Assessment-Driven Arm Therapy at Home Using an IMU-Based Virtual Reality System

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***Abstract*—Virtual reality therapy systems have the potential to increase the intensity and frequency of physical activity of stroke patients at home. This might help to increase the dose of rehabilitation, without the costs associated with clinic visits and therapist supervision. We present a therapy game that continuously estimates the patient's arm reachable three-dimensional (3D) workspace with a voxel-based model and selects targets to be reached accordingly, in order to increase challenge without causing frustration. This exercise is implemented on a novel, inertial measurement unit (IMU) based virtual reality system for the training of upper limb function. We present data from a pilot trial with 5 chronic stroke patients who trained for 6 weeks at home and without therapist supervision. On average, the patients' in-game assessed 3D workspace grew by 10.7% in volume and their score on the Fugl-Meyer Upper Extremity score improved by 5 points. The average self-selected therapy time, over the course of the therapy, was 16.8 h. These results suggest that the proposed assessment-driven target selection is viable for unsupervised home therapy and could form the basis for additional therapy games in the future.**

***Keywords*—stroke, serious games, voxel, workspace, reaching task, upper limb, difficulty adaptation, pilot trial**

I. Introduction

Virtual reality (VR) gaming platforms are a promising approach to motivate patients with neurological disorders to perform intensive and frequent physical activity at home [1]–[5]. This might help to increase the dose of rehabilitation, which is known to positively correlate with functional recovery [6], [7], without the costs associated with clinic visits and therapist supervision.

High motivation and usability are important for patient compliance, especially in a scenario of unsupervised home therapy. In addition, motivation is known to support motor learning [8]. Therefore, therapy should challenge patients at a level appropriate to their individual abilities and impairment in order to ensure usability, efficacy and keep a high level of motivation while avoiding frustration. Although commercial VR gaming platforms, designed for healthy users, have been successfully used in the clinic [2], their usability can be decreased in the case of elderly users [9] or stroke survivors. Moreover, they do not aim at training clinically meaningful movements, and commonly rely on a scripted progression of difficulty levels [10], which can be inappropriate for the patient's state of functional ability. For this reason, VR systems specifically designed for therapy often try to adapt their difficulty levels to the patient's performance and ability in an automated fashion [11]–[16].

In this paper, we focus on the training of arm reaching workspace, which is often reduced in stroke patients [17]–[19]. Previous work has treated workspace of the arm as a function of maximum elbow extension [11], [12], [20], which describes the distance between shoulder and hand, and therefore leads to a circular (planar case) or spherical (3D case) estimation of the patient's reachable workspace. However, patients' workspace border shows individual patterns [18] [19], often with large unreachable areas, which cannot be modelled accurately in this manner. Repeated placement of targets outside of a subject's reachable workspace will likely lead to frustration and jeopardise motivation and compliance. At the same time, it is important to regularly challenge patients by placing targets at the limit of their reach. Thus, therapy games involving reaching tasks should rely on a more detailed model of the cartesian reaching workspace, similar to [18], [19], [21], and use this information to create tasks that balance between challenge and success. We present a therapy game which continuously estimates the patient's arm reachable 3D workspace with a voxel-based model and accordingly selects targets to be reached. These targets are exclusively placed within or (less frequently) at the border of this assessed workspace, with the aim to increase arm reaching ability while, at the same time, preventing frustration. This game and its assessment-driven target selection algorithm are implemented on the ArmeoSenso system, a novel, inertial measurement unit (IMU) based VR system for the training of upper limb function. The system does not provide any physical support (e.g. by a robot), which decreases cost in hardware and specialised support staff. Further, it allows unrestricted free space arm movements, but also increases the need for carefully created, feasible, game tasks. We further present data from a pilot study in which five stroke patients trained with this system and the proposed assessment-driven therapy game for six weeks at their home, without human supervision or intervention.

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(a) (b) (c)

Fig. 1. (a) ArmeoSenso setup demonstrated by a healthy subject. (b) A stroke patient trains with the Meteors therapy game at home. (c) Screenshot of the Meteors therapy game with virtual arm (purple), planet (grey) and falling meteors (red, brown and green ellipsoids). The number on the top left of the screen shows the current score (white) and high score (red). The horizontal green bar at the top right corner indicates the remaining time until the patient has to assume a resting pose and the game is paused.

II. METHODS

A. Setup

The ArmeoSenso setup (Fig. 1a) consists of a motion capture system based on wearable sensors and an all-in-one personal computer (Inspiron 2330, Dell Inc., USA) with 23 inch touch-screen. The patient can use the hand of their unimpaired arm to interact with the touch-based user interface while the movement of the impaired arm is used as input to the therapy game. The patient wears three wireless IMUs (MotionPod 3, Movea SA, France) fixed to the functionally impaired lower and upper arm as well as the trunk, using custom-built straps (Balgrist-Tec, Zurich, Switzerland). This sensor setup is based on the Valedo®Motion system (Hocoma AG, Volketswil, Switzerland), which combines IMUs and augmented performance feedback for treatment of low back pain [22]. The IMUs measure acceleration, angular velocity and the local magnetic field strength in three dimensions respectively, with a sampling frequency of 200 Hz. This data is streamed wirelessly to a receiver block, which is connected to the PC and also serves as a battery charger for the sensors in between therapy sessions. Based on this data, as well as on a short sensor-to-body-orientation calibration at the start of each therapy session, the orientation of the trunk, upper arm and lower arm is estimated (based on [23]) in real-time. The hand orientation is not tracked and assumed to be neutral. The estimated body orientations are then mapped to a virtual arm through forward kinematics [24]. Therefore, all sizes in the therapy game, e.g. the diameter of targets, are scaled to the patient's arm. In this paper, all reported virtual sizes are with respect to a shoulder to elbow distance of 26 cm and a distance of 33 cm between the elbow and the centre of the hand. To discourage compensatory trunk inclination or rotation during reaching movements, the arm pose is computed and displayed relative to the trunk.

During therapy with the ArmeoSenso system, the patient actively moves his/her arm to interact with the VR environment without physical weight support, e.g. by a robotic device. In order to prevent physical exhaustion, the patient is visually instructed to rest for at least 4 s every 40 s. A green indicator at the top right corner (Fig. 1c) decreases in size over time and the game automatically pauses when it has vanished. Once the patient assumes a resting pose, set during the calibration (hand in lap), the system recognises the pose and the green indicator is filled again. The patient can rest at any time and for as long as he/she chooses to. This resting phase is also used by the motion capture algorithm to correct for drift in the estimated sensor orientation, which can accumulate over time [23]. The orientation of the magnetic field is mapped during the calibration phase, at the start of the therapy session, which allows for an accurate, long-term arm tracking even if the earth magnetic field is disturbed (e.g. by loudspeakers or ferrous steel structures) in the patient's home.

B. Meteors Therapy Game

Meteors is a therapy game developed for the ArmeoSenso system. The game aims at increasing the reachable workspace as well as the velocity and coordination of arm movements. The virtual arm is used to catch meteors falling from above on a planet (Fig. 1c).

The game is lost when more than 5 meteors are missed within a round (level) of 3 min. Otherwise, the patient wins the round and receives several rewards which are visually and acoustically celebrated. Due to the low latency arm tracking, the game allows for dynamic movements and encourages high engagement. In addition to frequent rewards such as winning a round or a new high score (based on the number of caught meteors and the difficulty level), larger rewards such as new planets are successively unlocked over time. To unlock all rewards, patients have to train for at least 15 hours.

C. Real-time Workspace Assessment and Target Placement

During the therapy game, a three dimensional model of the patient's reaching workspace (3D workspace) is constantly updated in the background. The model consists of voxels, cubes with a virtual side length of 10 cm, which quantize the cartesian space relative to the patient's trunk. Every 5 ms, the algorithm checks which voxel the current hand position belongs to and marks this voxel as reachable

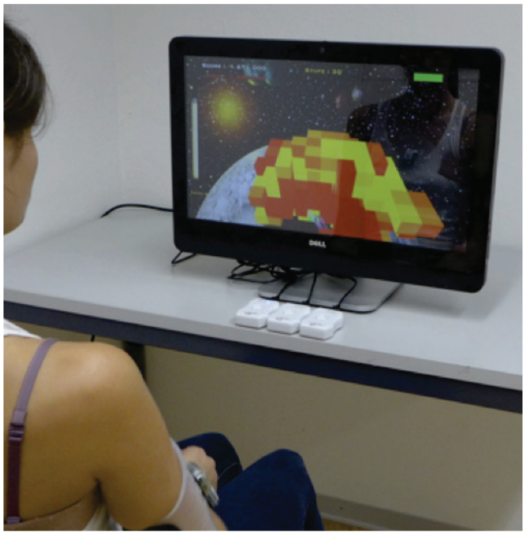

Fig. 2. Visualisation of the 3D workspace which is modelled in the background during the therapy game. The tracked 3D position of the hand, relative to the trunk, is used to assess the reachable 3D workspace. Once the hand has reached a finite region, represented by a voxel (cube) that was previously not visited, the region is added to the model of the reachable workspace visualised here. Bright yellow colours indicate voxels which are visited more often than red ones. This visualisation is not available to the patient.

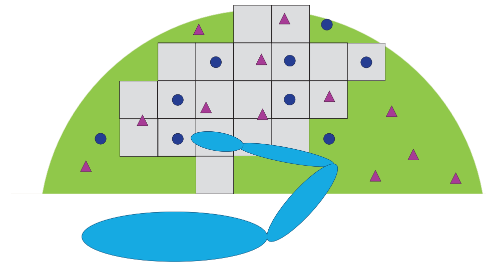

Fig. 3. Orthographic top view, illustrating the concept of automatic, assessment-driven target placement. The green half circle shows the reachable workspace for a healthy, grey squares illustrate the assessed patient workspace (voxels) with examples of target locations computed by the algorithm (blue circles). In contrast, an approach where the maximum elbow extension is used as a single parameter (purple wedges) would lead to an overestimation of the workspace size.

if it has not been marked as such already (Fig. 2). This voxel workspace is limited by the kinematic constraints of the arm as well as the field of view of the game. The constrained space consists of a sphere around the patient's shoulder, with radius equal to the maximum virtual arm length and cut off at $10\,\text{cm}$ in front of the shoulder. As such, the maximum number of reachable voxels in 3D is 234. All targets pass through the horizontal plane, if they are not caught beforehand. Therefor, a fully reachable projected workspace (corresponding to 34 voxels in the horizontal plane) would be sufficient to reach all targets.

The assessment-driven target selection algorithm then works as follows. The therapy game can call two functions to receive a target position which is (1) within or (2) on the border of the modelled workspace (Fig. 3). The first function picks a voxel marked as reachable at random, then computes the corresponding position in the game's coordinate system (relative to the trunk). The second function also picks a voxel marked as reachable at random, then tests all 26 neighbouring voxels, in random order, for reachability. If a tested voxel is not marked as reachable yet, the corresponding position is assumed to be on the border of the patient's reachable workspace and selected for the target placement. If all neighbouring voxels are marked as reachable, the process is repeated from the start until a suitable voxel and corresponding position is found. The Meteors game uses the first function for 75% of all targets to create a feasible task that doesn't frustrate the patient. The second function is used for the remaining 25% to create a challenge that might lead to an increased workspace.

Average speed, number and time interval of meteors are automatically adapted, depending on the patient's performance in the last round. In the case of a won round (less than 5 missed meteors within $3\,\text{min}$ of play time), difficulty increases with inverse proportion to the number of missed meteors. In the case of a lost round, difficulty decreases in proportion to the remaining time. As such, even targets within the patient's workspace can be challenging and the difficulty adapts quickly to the patient's performance in the case that the manually assigned start difficulty level was inappropriate. The workspace model and difficulty parameters are saved at the end of each therapy session and the following session automatically resumes with the same settings.

D. Pilot Study and Data Analysis

In a pilot study, we examined the feasibility of the proposed assessment-driven therapy game for self-directed home training with the ArmeoSenso system in chronic stroke survivors. The patients had the ArmeoSenso system setup at their home for six weeks and were instructed to train as much as they chose. The study was approved by the ethics commission of the Canton of Zurich (Ref. KEK-ZH 2013-0182). All subjects gave informed consent. Inclusion criteria were a minimum age of 18 years, a first-time stroke, motor deficits in the upper limb, the ability to lift the paretic arm against gravity and a minimum workspace size in the horizontal plane of $20\,\text{cm} \times 20\,\text{cm}$. In this paper, we present the preliminary results of five patients and the change in their workspace-related assessment scores over the course of the therapy. The patients had an average age of 62.4 years (min 48 years, max 79 years) and a Fugl-Meyer Assessment upper extremity score [17] (FMA-UE, maximal 66 points) of 39.8 points (min 14, max 60) at the start of the therapy.

III. RESULTS

All patients increased the size of their assessed 3D workspace over the course of the therapy, although there appears to be a ceiling effect towards the end of the therapy (Fig. 4). Still, the average voxel count of the first three weeks compared with the last three weeks increased significantly (two-sided Wilcoxon rank sum test, $p = 0.032$, $T = 17$) by 10.7% (min 6.8%, max 14.4%).

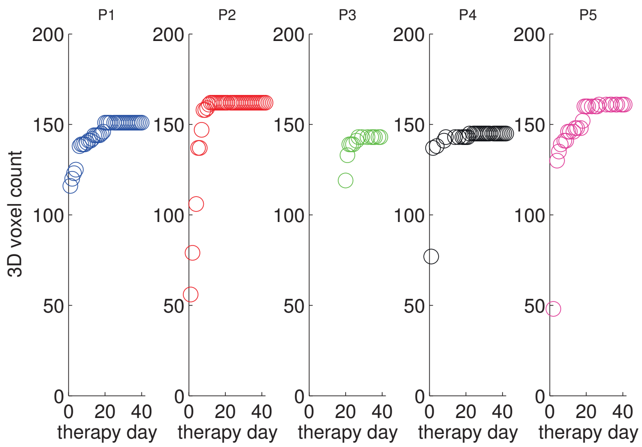

Fig. 4. Voxel count of the 3D workspace assessment, which was conducted during each Meteors therapy session in the background.

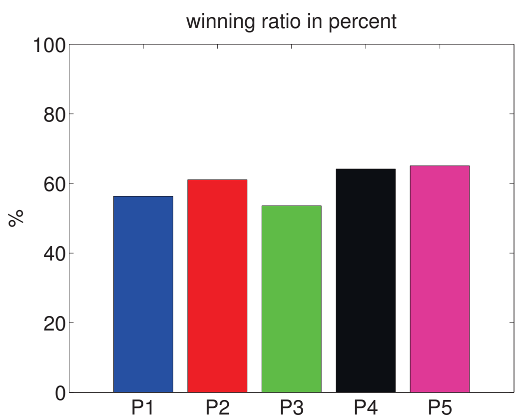

Fig. 5. Ratio of rounds won (less than 5 targets missed within 3 min) over all rounds played, in the Meteors therapy game.

On average patients won 60.0% (min 53.6%, max 65.0%, Fig. 5) of the played rounds (max 3 min each) which is close to the often stated 'ideal success rate' of 70% [25] [20] [26] indicating a good balance between reward and challenge.

As an example of the recorded target placement, we analysed one round of the therapy game (Fig. 6) in which the patient won the round by catching all but 4 out of 30 targets. While the success rate for targets within the assessed workspace remained within 75% to 100%, only half of the 4 targets placed on the border of the workspace were caught successfully. During this session, the 3D voxel count of the assessed workspace increased from 75 to 94 and the projected workspace by 2 voxels (from 26 to 28).

Over the course of the six week therapy, the five patients trained for an average of 16.8 h (min 7.2 h, max 34.3 h) . Two of them trained for more than the 15 h required to unlock all game rewards and another two patients got close to that mark at 11.9 h and 10.8 h respectively.

All patients improved on the FMA-UE score, on average by 5 points (min 4, max 7).

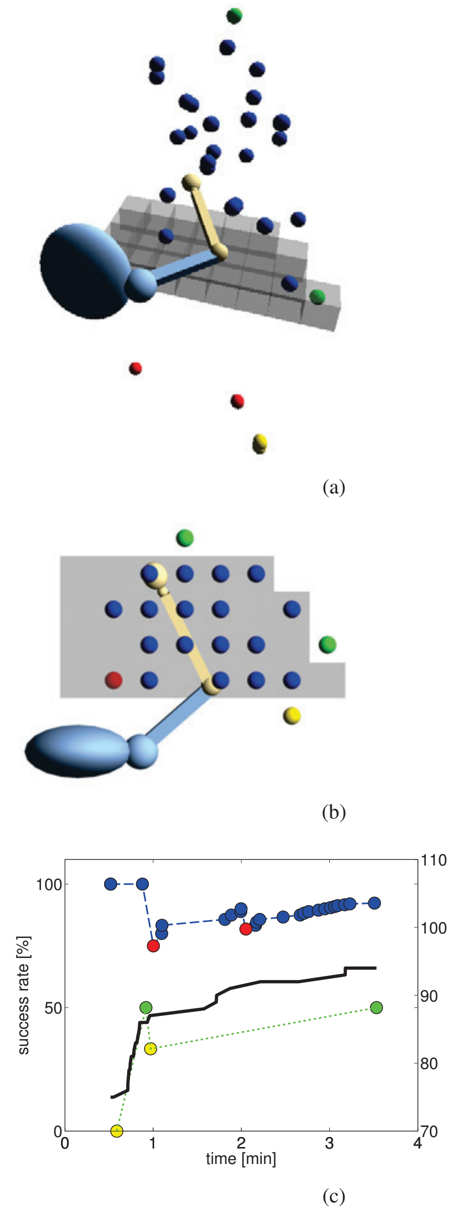

Fig. 6. Example of the target placement during a short therapy session (session 2, patient P2) consisting of a single round. Blue circles represent targets which the patient caught within the planar projection of the assessed (in game) 3D workspace (24 cases), red circles represent targets missed within the planar workspace (2 cases), green circles represent targets caught at the border of the planar workspace (2 cases) and yellow circles represent targets missed at the border of the planar workspace (2 cases). Since only 4 meteors were missed overall, this round counted as won. (a) Perspective view that shows the projected 3D workspace (grey, semi transparent voxels), as well as the position at which targets were caught. Missed targets are displayed at the bottom of the scene. All targets in the game are created at the same height and only the planar component of the desired position, computed by the algorithm is taken into account. However, the desired height is used to adapt the target's falling speed in an inverse manner in order to promote a reach closer to the desired height. (b) Orthographic top view of the same scene. (c) Corresponding success rate for targets which are placed within (blue dashed line) and at the border (green dotted line) of the workspace and the simultaneous increase of the voxel count in the 3D workspace model (black solid line). Time intervals without catches are due to the patient resting his/her arm, during which the therapy is paused.

IV. Discussion and Conclusion

In this paper we presented an assessment-driven exercise game, implemented on a novel IMU-based therapy system. Our aim was to increase patients' reaching workspace through a reaching task, without causing frustration through the placement of targets which are far out of reach. We evaluated our approach in a pilot trial with five chronic stroke patients who used the system at their home over a period of 6 weeks without external supervision. Patients significantly increased their assessed 3D workspace size (11% of voxel count), although improvements were smaller in the second half of the therapy. In addition, the patients improved their Fugl-Meyer Upper-Extremity score (5 points on average) which might be a consequence of an increase in reachable workspace. However, it is important to note that due to the low number of subjects ($N = 5$), which in some cases also received conventional therapy, as well as the lack of a control group, no conclusions about the efficacy of our approach can be drawn from this study. In addition, it is possible that our approach of marking reached voxels as permanently reachable could lead to an overestimation of the 3D workspace size. While this boolean voxel-based method is not as detailed as other approaches [21], the presented single session example suggests that it is nevertheless a powerful model to select feasible and challenging target locations with a simple algorithm, and encourages increase in workspace size.

Targeted therapy to increase reaching workspace, through assessment of a detailed model of the workspace shape, has already been shown to be successful (24 sessions in 8 weeks of therapy) [19] in the clinic. However, in this case a robot was used for (increasingly reduced) weight-support and the therapy included human supervision and intervention. Targets (5, all in the horizontal plane) were deliberately placed out of reach while a therapist occasionally provided verbal encouragement. In our case, the considerable patient-selected therapy duration (16.8 h on average over the course of 6 weeks) and high success rate (less than 5 targets missed in 60% of all rounds) suggest that the approach presented here is feasible in an unsupervised scenario at home, without physical support by a robot. Instead, VR therapy games based on wearable sensors are used to motivate and challenge the patient.

In the future, the workspace-based target placement functionality could be extended by a more complex model, e.g. by assessing maximum hand velocities or use of a probabilistic approach [21]. This could lead to a more accurate and insightful assessment of patients' abilities and also form the base for a more sophisticated selection of tasks. Further, the assessment-driven task selection could be enhanced by a standardised application programming interface (API). This API could facilitate the development of VR therapy games for traditional game developers, without domain knowledge in physiotherapy and stroke, which in turn could increase the variety and quality of exercises that patients can choose from.

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References

[1] D. K. Zondervan, R. Augsburger, B. Bodenhoefer, N. Friedman, D. J. Reinkensmeyer, and S. C. Cramer, "Machine-based, self-guided home therapy for individuals with severe arm impairment after stroke: a randomized controlled trial," *Neurorehabilitation and Neural Repair*, Oct. 2014.

[2] G. Saposnik, R. Teasell, M. Mamdani, J. Hall, W. McIlroy, D. Cheung, K. E. Thorpe, L. G. Cohen, and M. Bayley, "Effectiveness of virtual reality using Wii gaming technology in stroke rehabilitation: a pilot randomized clinical trial and proof of principle," *Stroke*, vol. 41, pp. 1477–1484, Jul. 2010.

[3] D. Webster and O. Celik, "Systematic review of Kinect applications in elderly care and stroke rehabilitation," *Journal of Neuroengineering and Rehabilitation*, vol. 11, Jan. 2014.

[4] N. A. Borghese, M. Pirovano, P. L. Lanzi, S. Wüest, and E. D. de Bruin, "Computational intelligence and game design for effective at-home stroke rehabilitation," *Games for Health Journal*, vol. 2, pp. 81–88, Apr. 2013.

[5] F. Kohler, T. Schmitz-Rode, and C. Disselhorst-Klug, "Introducing a feedback training system for guided home rehabilitation," *Journal of Neuroengineering and Rehabilitation*, vol. 7, Jan. 2010.

[6] G. Kwakkel, "Impact of intensity of practice after stroke: issues for consideration." *Disability and Rehabilitation*, vol. 28, pp. 823–830, Jan. 2009.

[7] E. Cooke, K. Mares, A. Clark, R. Tallis, and V. Pomeroy, "The effects of increased dose of exercise-based therapies to enhance motor recovery after stroke: a systematic review and meta-analysis," *BMC Medicine*, vol. 8, 2010.

[8] M. Lotze, C. Braun, N. Birbaumer, S. Anders, and L. G. Cohen, "Motor learning elicited by voluntary drive," *Brain*, vol. 126, pp. 866–872, Apr. 2003.

[9] K. Gerling and M. Masuch, "When Gaming is not Suitable for Everyone: Playtesting Wii Games with Frail Elderly," *1st Workshop on Game Accessibility: Xtreme Interaction Design*, 2011.

[10] R. Lopes and R. Bidarra, "Adaptivity Challenges in Games and Simulations: A Survey," *IEEE Transactions on Computational Intelligence and AI in Games*, vol. 3, pp. 85–99, Jun. 2011.

[11] P. Kan, R. Huq, J. Hoey, R. Goetschalckx, and A. Mihailidis, "The development of an adaptive upper-limb stroke rehabilitation robotic system," *Journal of Neuroengineering and Rehabilitation*, vol. 8, Jan. 2011.

[12] M. da Silva Cameirão, S. Bermúdez i Badia, E. Duarte, and P. F. Verschure, "Virtual reality based rehabilitation speeds up functional recovery of the upper extremities after stroke: a randomized controlled pilot study in the acute phase of stroke using the rehabilitation gaming system," *Restorative Neurology and Neuroscience*, vol. 29, pp. 287–298, 2011.

[13] L. Zimmerli, C. Krewer, R. Gassert, F. Müller, R. Riener, and L. Lünenburger, "Validation of a mechanism to balance exercise difficulty in robot-assisted upper-extremity rehabilitation after stroke," *Journal of Neuroengineering and Rehabilitation*, vol. 9, Jan. 2012.

[14] E. Papaleo, L. Zollo, L. Spedaliere, and E. Guglielmelli, "Patient-tailored adaptive robotic system for upper-limb rehabilitation," *IEEE International Conference on Robotics and Automation*, pp. 3860–3865, May 2013.

[15] M. Sivan, J. Gallagher, S. Makower, D. Keeling, B. Bhakta, R. J. OConnor, and M. Levesley, "Home-based Computer Assisted Arm Rehabilitation (hCAAR) robotic device for upper limb exercises after stroke: results of a feasibility study in home setting," *Journal of Neuroengineering and Rehabilitation*, vol. 11, 2014.

[16] J.-C. Metzger, O. Lambercy, A. Califfi, D. Dinacci, C. Petrillo, P. Rossi, F. M. Conti, and R. Gassert, "Assessment-driven selection and adaptation of exercise difficulty in robot-assisted therapy : a pilot study with a hand rehabilitation robot," *Journal of Neuroengineering and Rehabilitation*, vol. 11, 2014.

[17] A. R. Fugl-Meyer, L. Jääskö, I. Leyman, S. Olsson, and S. Steglind, "The post-stroke hemiplegic patient. 1. a method for evaluation of physical performance." *Scandinavian Journal of Rehabilitation Medicine*, vol. 7, pp. 13–31, 1975.

[18] T. M. Sukal, M. D. Ellis, and J. P. A. Dewald, "Shoulder abduction-induced reductions in reaching work area following hemiparetic stroke: neuroscientific implications," *Experimental Brain Research*, vol. 183, pp. 215–223, Nov. 2007.

[19] M. D. Ellis, T. M. Sukal-Moulton, and J. P. a. Dewald, "Impairment-based 3-D robotic intervention improves upper extremity work area in chronic stroke: targeting abnormal joint torque coupling with progressive shoulder abduction loading," *IEEE Transactions on Robotics*, vol. 25, pp. 549–555, Jun. 2009.

[20] M. S. Cameirão, S. B. I. Badia, E. D. Oller, and P. F. M. J. Verschure, "Neurorehabilitation using the virtual reality based Rehabilitation Gaming System: methodology, design, psychometrics, usability and validation," *Journal of Neuroengineering and Rehabilitation*, vol. 7, Jan. 2010.

[21] F. C. Huang and J. L. Patton, "Individual patterns of motor deficits evident in movement distribution analysis," *IEEE International Conference on Rehabilitation Robotics*, 2013.

[22] M. Bauer, C., Baumgartner, L., Schelldorfer, S., Ernst, M., Lawrence, "Technical validation of a new movement therapy system for treatment of low back pain," *Gait & Posture*, pp. 40–41, 2012.

[23] S. O. H. Madgwick, A. J. L. Harrison, and A. Vaidyanathan, "Estimation of IMU and MARG orientation using a gradient descent algorithm," *International Conference on Rehabilitation Robotics*, 2011.

[24] J. J. Craig, *Introduction to robotics: mechanics and control*. Pearson Prentice Hall Upper Saddle River, 2005, vol. 3.

[25] Y. Choi, F. Qi, J. Gordon, and N. Schweighofer, "Performance-based adaptive schedules enhance motor learning," *Journal of Motor Behavior*, vol. 40, pp. 273–280, Jul. 2008.

[26] S. V. Adamovich, G. G. Fluet, A. S. Merians, A. Mathai, and Q. Qiu, "Incorporating haptic effects into three-dimensional virtual environments to train the hemiparetic upper extremity," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 17, pp. 512–520, Oct. 2009.