Gesture Therapy: An Upper Limb Virtual Reality-Based Motor Rehabilitation Platform

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***Abstract*—Virtual reality platforms capable of assisting rehabilitation must provide support for rehabilitation principles: promote repetition, task oriented training, appropriate feedback, and a motivating environment. As such, development of these platforms is a complex process which has not yet reached maturity. This paper presents our efforts to contribute to this field, presenting Gesture Therapy, a virtual reality-based platform for rehabilitation of the upper limb. We describe the system architecture and main features of the platform and provide preliminary evidence of the feasibility of the platform in its current status.**

***Index Terms*—Rehabilitation, serious games, stroke, virtual reality.**

I. Introduction

Individuals with motor impairment undergo rehabilitation therapy in order to fully or partially recover their mobility and psycho-social health. The former is restored by motor rehabilitation therapies which aim at alleviating motor impairment and boosting the patient's quality of life. A large range of different interventions are available depending on treatment components incorporated [1], including constraint induced movement therapy, electromyographic biofeedback, electromechanical assisted training, electrostimulation, high intensity therapy, robotics, repetitive task training, splinting, and physical fitness training among others. Recently other approaches have began to flourish such as music-supported therapy, telerehabilitation, and virtual reality (VR)-based therapies.

Gesture therapy (GT) is a novel virtual reality-based platform for upper limb rehabilitation aimed at lower or middle income countries and home usage [2]–[4]. Similarly to other existing virtual reality-based platforms, GT disguises the rehabilitation exercises as actions within computer games. GT differentiates from its counterparts in aspects such as the specially designed controllers, and the use of artificial intelligence probabilistic decision models for guiding the therapy. This paper describes the GT platform and present kinematic data from a recent feasibility pilot. Technological contributions include specifically designed controllers, a 3-D monocular tracking system and an adaptation algorithm for optimizing game challenge according to patient's performance. Clinical contributions include further evidence of the usefulness and validity of virtual reality based therapies and an assessment of the neuroplastic changes associated to this therapy. Part of this paper overviews work previously published in conference paper format [2]–[5]. In addition, we further present here the new game set.

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II. Virtual Reality for Motor Rehabilitation

Principles thought to encourage effective rehabilitation are as follows.

- **Repetition**: In contrast with evidence that more practice is better [6] and that purposeful movements is an integral part of improving functional status, repetitions during common physical and occupational therapy are not enough and those of purposeful movements are economized [7]. New assistive technologies such as VR potentially allow patients to practice more intensively on their own [6], but to date no study has demonstrated this increment in practice on the patient's own when using VR.
- **Feedback**: Feedback improves learning rate and is of utmost importance for motor learning [8]. Feedback evokes neurophysiological processes that induce profound cortical and subcortical changes. In general, computer games excel at providing feedback [8] further contributing to keep the player engaged [9]. Notwithstanding, the potential of VR to provide more and better feedback to the user remains to be fulfilled with only a few studies to date having demonstrated the added value of feedback delivered through VR [10].
- **Motivation**: Patient motivation is central to exercise adherence [11], [12]. Variation in the game, challenge, and competition are elements that can enhance motivation [12]. Rehabilitation games can motivate patients by connecting them with friends and family giving them a sense of social connectedness [13].
- **Task oriented training**: Functional reorganization of the motor cortex (remapping), in the rat and the primate, oc-

curs only in response to development of skilled forelimb movements, and not simply to increased forelimb use [8]. In humans, task oriented training using VR has already demonstrated its usefulness for fractionation, the ability to move each finger individually in isolation [14], [15].

A. Pros and Cons of Virtual Reality Based Motor Rehabilitation

A number of potential benefits of virtual reality-based motor rehabilitation therapies are recurrently claimed in the literature. First, virtual reality-based rehabilitation has shown validity by complying with the key principles in rehabilitation outlined above. Second, virtual reality-based rehabilitation can be adapted to the user need and progress. The dose, frequency, challenge, task variability, etc., are easily modifiable in a virtual environment. Third, virtual reality-based rehabilitation may be customized to the therapy requirements. It can be tailored for different pathophysiologies and/or different target groups. Fourth, virtual reality-based rehabilitation theoretically could require low clinical supervision facilitating home use [16], saving costs [17], enabling telerehabilitation [17], and opening opportunities to practise everyday activities that cannot be practised within the hospital environment [18]. A few other benefits have also been suggested. These include low cost, quick development, less dangerous in certain applications, or flexible schedule. Also distractors may be eliminated or added on demand, complex tasks can be decomposed into simpler tasks, and systems have wide testing capabilities (methodologies, feedback forms, timings, regulatory conditions, etc.). They facilitate increased standardization of assessment and treatment protocols, as well as permit objective measurement of behavior and performance. Finally, well designed virtual environments can provide enhanced ecological validity when compared with traditional rehabilitation tasks [19]. The evidence supporting these benefits is still being developed.

Of course, it also has some drawbacks. The systems often require specialist expertise to set up and operate [9]. Immersive systems may be accompanied by cybersicknesses [20]. Patients may be unfamiliar with computer games and the whole virtual reality environment [9], and these games are not necessarily enjoyed by everyone.

B. Learning in Virtual Environments Versus Learning in Real Environments

Rose *et al.* [21] have suggested that virtual environments may 1) stimulate neuroplastic changes, 2) enhance learning and problem solving, and 3) reduce cognitive impairment. Humans can *learn* motor skills in a virtual environment and they can *transfer* that motor learning to a real world environment [8]. Even patients with significant motor and cognitive impairment are capable of at least some learning within a virtual reality environment [8]. Evidence from a variety of learning conditions in healthy subjects and a small amount of evidence in patient populations suggest that there is a positive transfer from virtual to real environments [22]–[26], even though the extent of the transfer and the particular elements and conditions that facilitate the transfer are not yet fully understood [23].

C. Existing VR Platforms for Upper Limb Rehabilitation

In the last decade, a number of virtual reality based rehabilitation platforms have been developed. Table I provides an overview of academic and commercial virtual reality based rehabilitation solutions for the upper limb. Despite advances, the full potential of a rehabilitation therapy based on virtual reality has not yet been realized, and there is still much room for improvements.

III. Gesture Therapy

GT [2]–[4] is a virtual reality based motor rehabilitation therapy which favours the principles of rehabilitation described above (repetition, feedback, motivation, and task specific training) by challenging the patient to fulfill daily tasks in a safe virtual environment (see Fig. 1). The tasks are presented in the form of short serious games. Earlier trials [4], [5] suggest that GT provides measurable improvements in motor dexterity comparable to more classical occupational therapy but with an edge on motivation. Conceptually, the GT platform consists of five interacting modules.

- **Physical System**: Encompasses the hardware platform incorporating a computer (Windows or Unix), a webcam and controllers e.g., a handgrip, further described below. GT has been developed targeting home usage and as such one of its most important features is its low cost. The system hardware is specially chosen to keep cost to a minimum, and the complete set of equipment costs less than 1000 USD with the computer being the most expensive part.
- **Tracking System**: This is the software responsible for tracking the handgrip; proxy of arm movement. The software receives information from both the monocular tracking system (i.e., webcam) and the controller. The monocular tracking system provides the location of the gripper, and pressure data is obtained from the controller [2], [3]. Often, it will be the colored ball on the top of the handgrip which will be tracked since the distinctive color of this ball facilitates the tracking. However, as further described below, the tracking system is not hard linked to tracking the handgrip; the target for tracking is selected during the training stage of the tracking system and thus the hand of the user i.e., the patient, can be tracked directly if desired.
- **Simulated Environment**: The central module of the platform is responsible for presenting the game and interacting with the user. This module is in charge of providing the feedback to the user and the therapist. Currently visual and auditory feedback are available depending on the game. The module is also responsible for tracking progress through the therapy. A database stores information about patient interaction with the system. The in-game information is used by the adaptation module to adjust game difficulty in real time. Although a basic database already stores in-game information, we are currently working towards enlarging the database to include capabilities for inter-game information and user profiling.
- **Trunk Compensation Detector**: Trunk compensation is detected by tracking the user head using basic Haar fea-

TABLE I
SUMMARY OF VIRTUAL REHABILITATION SOLUTIONS FOR THE UPPER LIMB BY YEAR OF PUBLICATION. PURELY ROBOTIC SOLUTIONS SUCH AS THAT IN [27] OR THE MIME SYSTEM [28] ARE NOT INCLUDED, BUT HYBRID SYSTEMS USING VIRTUAL REALITY ARE INCLUDED, e.g., MIT MANUS

Name, Ref. & Year	**Brief Description**	**Virtual Environments**	**Clinical Trials & Case studies**
Driver's SEAT [29] (1999)	A 1 degrees of freedom (dof) steering wheel	Driving (rural, suburban and urban)	Not described
MIT Manus [30] (1998)	Robotic platform including a planar module (2 dof) and a wrist module (3 dof) with armrest	Drawing circles, stars, squares and diamonds, and navigating through windows	Robotic training additional to standard therapy improves motor recovery. The improved outcome was sustainable over 3 years
Rutgers orthopedic telerehabilitation system [16] (2000)	Input device is the "Rutgers Master" glove for the hand.	Games; Power putty, digikey, peg board, hand ball	It demonstrated improvements in terms of range of motion, velocity, fractionation and thumb strength in case studies
ARM Guide [31] (2000)	Passive linear constraint with 1 dof motor exoskeleton	Reaching task. Feedback is provided in video monitor.	Several case studies suggests increments in reach and velocity plus a reduction in tone.
Java Therapy [32] (2001)	Force feedback joystick with web based games. Requires armrest.	Games inc. Breakout, othello, torpedo and tail gunner	A case study is inconclusive [17]
Virtual Environment Training System [33] (2002)	A desktop display and electromagnetic motion-tracking devices	Putting envelope in mailbox. Reaching exercises.	A small cohort (n=9) exhibited improvements (15% in Fugl-Meyer and 31% in Wolf Motor Test) in 2 reaching movements.
TheraJoy [34] (2002)	Modified mass-marketed force feedback joystick	Games are used but no further details provided	Not described
Gentle/s [35] (2003)	Large screen with a 3 dof haptic interface.	Empty room, real room and detail room.	Requires elbow orthosis. The system was able to motivate people.
TheraDrive [36] (2004)	Force-feedback steering wheel	SmartDriver (Commercial driving videogame)	Clinical benefits in terms of motor performance and an edge on motivation
GestureTek's GX and IREX platforms [37] (2004)	Video capture VR system + gloves + large screen	Games inc. soccer, birds and balls and snowboard	Balance improvements similar to conventional therapy, but with increased enjoyment. IREX favours ipsilesional SM1 reactivation [38]
Sony PlayStation + EyeToy [37] (2004)	Off-the-shelf video capture virtual reality gaming platform	Games inc. Knockout, Do it yourself, Colors and Mr. Chef.	A case study showed improvements in motor dexterity mainly due to major sensory improvements
VR Physical Therapy [39] (2005)	Data glove and games system for telerehabilitation	Games; Puzzles inc. Merlin's revenge	Not described
TheraGame [40] (2006)	Video capture (Webcam) VR system	Games inc. Tetris, frog, colorSok and motion music	Patient with neurological deficits found the system engaging.
T-WREX [41] (2006)	5 dof exoskeleton (WREX) used as 3D mouse + a grip sensor	JavaTherapy 2.0 (inc. shopping, washing, cracking eggs)	T-WREX is effective in enhancing UL motor recovery and patient motivation.
Xbox [42] (2006)	Modified Xbox + glove	2 games; Butterfly/UFO scaring and Clean up, shared with [43].	Not described
ARMeo (Hocoma) [31] (2000-6)	Passive linear constraint with 1 dof motor. This is the commercial version of [31] and [41]	Games inc. Rain mug, fruit shopping, egg cracking and reveal picture	Not described
Universities of Derby and Ulster's serious games [44] (2008)	Immersive head mounted display (HMD) and gloves	Games inc. Rabbit chase, arrow attack, orange catching, and whack-a-mouse	Small clinical trial suggested clinical benefits in terms of motor performance that was sustained 6 weeks after intervention
Play Station 3 [43] (2008)	PlayStation 3 + glove	2 games; Butterfly/UFO scaring and Clean up, shared with [42].	Pilot study in children suggests some improvements in ADL.
Wii [45] (2008)	Wii	Wii sports games inc. Boxing, tennis, bowling and golf	A case study of palsy resulted in augmented rehabilitation when complementing physical therapy.
Elinor Game Platform [46] (2009)	A game console controlled with 2 handles	15 games based on classical concepts	Case studies are not assessed clinically, but only claimed to exhibit gamers behaviour.
Virtual Piano Trainer [14] (2009)	Virtual piano with cyberglove, cybergrasp and two arm tracking sensors	Virtual piano	A pilot study suggested improvements in fractionation
iStretch [47] (2010)	1 dof robotic system for the early stages of physiotherapy	Reaching task	Not described
Adaptive Mixed Reality Rehabilitation system [48] (2010)	A table with 4 target buttons + large screen + 2 speakers	4 different training environments: Virtual, hybrid I and II and physical	A pilot (n=4) showed significant improvement in reaching and grasping performance compared to controls under traditional therapy.
None given [13] (2010)	Wii based + vision system	8 games inc. baseball catch, helicopter flying, frog Simon and under-the-sea	Results with case studies were encouraging
Hadassah University Hospital system [49] (2012)	A motion capture VR system integrating online self-face viewing and mirror visual feedback	Various game-like tasks; catch money and pick fruit among others	A study (n=6) demonstrated feasibility in terms of adherence and improvement in task performance
Art-empowered VR [50] (2013)	2 large displays, a tracking system of head and arm, and a pneumatically actuated glove	March Hare's cottage environment	Preliminary results (n=4 of 9) suggest grip and pinch improvements.
Spatial Augmented Reality [51] (2013)	Computer, webcam, projector and table for projection	4 tasks; reaching, holding and tilting, pointing and grasping	Two subjects feasibility pilot poorly described.
None given [52] (2013)	Hybrid; 7 dof passive robot (Trackhold), VR and 128 channels EEG	5 environments; sponge, bug hunt, grab 2D, grab 3D and Twirl	Pilot (n=2) demonstrated feasibility to monitor neuro-motor recovery. lateralization.

tures and a cascade of classifiers [53]. The compensation detector estimates trunk inclination by exploiting a limitation of the algorithm which fails to detect faces at untrained angles. Compensation is assumed to occur if incli-

Fig. 1. GT platform. Webcam tracks hand/gripper movements and translate that into commands to control the games. In addition the pressure sensor incorporated in the gripper facilitates hand training.

nation exceeds a threshold determined during training of the classifiers [4], i.e., when the classifiers fail to detect the face. Although this procedure assumes that the head moves in synchrony with the trunk during compensation, this assumption has proved empirically to be reasonably robust for practical purposes. Nonetheless, the underlying assumption that head and face tracking can provide reliable information on trunk displacement remains unproven, and in any case it shall represent a noncausal association. After trunk compensation movement is detected, the system may provide an alarm or block the game. This functionality can be switched on and off on demand as the role of compensation may depend on the patient's progress [6], [54].

- **Adaptation Module**: This module is capable of adjusting the 3-D space in which the exercise occurs. It uses in-game information to dynamically adjust the difficulty of the task. The system identifies user dexterity and adjusts the game difficulty accordingly capitalizing on a partially observable Markov decision process (POMDP) [55]. Inter-game adaptation is part of the ongoing work in our lab but has not yet been formally incorporated to the platform. The adaptation module is critical for relocating therapy sessions from rehabilitation centers to home, and also to decrease the need for on-site assistance of professional therapists.

A. System Architecture and Implementation

A schematic representation of the system architecture is illustrated in Fig. 2. Basically, a vision module gets the input video stream from the camera, as well as the pressure data from the controller. The vision module extracts arm and hand position from the video, and passes this information together with the pressure information to a game engine for game control. The game engine is responsible for the proper game rendering and behavior. It further monitors user's speed and smoothness of trajectory which are communicated to the adaptation policy. The adaptation policy decides upon the best action to take regarding increasing/decreasing game difficulty relying on the aforementioned POMDP. This decision is then communicated back to the game engine.

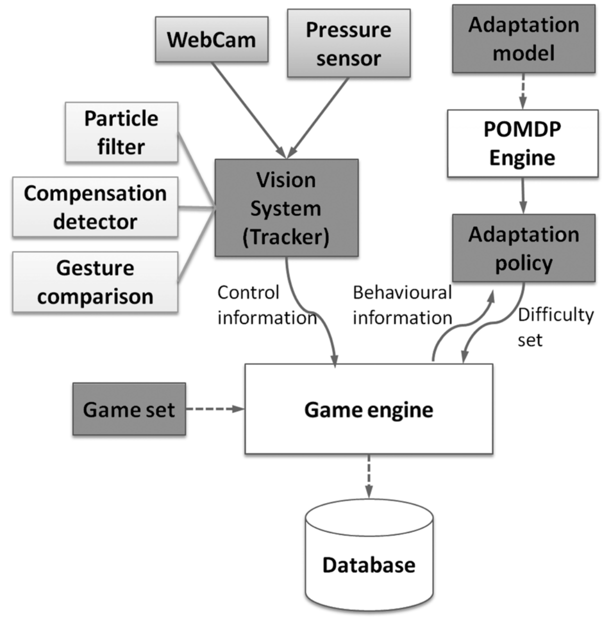


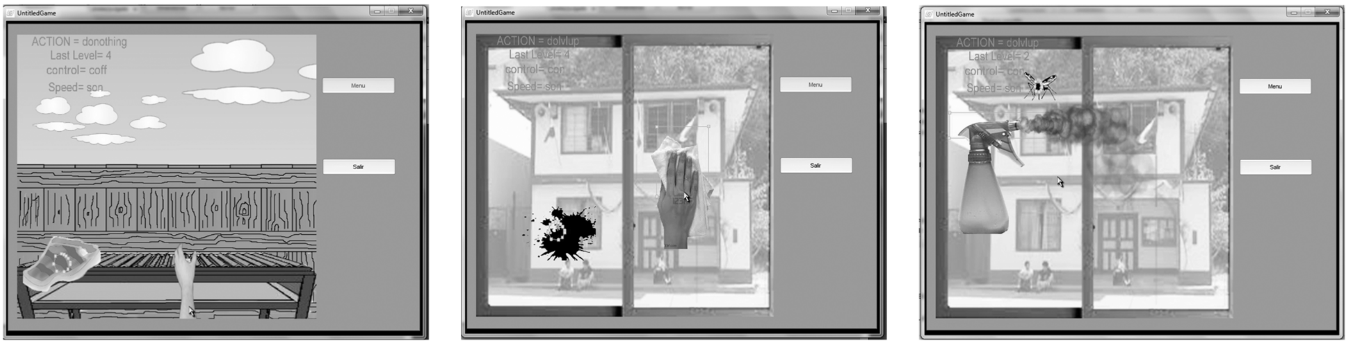
Fig. 2. GT system architecture. The major elements include the monocular vision tracking system which in addition incorporates the information from the pressure sensor, the game engine (Torque) responsible for the animation of the game set and the adaptation module resolved with a POMDP engine based on Perseus algorithm. Further description can be found in the main text. White elements correspond to external engines, dark grey boxes encapsulate platform modules, mid-grey boxes represent hardware elements and light grey boxes correspond to submodules.

The system is built upon a game engine (Torque, Garage Games, Las Vegas, NV, USA) [56] and a Markov Decision Process engine (Perseus) [57]. The vision module (C++) writes system inputs in a shared memory address which is read by the game engine. The game engine (Torque, Garage Games, Las Vegas, NV, USA) [56] outputs system usage to a MySQL database including information such as speed and smoothness of trajectory. The gameplay automatically adapts to the user progress capitalizing on the afore described POMDP [55]. The rules of an adaptation model is specified in POMDP engine Perseus [57], which computes the optimum adaptation policy which is then communicated to the game engine. A JNI (C++/Java) interface permits communication between the game engine and the POMDP.

B. The Game Set

Games for rehabilitation should comply with particular game design principles [9], [13], [55]. So far, we have developed a set of three games adhering to these principles (see Fig. 3).

- **Steak**: The user must "turn" a steak in a grill before it burns. The steak changes its color to a darker brown as time passes. A virtual hand must touch (i.e., turn) the steak in the grill to prevent it from burning. After the steak is touched, a new steak appears somewhere else in the grill. The distance at which the new steaks appear is automatically selected by the adaptation module. The time it takes before the steak burns can be adjusted. The game focuses in an abduction/adduction movement of the arm. This game is intended for early therapy.



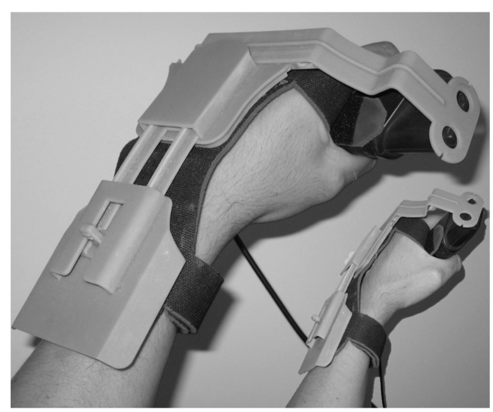
(a) (b) (c)

Fig. 3. Game set. Left: Steak. Middle: Clean window. Right: Fly killer. Each game is designed according to a set of criteria thought to be beneficial for rehabilitation and aims to promote different rehabilitatory movements. Full description of the games is given in the main text.

- **Clean window**: A hand holding a cloth wipes a window glass to remove stains. As the old stains are wiped, new stains appear randomly over the window. Game difficulty is modulated by means of adjusting the distance at which the new stains appear. The distance (Euclidean) is measured pixels from the screen position of the previous stain. Similarly to the game steak the aim is to touch the goal, in this case the stain, but differently from the steak game the allowed movement in this game is two-directional; abduction/adduction and elevation/depression. This is thus a game for late rehabilitation.
- **Fly Killer**: In this game, the patient armed with an insecticide sprayer tries to kill a buzzing mosquito that approaches at different heights. The task goal is to kill the mosquito before it comes too close to the hand. The patient is armed with an insecticide sprayer that s/he must align in height with the mosquito and then press the gripper to spray the insecticide. The mosquito speed and the pressure necessary to spray are configurable parameters. The vertical distance at which the next mosquito appears is dictated by the adaptation policy. The game favours elevation/depression movements and power gripping.

Suitability of this game set has been assessed by therapists at the National Institute of Neurology and Neurosurgery in Mexico. Positive aspects cited by the clinicians were 1) the ease of use both for the clinician and the patient, 2) the possibility to change the game duration as they are often delivered in short blocks during the therapy session, 3) the reward feedback at the end of the game was also stressed as an important element, and 4) the trunk compensation feature which was suggested to be responsible for posture correction consequence of the greater postural awareness by the patient. Also, and in particular of the clean window game clinicians welcomed the wider amplitude of the movements. Nonetheless, the rehabilitation therapists demanded more game variety, avatar personalization, patient history storing, more rewards to excite the limbic system in the brain, metrics to evaluate attention and coordination and easier timing control. And thinking about the application of GT for children with cerebral palsy the therapists recommended to develop new games especially themed for kids and perhaps to disguise them in an interactive storytelling. We are in the process of improving and enlarging our game set.

(a)



(b)

Fig. 4. GT platform controller. Top: Grippers for arm rehabilitation. Bottom: Harness for people too paretic to hold the gripper.

C. The Controller; the Gripper

The gripper [see Fig. 4(a)] has a main hollow plastic body that provides structural support, a pressure sensor in the front and a resting zone in the rear for ergonomic handling [58]. The gripper is complemented with communication electronics to transmit grip strength and an USB interface for power supply. A sphere made of matte material facilitates visual identification. For patients too paretic to hold the gripper an additional support [see Fig. 4(b)] is affixed to the forearm and ensures the patient holds the gripper safely and further permits correction of the wrist position with respect to the forearm during the execution of the rehabilitation exercises. All clinical trials so far have been carried out with this gripper.

D. Tracker

The tracking algorithm is based on a particle filter which recognizes the tracking target based on color and texture features [2], [3]. Particle filters are a probabilistic technique based on Monte Carlo methods. They maintain a sampled representation of the target object's distribution, where each sample is a particle, that is a point in a state space with a certain mass depending on its significance. The particle collection evolves with time with the incorporation of new observations, i.e., color and texture in our case, and the prediction of the object movement. On every iteration of the filter, a new generation of particles arises incorporating the new positions and their probabilistic beliefs based upon the observations. Implementation is based on OpenCV [59] with modifications to ensure compatibility with a large search space i.e., the combination of patches sizes, patches locations within the frame, size of the target to estimate depth and target location given the video resolution. To avoid break down, the number of particles and the size of the training zone are both configurable parameters from the graphical user interface. For initializing the tracking, it is only necessary to take a sample image of the target, e.g., the gripper's ball. Upon selecting the training sample the tracking process begins and the selected target object can now move freely. The system is robust to partial occlusion and even to the target object momentarily leaving the scene. The tracker processes a 320×240 pixels live stream video at 30 Hz. The controller is tracked in 2D and depth is estimated based on the volume of the particle filter distribution surrogating object size.

In addition to the naive training a simple calibration is necessary before each session. In order to calibrate the system, the user moves his arm from one end to the opposite end of the region encompassing the maximum area of movement that he can reach. The calibration process adjusts the real scene space coordinates to the games' space boundaries.

E. Adaptation

A POMDP is used to adapt the difficulty level from speed and deviation from smooth motion paths [55]. Our POMDP implementation is built upon symbolic-Perseus algorithm [57] and software [60] that allows factored representations of state and observation variables. The user dexterity is derived from two observable variables; *Control* and *Speed* from which the hidden variable *Performance* is estimated. Control is determined as the deviation in the trajectory from a straight movement from origin—cursor position at the instant of target popping—to target location. For this, the travelled path is reconstructed from the visited pixels. The total length of the travelled path from origin—cursor position at the instant of target popping—to target location is calculated as the sum of the differential straight lines from one visited pixel to the next visited pixel. Deviation is calculated by comparing this total path length with the length of an ideal straight path going from origin to target location. The more deviation from this straight path, the less control. Control is considered in three ranges; low, normal, and good. Speed corresponds to the ratio of distance along the optimum path and execution time. Similarly to control, speed is also considered in three ranges; low, normal, and good. Control and speed are combined to decide about performance of the user—bad, good, and outstanding. The user's performance in turn governs the game difficulty. The game *Difficulty* can take three possible values: easy, medium, and hard. The level of performance dictates the action of the system, i.e., increase, keep or decrease game difficulty. Decisions are made in order to keep the difficulty level in balance with respect to the performance level. Fig. 5 provides an example of the behavior of the adaptation algorithm during a typical session. We are now expanding on this work by developing a dynamic adaptation algorithm that can change its underlying decision policy online during the therapy administration using reinforcement learning [61].

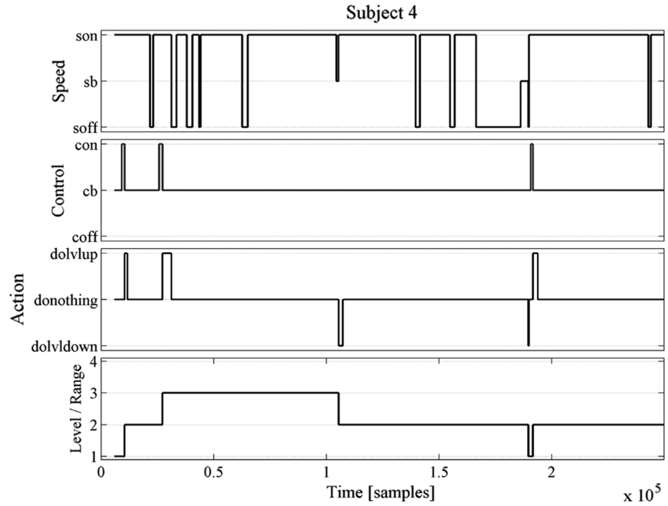


Fig. 5. Exemplary timecourse of the observable variables (*speed* and *control*), the action taken by the decision algorithm (*action*), and the output (*level*) for an exemplary subject. The level of the game is modified according to the values of observations from which user performance is inferred.

TABLE II
SUMMARY OF RESULTS OF THE FEASIBILITY PILOT

	Group
Age [years] ($\mu \pm \sigma$)	52.0 ± 14.66
Gender	5 female, 1 male
Months post-stroke ($\mu \pm \sigma$)	29.5 ± 13.47
Hemiparetic side	6 right, 0 left
Fugl-Meyer at start ($\mu \pm \sigma$)	37 ± 5.56
Gaming time [min] [1] ($\mu \pm \sigma$)	53 ± 29.06

[1] Gaming time refers strictly to time spent on the games. The GT sessions require some time for the calibration, switching games and clinicians feeding back to the adaptation module, thus the total therapy time is actually larger than strictly the gaming time.

IV. Feasibility Pilot

In order to evaluate the feasibility of the platform in its current form, a small feasibility pilot has been carried out at the National Institute of Neurology and Neurosurgery in Mexico City. Kinematic data from six chronic stroke patients while using the described system was collected over a period of one month. All participants were concurrently receiving physical therapy, and

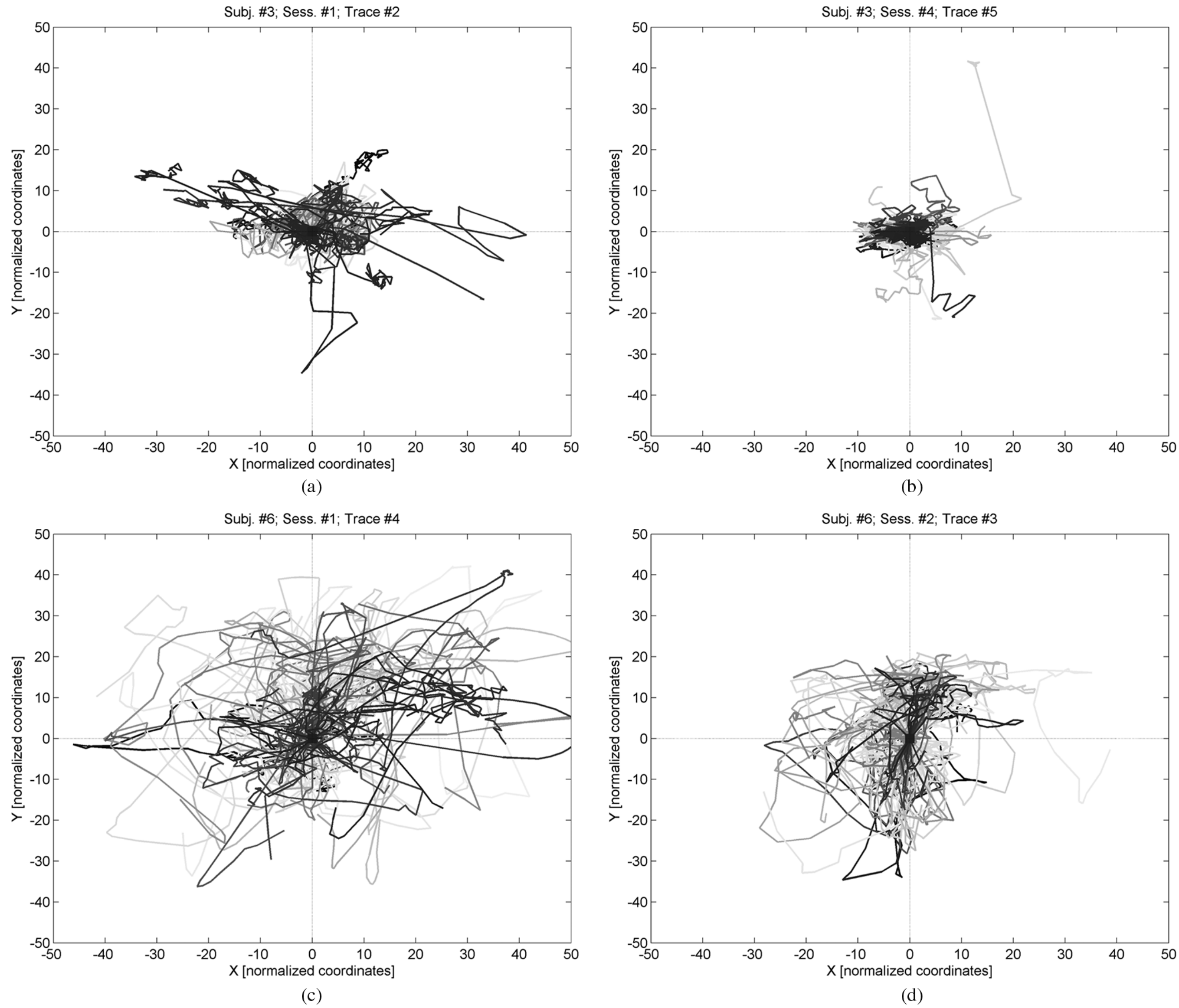


Fig. 6. Exemplary kinematic traces for two different subjects illustrating the longitudinal differences in control from first to last session. Top: Subject 3, the one with the largest improvement in control. Bottom: Subject 6, the one with poorest control performance. For the sake of visualization, target locations have all been centered to normalized coordinates [0,0]. Shades of grey facilitate distinction of different traces, but have no other meaning associated. Each subplot represents 3 min of gaming time. (a) First session; subject 3. (b) Last session; subject 3. (c) First session; subject 6. (d) Last session; subject 6.

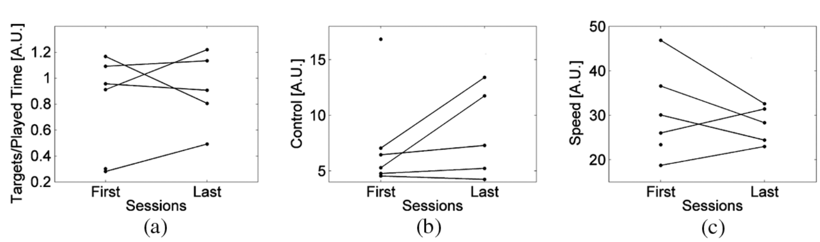


Fig. 7. Performance results from the feasibility study comparing first versus last session. One of the subjects only completed one session. Left: Targets per unit time. Middle: Control. Right: Speed.

voluntarily agreed to participate. Table II summarizes the cohort characteristics. During this period, usage of the GT platform was determined by therapist criterion, and number of sessions with GT for each participant varied from 1 to 4. All three games were played at least once, and game timing was pre-set to 3 min (although this can be altered by the therapist at any time).

Fig. 6 illustrates exemplary traces of kinematic data. Longitudinal differences in control from first to last session can be appreciated for the subject with the largest improvement in control (Subject 3), but not for a subject not exhibiting control improvement (Subject 6). Performance results from the feasibility study are summarized in Fig. 7. The two-tailed Wilcoxon sign rank for paired observations at 5% significance level was used to test for statistical significance in all three performance metrics; number of targets per time unit, control and speed. Neither changes in targets per time unit $(p = 1)$, control $(p = 0.125)$ nor speed $(p = 0.3125)$ were found significant. Different plausible and nonexclusive explanations can be stated. First, the amount of therapy received in this feasibility study was short and insufficient to permit appreciation of differences. Note that this feasibility dose is lower than that administered in our clinical trials for earlier versions of the platform [4], [5]. Second, the game challenge adaptation mechanism with its current policy emphasizing coupled progress of speed and control, favours a slower but surer progress, and may be responsible for some of the drops in speed and increases in control. Finally, the adaptation module increases the challenge by means of enlarging the distance between consecutive targets as the patient progresses. Therefore, the inherently longer paths from the user's avatar onset position to the target location is a candidate for explaining the apparent lack of progress in terms of targets per time unit.

V. Conclusion

GT was conceived as a solution particularly suitable for home usage, and as such, it has a very low cost. Among the main features of this platform are 1) its game set developed using game design criteria considered to be relevant for rehabilitation, 2) its innovative controller, 3) its monocular 3-D tracking system, 4) its capability to detect compensatory movements also from the vision system, and 5) its adaptation module which capitalizes on decision-theoretic models to fit the patient progress. Clinical trials carried out over an earlier version of the platform [4], [5] suggest that GT might support motor recovery comparable to that of occupational therapy to stroke survivors but increasing motivation as measured by the Intrinsic Motivation Inventory as well as subjective comments from the patients. The feasibility pilot described in Section IV using the platform version presented in Section III provides preliminary evidence of the usefulness of the GT application with its latest developments.

The most important contribution of GT are as follows. **First**, we have developed a controller specifically designed for stroke patients that among other features do not require elbow rest, can be used by patients with very different degree of paresis [5], and permit gripping. **Second**, a novel 3-D monocular tracking system capable of estimating depth from a single webcam. We are in the process of obtaining patents for the gripper and the monocular tracking system. **Third**, we have exploited probabilistic models from artificial intelligence to produce an intelligent game set that adapts game challenge to patients in-game performance. **Fourth**, through our (earlier) clinical trials and current feasibility pilot, we have contributed to the growing evidence of the usefulness and validity of virtual reality based therapies, and in particular of GT. **Finally**, we have provided a picture of how the brain responds to GT [5], [62]. In this sense we are only starting to understand the therapy induced cortical reorganization associated with motor recovery. We are now adding user profiling capabilities, enlarging our game set and improving the user interface. We are also planning to use transfer learning to provide inter-session adaptation and therapy planning.

In addition, we are now establishing the validity of the platform for disabilities in children resulting from cerebral palsy. This is a multicenter study that will elucidate the clinical benefits of GT in circumstances other than stroke and adult population. Preliminary subjective appreciation is that children enjoy the VR games more than adults, but they require continuous supervision while playing the games so they do perform the exercises correctly. We conjecture that perhaps incorporating a virtual therapist that monitors the child movements and encourages the correct movements and discourages erroneous execution may be beneficial.

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References

[1] P. Langhorne, F. Coupar, and A. Pollock, "Motor recovery after stroke: A systematic review," *Lancet Neurol.*, vol. 8, pp. 741–754, 2009.

[2] L. E. Sucar, R. Leder, J. Hernández, I. Sánchez, and G. Azcárate, "Clinical evaluation of a low-cost alternative for stroke rehabilitation," in *Proc. IEEE Int. Conf. Rehabil. Robot.*, Jun. 23–26, 2009, pp. 863–866.

[3] L. E. Sucar, A. Molina, R. Leder, J. Hernández, and I. Sánchez, "Gesture therapy: A clinical evaluation," in *Proc. 3rd Int. Conf. Instit. Comput. Sci., Social-Informat. Telecommun. Eng. Pervasive Comput. Technol. Healthcare*, Apr. 1–3, 2009, pp. 1–5.

[4] L. E. Sucar, R. Luis, R. Leder, J. Hernández, and I. Sánchez, "Gesture therapy: A vision-based system for upper extremity stroke rehabilitation," in *Proc. 32nd Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, 2010, pp. 3690–3693.

[5] F. Orihuela-Espina, I. Fernández del Castillo, L. Palafox, E. Pasaye, I. Sánchez-Villavicencio, R. Leder, J. Hernández-Franco, and L. E. Sucar, "Neural reorganization accompanying upper limb motor rehabilitation from stroke with virtual reality-based gesture therapy," *Topics Stroke Rehabilil.*, vol. 20, no. 3, pp. 197–209, 2012.

[6] G. Kwakkel, "Intensity of practice after stroke: More is better," *Schweizer Archiv für Neurologie und Psychiatrie*, vol. 160, no. 7, pp. 295–298, 2009.

[7] C. E. Lang, J. MacDonald, and C. Gnip, "Counting repetitions: An observational study of outpatient therapy for people with hemiparesis post-stroke," *J. Neurol. Phys. Ther.*, vol. 31, pp. 3–10, Mar. 2007.

[8] M. K. Holden, "Virtual environments for motor rehabilitation: Review," *CyberPsychol. Behav.*, vol. 8, no. 3, pp. 187–211, 2005.

[9] J. W. Burke, M. D. J. McNeill, D. K. Charles, P. J. Morrow, J. H. Crosbie, and M. S. M. , "Serious games for upper-limb rehabilitation following stroke," in *2009 Conference in Games and Virtual Worlds for Serious Applications*, G. Rebolledo-Mendez, F. Liarokapis, and S. de Freitas, Eds., Coventry, U.K., Mar. 23–24, 2009, pp. 103–110.

[10] S. K. Subramanian, C. B. Lourenco, G. Chilingaryan, H. Sveistrup, and M. F. Levin, "Arm motor recovery using a virtual reality intervention in chronic stroke: Randomized control trial," *Neurorehabil. Neural Repair*, vol. 27, no. 1, pp. 13–23, 2013.

[11] R. Colombo, F. Pisano, A. Mazzone, C. Delconte, S. Micera, M. C. Carrozza, P. Dario, and G. Minuco, "Design strategies to improve patient motivation during robot-aided rehabilitation," *J. NeuroEng. Rehabil.* vol. 4, no. 1, p. 3, Feb. 2007.

[12] K. Harris and D. Reid, "The influence of virtual reality play on children's motivation," *Can. J. Occupat. Ther.*, vol. 72, no. 1, pp. 21–29, Feb. 2005.

[13] G. Alankus, A. Lazar, M. May, and C. Kelleher, "Towards customizable games for stroke rehabilitation," in *Proc. ACM Conf. Human Factors Comput. Syst. (CHI) Ther. Rehabil.*, E. Mynatt, G. Fitzpatrick, S. Hudson, K. Edwards, and T. Rodden, Eds., Apr. 10–15, 2010, pp. 2113–2122.

[14] S. V. Adamovich, G. G. Fluet, A. Mathai, Q. Qiu, J. Lewis, and A. S. Merians, "Design of a complex virtual reality simulation to train finger motion for persons with hemiparesis: A proof of concept study," *J. NeuroEng. Rehabil.*, vol. 6, p. 28 (10 pp.), 2009.

[15] A. S. Merians, D. Jack, R. Boian, M. Tremaine, G. C. Burdea, S. V. Adamovich, M. Recce, and H. Poizner, "Virtual reality-augmented rehabilitation for patients following stroke," *Phys. Ther.*, vol. 82, no. 9, pp. 898–915, Sep. 2002.

[16] G. Burdea, V. Popescu, V. Hentz, and K. Colbert, "Virtual reality-based orthopedic telerehabilitation," *IEEE Trans. Rehabil. Eng.*, vol. 8, no. 3, pp. 430–432, Sep. 2000.

[17] D. J. Reinkensmeyer, C. T. Pang, J. A. Nessler, and C. C. Painter, "Web-based telerehabilitation for the upper extremity after stroke," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 10, no. 2, pp. 102–108, Jun. 2002.

[18] K. E. Laver, G. Stacey, S. Thomas, J. E. Deutsch, and M. Crotty, "Virtual reality for stroke rehabilitation," *Cochrane Database Systemic Rev.*, vol. 9, p. 70 pp., 2011.

[19] A. S. Rizzo and G. J. Kim, "A SWOT analysis of the field of virtual reality rehabilitation and therapy," *Presence*, vol. 14, no. 2, pp. 119–146, Apr. 2005.

[20] J. J. LaViola, Jr., "A discussion of cybersickness in virtual environments," *SIGCHI Bull.*, vol. 32, no. 1, pp. 47–56, 2000.

[21] F. D. Rose, E. A. Attree, B. M. Brooks, and D. A. Johnson, "Virtual environments in brain damage rehabilitation: A rationale from basic neuroscience," *Studies Health Technol. Informat.*, vol. 58, pp. 233–242, 1998.

[22] E. Todorov, R. Shadmehr, and E. Bizzi, "Augmented feedback presented in a virtual environment accelerates learning of a difficult motor task," *J. Motor Behav.* vol. 29, no. 2, pp. 147–158, 1997.

[23] F. D. Rose, E. A. Attree, B. M. Brooks, D. M. Parslow, P. R. Penn, and N. Ambihaipahan, "Training in virtual environments: Transfer to real world tasks and equivalence to real task training," *Ergonomics* vol. 43, no. 4, pp. 494–511, 2000.

[24] B. M. Brooks, J. E. McNeill, F. D. Rose, R. J. Greenwood, E. A. Attree, and A. G. Leadbetter, "Route learning in a case of amnesia: A preliminary investigation into the efficacy of training in a virtual environment," *Neuropsychol. Rehabil.*, vol. 9, no. 1, pp. 63–76, 1999.

[25] J. S. Webster, P. T. McFarland, L. J. Rapport, B. Morrill, L. A. Roades, and P. S. Abadee, "Computer-assissted training for improving wheelchair mobility in unilateral neglect patients," *Arch. Phys. Med. Rehabil.*, vol. 82, pp. 769–775, 2001.

[26] D. L. Jaffe, D. A. Brown, C. D. Pierson-Carey, E. L. Buckley, and H. L. Lew, "Stepping over obstacles to improve walking in individuals with poststroke hemiplegia," *J. Rehabil. Res. Develop.*, vol. 41, no. 3A, pp. 283–292, May/Jun. 2004.

[27] M. P. Dijkers, P. C. deBear, R. F. Erlandson, K. Kristy, D. M. Geer, and A. Nichols, "Patient and staff acceptance of robotic technology in occupational therapy: A pilot study," *J. Rehabil. Res. Develop.*, vol. 28, no. 2, pp. 33–44, 1991.

[28] C. G. Burgar, P. S. Lum, P. C. Shor, and M. V. D. Loos, "Development of robots for rehabilitation therapy: The Palo Alto VA/Stanford experience," *J. Rehabil. Res. Develop.*, vol. 37, no. 6, pp. 663–673, Nov./Dec. 2000.

[29] M. J. Johnson, M. V. D. Loos, C. G. Burgar, and L. J. Leifer, "Driver's seat: Simulation environment for arm therapy," in *Proc. 6th Int. Conf. Rehabil. Robot.*, M. V. D. Loos, Ed., Stanford, California, Jul. 1–2, 1999, pp. 227–234.

[30] H. I. Krebs, T. Brashers-Krug, S. L. Rauch, C. R. Savage, N. Hogan, R. H. Rubin, A. J. Fischman, and N. M. Alpert, "Robot-aided functional imaging: Application to a motor learning study," *Human Brain Mapp.*, vol. 6, pp. 59–72, 1998.

[31] D. J. Reinkensmeyer, L. E. Kahn, M. Averbuch, A. McKenna-Cole, B. D. Schmit, and W. Z. Rymer, "Understanding and treating arm movement impairment after chronic brain injury: Progress with the ARM guide," *J. Rehabil. Res. Develop.*, vol. 37, no. 6, pp. 653–662, Nov./Dec. 2000.

[32] D. J. Reinkensmeyer, C. T. Pang, J. A. Nessler, and C. C. Painter, "Java therapy: Web-based robotic rehabilitation," in *Integration of Assistive Technology in the Information Age*. Amsterdam, The Netherlands: IOS Press, 2001, Proc. 7th Int. Conf. Rehabil. Robot., pp. 66–71.

[33] M. K. Holden and T. Dyar, "Virtual environment training: A new tool for neurorehabilitation," *Neurobiol. Rep.*, vol. 26, no. 2, pp. 62–71, 2002.

[34] C. Ellsworth and J. Winters, "An innovative system to enhance upperextremity stroke rehabililtation," in *Proc. 2nd Joint EMBS/BMES Conf.*, J. W. Clark, L. V. McIntire, P. Y. Ktonas, A. G. Mikos, and F. H. Ghorbel, Eds., Oct. 23–26, 2002, vol. 3, pp. 2367–2368.

[35] R. Loureiro, F. Amirabdollahian, M. Topping, B. Driessen, and W. Harwin, "Upper limb robot mediated stroke therapy—ENTLE/s approach," *Auton. Robots*, vol. 15, pp. 35–51, 2003.

[36] M. J. Johnson, M. Trickey, E. Brauer, and X. Feng, "Theradrive: A new stroke therapy concept for home-based, computer-assissted motivating rehabilitation," in *Proc. 26th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, D. Hudson and Z.-P. Liang, Eds., San Francisco, CA, Sep. 1–5, 2004, pp. 4844–4847.

[37] P. L. Weiss, D. Rand, N. Katz, and R. Kizony, "Video capture virtual reality as a flexible and effective rehabilitation tool," *J. Neuro-Eng. Rehabil.*, vol. 1, p. 12, 2004.

[38] S. H. Jang, S. H. You, M. Hallet, Y. W. Cho, C.-M. Park, S.-H. Cho, H.-Y. Lee, and T.-H. Kim, "Cortical reorganization and associated functional motor recovery after virtual reality in patients with chronic stroke: An experimenter-blind preliminary study," *Arch. Phys. Med. Rehabil.*, vol. 86, pp. 2218–2223, 2005.

[39] K. August, D. Bleichenbacher, and S. Adamovich, "Virtual reality physical therapy: A telerehabilitation tool for hand and finger movement exercise monitoring and motor skills analysis," in *Proc. IEEE 31st Annu. Northeast Bioeng. Conf.*, Apr. 2–3, 2005, pp. 73–74.

[40] R. Kizony, P. L. Weiss, M. Shahar, and D. Rand, "Theragame—A home based virtual reality rehabililtation system," in *Proc. 6th Int. Conf. Disabil., Virt. Reality Assoc. Technol.*, T. Brooks and S. Cobb, Eds., Esbjerg, Denmark, Sep. 18–20, 2006, pp. 209–214.

[41] R. J. Sanchez, J. Liu, S. Rao, P. Shah, R. Smith, T. Rahman, S. C. Cramer, J. E. Bobrow, and D. J. Reinkensmeyer, "Automating arm movement training following severe stroke: Functional exercises with quantitative feedback in gravity-reduced environment," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 14, no. 3, pp. 378–389, Sep. 2006.

[42] K. Morrow, C. Docan, G. Burdea, and A. Merians, "Low-cost virtual rehabilitation of the hand for patients post-stroke," in *Proc. Int. Workshop Virt. Rehabil.*, G. Burdea, P. T. Weiss, J. Cottraux, and A. S. Rizzo, Eds., 2006, pp. 6–10.

[43] M. Huber, B. Rabin, C. Docan, G. Burdea, M. E. Nwosu, M. Abdelbaky, and M. R. Golomb, "PlayStation 3-based tele-rehabilitation for children with hemiplegia," in *Virt. Rehabil.*, J. Fung and P. T. Weiss, Eds., Vancouver, Canada, Aug. 25–27, 2008, pp. 105–112.

[44] M. Ma and K. Bechkoum, "Serious games for movement therapy after stroke," in *Proc. IEEE Int. Conf. Syst., Man Cybern.*, Singapore, Oct. 12–15, 2008, pp. 1872–1877.

[45] J. E. Deutsch, M. Borbely, J. Filler, K. Huhn, and P. Guarrera-Bowlby, "Use of low-cost, commercially available gaming console (Wii) for rehabilitation of an adolescent with cerebral palsy," *Phys. Ther.*, vol. 88, no. 10, pp. 1196–1207, 2008.

[46] A.-S. Alklind Taylor, P. Backlund, H. Engström, M. Johannesson, and M. Lebram, "Gamers against all odds," in *Edutainment'09 Proc. 4th Int. Conf. E-Learning Games: Learn. Play. Game-based Edu. Syst. Design Develop.*, M. Chang, R. Kuo, Kinshuk, G.-D. Chen, and M. Hirose, Eds., 2009, pp. 1–12.

[47] J. Hoey, A. Monk, and A. Mihailidis, "People, sensors, decisions: Customizable and adaptive technologies for assistance in healthcare," in *POMDP Practitioners Workshop: Solving Real-World POMDP Problems 20th ICAPS 2010*, Toronto, ON, Canada, May 12, 2010, p. 9 pp.

[48] Y. Chen, N. Lehrer, H. Sundaram, and T. Rikakis, "Adaptive mixed reality stroke rehabilitation: System architecture and evaluation metrics," in *Proc. 1st Annu. ACM SIGMM Conf. Multimedia Syst.*, W.-C. Feng, Ed., Phoenix, AZ, Feb. 22–23, 2010, pp. 293–304.

[49] S. Shiri, U. Feintuch, A. Lorber-Haddad, E. Moreh, D. Twito, M. Tuchner-Arieli, and Z. Meiner, "A novel virtual reality system integrating online self-face viewing and mirror visual feedback for stroke rehabilitation: Rationale and feasibility," *Topics Stroke Rehabil.*, vol. 19, no. 4, p. 277286, 2012.

[50] D. Tsoupikova, N. Stoykov, D. Kamper, and R. Vick, "Virtual reality environment assisting post stroke hand rehabilitation: Case report," *Stud. Health Technol. Informat.*, vol. 184, pp. 458–464, 2013.

[51] H. Mousavi Hondori, M. Khademi, L. Dodakian, S. C. Cramer, and C. V. Lopes, "A spatial augmented reality rehab system for post-stroke hand rehabilitation," *Stud. Health Technol. Informat.*, vol. 184, pp. 279–285, 2013.

[52] M. Steinisch, M. G. Tana, and S. Comani, "A post-stroke rehabilitation system integrating robotics, VR and high-resolution EEG imaging," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 21, no. 5, pp. 849–859, Sep. 2013.

[53] P. Viola and M. Jones, "Robust real-time object detection," in *Proc. 2nd Int. Workshop Stat. Computat. Theories Vis.—Model., Learn., Comput. Sampl.*, S.-C. Zhu, A. Yuille, and D. Mumford, Eds., Vancouver, BC, Canada, Jul. 2001, pp. –.

[54] M. F. Levin, "Can virtual reality offer enriched environments for rehabilitation?," *Exp. Rev. Neurotherapeut.*, vol. 11, no. 2, pp. 153–155, 2011.

[55] H. Avilés, R. Luis, J. Oropeza, F. Orihuela-Espina, R. Leder, J. Hernández-Franco, and E. Sucar, "Gesture therapy 2.0: Adapting the rehabilitation therapy to the patient progress," in *Proc. Workshop Probabil. Problem Solving Biomed. 13th Conf. Artif. Intell. Med.*, A. Hommerson and P. Lucas, Eds., Bled, Slovenia, Jul. 2011, pp. 3–14.

[56] Torque Game Engine [Online]. Available: http://www.garagegames.com/products/tge

[57] Symbolic Perseus [Online]. Available: http://www.cs.uwaterloo.ca/ppoupart/software.html

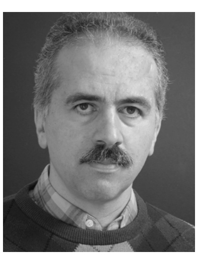
[58] L. E. Sucar, R. Luis-Velasquez, D. Carrillo-López, J. Hernández-Franco, and R. E. Cordero-Cesar, "Mango portátil para rehabilitacíon de extremidades superiores," Int. PCT Patent PCT11/140, 2011.

[59] OpenCV [Online]. Available: http://opencv.org/

[60] J. Hoey, P. Poupart, A. V. Bertoldi, T. Craig, C. Boutilier, and A. Mihailidis, "Automated handwashing assistance for persons with dementia using video and a partially observable Markov decision process," *Comput. Vis. Image Understand.*, vol. 114, p. 503519, 2010.

[61] S. Ávila-Sansores, F. Orihuela-Espina, and L. E. Sucar, "Patient tailored virtual rehabilitation," in *Proc. Int. Conf. NeuroRehabil.*, J. L. Pons, D. Torricelli, and M. Pajaro, Eds., Nov. 14–17, 2012, pp. 879–883.

[62] F. Orihuela-Espina and L. E. Sucar, Functional reorganization strategies associated to motor rehabilitation gesture therapy Coordinacin de Ciencias Computacionales. Instituto Nacional de Astrofsica, ptica y Electrnica (INAOE), Tech. Rep. CCC-11-001, Jun. 2011.



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