5) and the actual workspace of the patient (blue region in Fig. 5).

(ii) **Workspace area ratio** between the actual workspace (A_{act}) and the target workspace (A_{tgt}).

$$Area\ ratio = \frac{A_{act}}{A_{tgt}}$$

(iii) **Assessment time** taken to completed this assessment game.

(iv) **Movement efficiency** which measures the efficiency of the movements performed to complete this assessment game. This is calculated as the movement path normalized to the actual workspace area (A_{act}) and the number of reaching directions. Let $x[n]$ and $y[n]$ represent the x and y coordinates of the movement path for the assessment game, where n represents the time index. Then movement efficiency is calculated using the following equation:

$$Movement\ efficiency = \frac{1}{N \cdot \sqrt{A_{act}}} \sum_{n} \sqrt{(dx[n])^2 + (dy[n])^2}$$

Where, $dx[n] = x[n] - x[n-1]$, $dy[n] = y[n] - y[n-1]$ and N is the number of reaching directions.

The *Range of Vertical Force* game (Fig. 4b) assesses the arm support/lifting capacity in different points of the plane by placing the cursor over a ball and lifting the arm. As the arm is unloaded from the device, the size of the ball is increased to the diameter of a peripheral ring which indicates the target unloading level. The different levels are configured by the number of balls in the plane and the percentage of arm weight to be lifted to get the maximum score at each ball.

The *Trajectory* game (Fig. 4c) monitors the ability to perform a controlled movement along a trajectory signaled by a discrete path of balls. The various levels are defined by the number of balls, the trajectory difficulty (hexagon, star, or spiral) and the path width. In initial levels, the user must trace the path of a simple shape, whereas in more advanced levels the user may trace a spiral (clockwise for right-arm patients, counter-clockwise for left). Three movement performance measures were calculated for this assessment game as well:

(i) **Percentage success** indicates the percentage of the targets reached successfully.

(ii) **Average distance to targets** estimates the mean of the closest distance between the different targets and the movement path. The points on the movement path that are closest to the targets (red dots) are indicated by blue diamonds (Fig. 7). This measure indicates how close a patient was able to get to the different targets.

(iii) **Completion time** measures the time taken to complete the given assessment game.

The *Force Control* game (Fig. 4d) involves a sustained support force while performing an extension reach movement, maintaining the vertical support force as close as possible to a desired value determined previously during the *Range of vertical force* game. Users are given feedback on their level of support as well as whether or not an inadequate level of force control is reached.

Strict overall times and intermediate countdowns in the case of inactivity are employed in all the assessment games to ensure that assessments are carried out efficiently. The assessment games and their development is further described in [7].

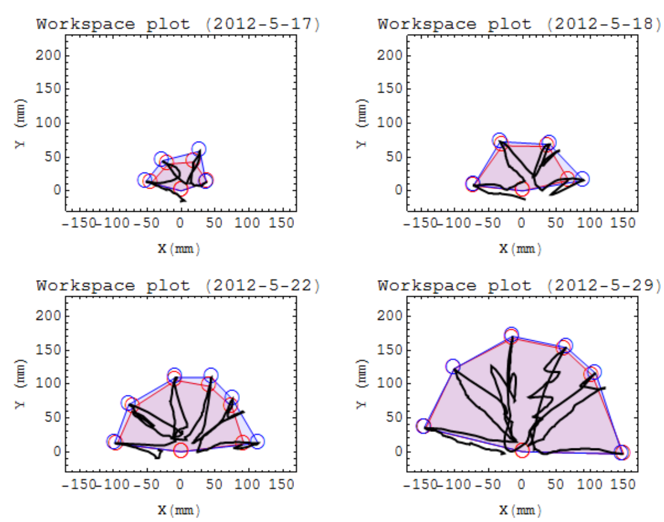

Figure 5. Evolution of the range of motion for the *Discover the picture* game. The red circles indicate the target location for different reaching directions (and the center rest location), while the blue circles indicates the farthest point reached by the subject in the different reaching directions. The black trace indicates the movement path of the subject during the assessment game.

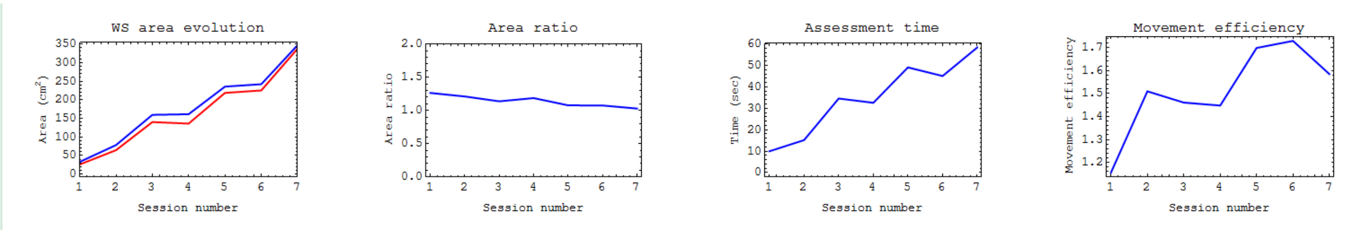

Figure 6. Evolution of the four movement performance measures for the *Discover the picture* assessment game. The four plots from left to right correspond to the workspace area (red corresponds A_{tgt} and blue corresponds to A_{act}), workspace area ratio, assessment time and movement efficiency.

C. Game Level adaptation

The concept of levels have three aspects: motion level, force level, and task level. The motion level is set by the range-of-motion assessment game and should alter the range of motion of all successive games (assessment and training) for the session. For this reason, range-of-motion must be the first assessment performed. The force level is set by the range-of-force assessment game and should also alter all successive games. The range-of-motion game does not involve a force level assignment as the objective is to measure range of movement in the fully-supported condition. Similarly, control-of-motion and control-of-force can be used to determine additional aspects of level definition, however in this study, only the levels of range have been used in the automatic adaptation of game levels.

Adapting the task level is another way of matching the task difficulty to the ability of the patient. It modifies the number of elements and/or the general complexity of the task. Depending on the game, aspects such as the allowed time to complete the task, the precision needed to “touch” an object, the length and complexity of word completions, or the AI level of the PC opponent. There are currently 5 levels for each game.

Each game is scored based on a combination of evaluated features. Currently, the scoring levels are adapted automatically based on performance. In this case, the motion and force levels are adjusted by the range-of-motion and range-of-force games, respectively, and the task level is adapted based on performance 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 prompt a level increase.

D. Pilot testing

A 2-week clinical pilot test was conducted with sub-acute stroke patients in conjunction with a longer usability evaluation using the passive (non-motorized) ArmAssist prototype. The patients were assigned a set of training games by the therapist, and the set of assessment games were performed before and after the training.

IV. Results

Figure 5 shows the evolution of the range of motion for the *Discover the picture* game during 4 different training sessions. From the start of the pilot testing, the patient already had a large workspace and therefore the game level increased quickly as indicated by the larger workspace (red shaded zone) and higher number of target locations (red circles). The range assessment metrics of workspace area, workspace area ratio, assessment time, and movement efficiency are shown in Figure 6. The metrics indicate that for a relatively constant area ratio, the efficiency of movement metric decreases with training at constant game levels (indicating higher efficiency) and increases for higher levels. Similarly, the time to complete the task generally increased with increasing levels from 10 to 60 seconds. It can be noted that the time to complete the assessment increases at a slower rate than the corresponding increase in workspace area.

Figure 7 shows the evolution of the control of movement

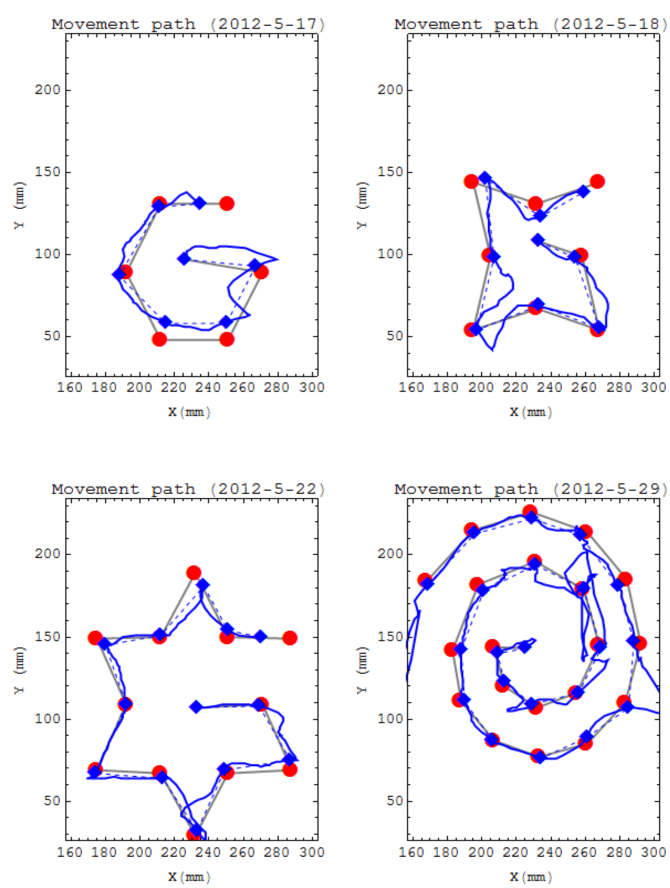

Figure 7. Evolution of the control of movement for the *Trajectory* game. The red circles indicate the target locations, while the blue diamonds positions in the movement path that are closest to the targets. The blue trace indicates the movement path of the subject during the *trajectory* assessment game.

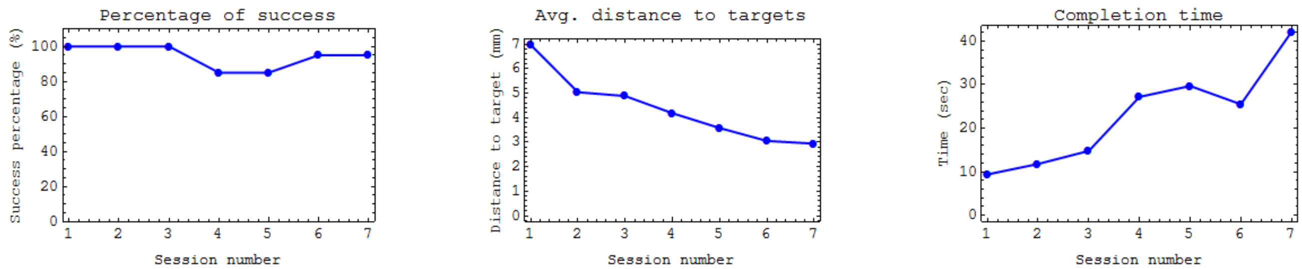

Figure 8. Evolution of the three movement performance measures for the *Trajectory* assessment game. The three plots from left to right correspond to the percentage success, average distance to target, and completion time.

from the *Trajectory* game, and Figure 8 shows the corresponding assessment metrics (percentage success, average distance to the target, and completion time). The percentage of success was very high in early levels due to the patient's already high level of motor control. The average distance to the targets decreases from about 7mm to 2.8mm over the 7 sessions. As the difficulty increases, the number of targets along the path increased from 6 to 20 while the total task completion time correspondingly went up from just under 10 seconds to 42 seconds. If the completion times are considered on a per-target basis, the completion times reduce from 0.61 to 0.48 seconds per target (21% reduction) while the error reduced by 60%.

The trends shown in Figures 5-8 indicate improvement in both range of motion and control of motion. However, it can be noted that the automatic level adaptation implemented in the range of motion (*Discover the picture*) assessment makes it difficult to differentiate between true performance improvement and apparent improvement due to the targets having been set farther away. In the case of the control of motion (*Trajectory*) task, where the distance between some targets were smaller than between others, the completion time per target is difficult to compare between levels. Because of the changing levels over the relatively short training duration in the pilot test, the results of the movement efficiency metric are inconclusive.

V. CONCLUSION

The telerehabilitation system and training adaptation structure described in this paper has been developed and is undergoing testing 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 and initial evaluation of results from range of motion and control of motion data has been presented. In their current versions, the range-of-motion, and control-of-motion assessments are performed by uncovering a picture and by following a trajectory of target points within the previously established range of motion. Initial results of mobility assessment show promise toward the ability to characterize 2D mobility performance based on the measures recorded by the prototype system, but further definition of metrics and their analyses are needed and will be the topic of further study in the project.

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