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Time Independent Functional Task Training:

A Case Study on the Effect of Inter-Joint Coordination Driven Haptic Guidance in Stroke Therapy

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Abstract—**After a stroke abnormal joint coordination of the arm may limit functional movement and recovery. To aid in training inter-joint movement coordination a haptic guidance method for functional driven rehabilitation after stroke called Time Independent Functional Training (TIFT) has been developed for the ARMin III robot. The mode helps retraining inter-joint coordination during functional movements, such as putting an object on a shelf, pouring from a pitcher, and sorting objects into bins. A single chronic stroke subject was tested for validation of the modality. The subject was given 1.5 hrs of robotic therapy twice a week for 4 weeks. The therapy and the results of training the single stroke subject are discussed. The subject showed a decrease in training joint error for the sorting task across training sessions and increased self-selected movement time in training. In kinematic reaching analysis the subject showed improvements in range of motion and joint coordination in a reaching task, as well as improvements in supination-pronation range of motion at the wrist.**

Keywords-stroke, therapy, robotics, synergies, haptics, coordination

I. INTRODUCTION

Abnormal coordination is commonly observed in hemiparetic arm movements after stroke, often due to abnormal muscle synergies, weakness, and spasticity [1]. This can be very disruptive to function in activities of daily life. For example reach to grasp movements, like manipulating an object on a shelf, are often disrupted by the abnormal muscle synergy of simultaneous shoulder elevation and elbow flexion [2,3]. Stroke victims may overcome these deficits through the reliance on compensation patterns, such as excessive trunk movement, for functional activities but studies have suggested that therapy interventions focused on compensation may limit functional recovery [4, 5]. Recovery of proper joint coordination is possible with a focused intervention [5] and may aid in real world use of the limb in activities of daily living [6].

The use of robotic devices to treat upper limb movement deficits is becoming increasingly accepted. Although meta-analysis and systematic review of robotic therapy studies have shown significant increases in strength and range of motion, there were no overall advantages of using robots in recovery of activities of daily living (ADL) ability [7-9]. At the same time a recent multi-site clinical trial of several upper limb robots found robots to be comparable to dose-matched conventional therapy, but superior to usual and customary care in motor function scales at the 36-week follow-up time point [10]. These mixed results motivate further analysis of these robotic approaches as well as new untested approaches to maximize restoration of ability in activities of daily living.

The field of robotic devices for rehabilitation is very diverse mechanically, ranging from a focus on robots for single arm joint training [11, 12], to arm end point based robots, and full arm exoskeletons [13]. Control methods for these robots during therapy have been equally diverse. Although rehabilitation robots have moved away from passive movement therapy due to studies showing the necessity of subject engagement [14], the type and quantity of assistance that should be provide is still debatable. Since subject ability is often very low it becomes difficult to ensure successful completion of the task without the robot doing all the work. Adaptive control algorithms for the constraint and assistance provided by the robot have also been developed [15] to minimize guidance, since excessive assistance may impair task learning [16]. Some groups have used end point tunnels to provide minimal guidance through the desired movement [17-19]. However, end point paths do not necessarily insure proper joint coordination through the trained movement, and in many cases allow use of compensatory strategies.

We have developed a robotic intervention for arm rehabilitation that specifically targets impaired inter-joint coordination by requiring active patient participation in coordinating multiple joints similar to a recently reported training mode developed for gait training [20]. We implemented this training mode in the ARMin III exoskeleton [21], which can apply torques directly to each of the 6 DOF of the arm (3 shoulder torques, elbow flexion-extension, supination-pronation, wrist flexion-extension). The HandSOME device was attached for passive tone compensation of the hand allowing for real world or virtual object grasp training [22]. The following paper describes the therapy program designed for functional, patient initiated training. The Time Independent Functional Training (TIFT), modality is discussed and results are presented from a single chronic stroke subject trained across approximately 4 weeks with 1.5 hour sessions delivered twice a week.

TIFT allows the patient to learn the desired movement in joint space at his or her own pace while still requiring the patient to actively complete the movement. This system provides guiding joint-space walls to keep the subject close to the ideal joint-space path and holds the subject's arm at the current point in the trajectory if they stop actively producing the required inter-joint coordination.

II. TIFT Controller For Rehabilitation

Three functional tasks: 1) putting an object on a shelf, 2) pouring from a pitcher and 3) sorting objects into bins, were developed for therapeutic use with the ARMin III robot. The combination of the ARMin III and HandSOME devices implemented in the shelf task can be seen in Figure 1a as well as the virtual interface that was used during training in Figure 1b. Compensation for the robot's weight, viscous friction, and static friction were implemented to decrease the impedance of the robot in all modes according to previously reported methods [23].

A. B.

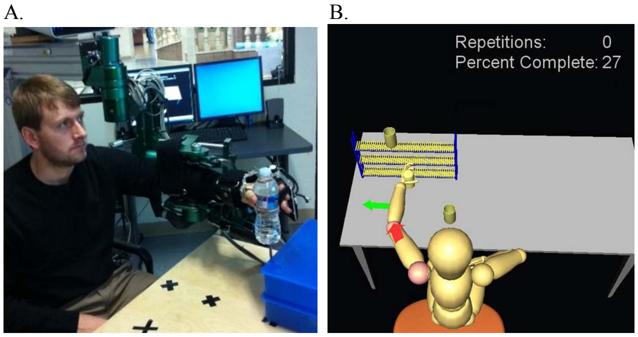

Fig. 1A. ARMin device fitted to a normal subject and in Fig. 1B. the corresponding visual interface used for training of the shelf task. The subject is approximately one quarter of the way through the task, which is lifting and placing the bottle on the shelf and returning your hand to the table.

The shelf task focuses on correcting the abnormal coordination patterns in the shoulder elevation and elbow extension movement due to the associated abnormal muscle synergy. The path utilized for the shelf task is shown in Figure 2. Figure 2a shows the path of the shoulder and the elbow separately with a line indicating the location of the joints at 27% completion as shown in Figure 1. Figure 2b shows the linear coordination pattern of the elbow and shoulder through the movement, again with a marker denoting 27% completion. The subject starts in the lower right corner, moves up to the left to place the object on the shelf and then back along the same path line to the original position to complete the movement.

The TIFT modality ensures that the subject remains on this coordination pattern shown in Figure 2 by implementing joint space walls within a set dead-band around the path and only allowing progression if the arm joints are properly coordinated. If the subject is moving both joints in the proper direction to complete the path, they will not feel any resistance from the robot. However, if the subject attempts an incorrect movement pattern (ie: shoulder elevation with elbow flexion), the robot will prevent movement through the path until there is proper coordination of the two joints. The robot applies haptic walls that are exponentially related to each individual joint's error from its ideal position. The ideal joint position is determined by the percentage complete of the task as shown in Figure 2a. The joint with the minimum amount of progression through the path determines the current percentage complete of the task. This prevents abnormal compensation patterns and helps break through abnormal synergies. The system also prevents backward movement and will hold the subject in place if they need to rest due to fatigue. Further details on the TIFT modality implementation can be found in a previous paper [24].

Two different TIFT settings were used for the task training. In the shelf task the deadband was set to zero so that any joint space error caused the robot to provide exponential walls that pushed the subject back toward the path. The sorting and pouring tasks were implemented with a 2^o deadband at each joint.

A.

B.

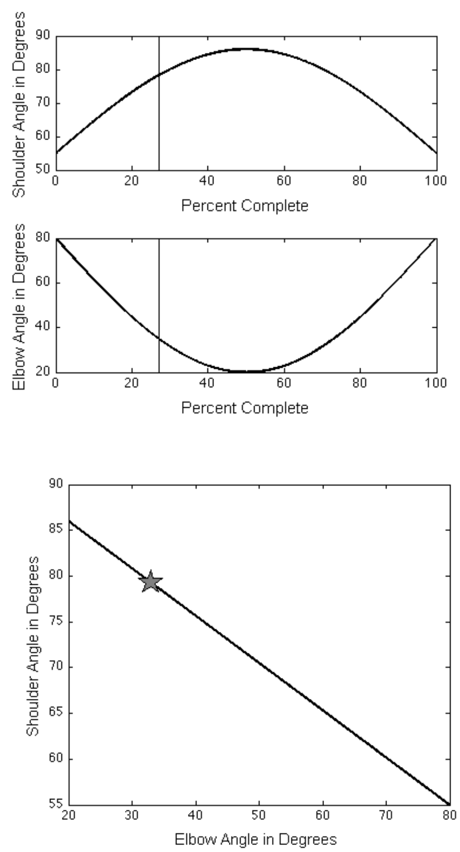

Figure 2. Fig. 2a show the joint movement through the shelf task and figure 2b shows the joint coordination. The gray vertical lines in Fig 2a mark the joint angles associated with 27% completion of the shelf task and the gray star shows the corresponding location on a joint space representation.

The pouring task was focused on supination-pronation and shoulder internal/ external rotation, while the sorting task focused on shoulder elevation and horizontal adduction/ abduction.

A visual interface for therapy was projected in front of the subject to assist with the completion of the movement as shown in Figure 1b. The visual interface displays the desired movement of the arm with color-coded arrows placed on the appropriate joints of the avatar. The joint's arrow is green when the subject is properly rotating that joint and red if that joint is limiting the motion. If the subject properly coordinates their arm during the movement, the arrows will remain green throughout the movement. The subject is told to "move in the direction of the red arrow to make it green" in order to complete the task. Subjects were provided with additional feedback about the number of repetitions performed and the percent complete of the task. Audio feedback was provided to indicate that the subject had reached the endpoints of the task. An important part of therapeutic intervention is ensuring that the tasks are challenging but doable. Difficulty of the TIFT tasks can be adjusted through changes in range of motion, the addition of human arm weight compensation, and addition of assistive torque at the most difficult joint. The mode can also be switched into single joint control for specific focus on target muscles if needed, where the robot will move the other joints through the path utilizing a PD position controller according to the movement of the single controlling joint.

The subjects are able to use real or virtual objects during training. This allows for progression in type of objects that are grasped to practice grip strength and grasp modulation during arm movements.

The general method used for administering robotic therapy was as follows. An evaluation was done at the beginning of each task, where the robot was set to the highest range of motion (ie highest shelf height or sorting distance) without any added assistance to the TIFT program (ie no subject arm weigh compensation or assistive torques). The subject was then told to make three attempts at the path. If the subject completed only one or none, arm gravity compensation was added until the subject could comfortably train at that task. If 100% arm weight compensation did not allow for task completion, then the range of motion would be reduced. In the pouring task, a constant joint torque assistance was provided to aid in completion since arm weight effects were minimal in that movement pattern. If the subject was able to complete the task three times consistently with relative ease (within approximately 30 seconds) then arm weight compensation was reduced until the task was at a sufficiently difficult level to challenge the subject.

The most problematic joint in the movement can be determined through examination of the feedback avatar. Through this examination the most challenging joints for individual subjects can be determined and focused on, such as a subject's limitation in the pouring task being inability to supinate the wrist.

III. THERAPY REHABILITATION

Therapy was overseen by a trained physical therapist to ensure proper fit in the robot, but a technician administered all robotic therapy. Our subject, a 47-year old, right-handed woman with left hemiparesis, was 6 years post stroke at the start of the trial. The subject showed a generally positive outlook with the self-administered SF-36 [25] survey giving a 100 in General Health, Social Function, and Pain, despite a reported 25 in Physical Function. The subject showed relatively good range of motion of the shoulder but was very limited in wrist motion and finger extension. Elbow extension was also difficult. Before therapy clinical analysis showed a Fugl-Meyer [26] score of 22 and an Action Research Arm Test (ARAT) [27] score of 21.

For evaluation the stroke subject was moved through the path once by the robot and then asked to move through the path with the TIFT controller three times before changes were made to the program in accordance with the therapy guidelines. No additional assistance was provided in these evaluation trials, and all training data presented in the paper is taken from these evaluation movements, where the focus was solely on arm movement and not grasp. After evaluation each task was trained for approximately 15 minutes with 5 minutes of games (ball and labyrinth games reported in Staubli et al [28] with minor changes), played between task training to break up the training. The remaining time was spent on the functional tasks of the subject's choosing. Task training included the grasp of real objects during the sorting task and occasionally during the shelf task. In later training sessions the subject would grab various objects off a table and move them between locations unassisted during the sorting task. This helped the subject to learn to coordinate arm speed and hand aperture in the task. Objects varied in size, weight, and fragility to help train the needed changes in movement to the object as well as proper grasp strength control.

IV. ARMIN TRAINING RESULTS

The subject showed progress in learning the proper joint coordination across the training sessions as examined through the evaluations done at the beginning of each task training session (Fig. 3). Smaller joint errors indicate less reliance on the guiding walls and improved coordination. Clear reductions in joint error and movement time were present in the sorting task. Joint error in the shelf task was relatively small across training due to the lack of deadband in this task, and thus a trend in joint error is not visible across training, although self selected movement time did decrease across training as shown in Figure 3. The pouring task was difficult for the subject and in some training sessions could not be completed without assistance from the robot. As a result, only the 7th and 8th training day's data are included in Figure 3. Assistance for the pouring task during training was provided as a constant continuous torque at the lagging joint, which for our subject was wrist supination-pronation. Focused intervention with assisting supination torque allowed the subject to progress to completion of the pouring task later in the training.

During training, the subject completed many sorting tasks with real objects of many different shapes, sizes, and fragility. The subject practiced controlling the arm motion to an object, grasp of the object, and moving the object to the other side of the table. The average number of grasp movements practiced was approximately 110 per session for the last four training sessions and about 55 per session for the first four training sessions where the main focus was on the shoulder movement during the sorting task.

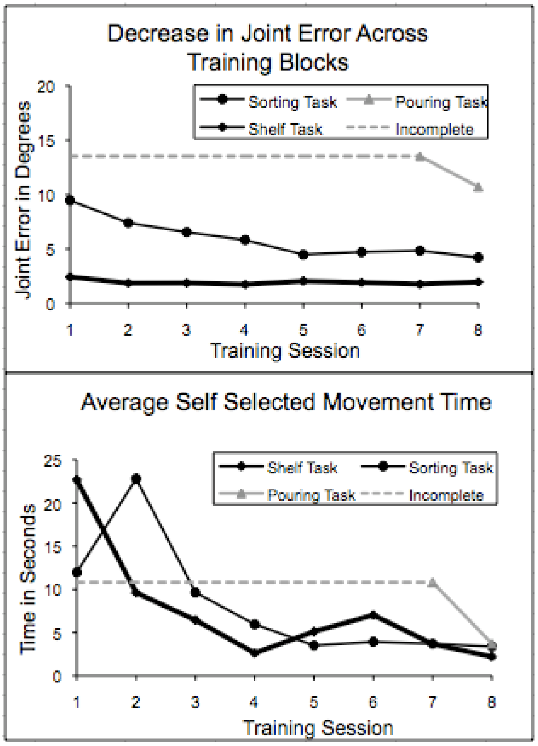

Fig. 3. The top image shows the reduction of joint error across training blocks. The dotted line expresses that the subject was unable to complete the pouring task unassisted for evaluation until the 7th training block. The lower figure shows the reduction of self selected movement time across training blocks

V. Kinematic and Clinical Analysis

Kinematic and clinical measures analysis was done before and after therapeutic intervention. Clinical evaluation post training showed an overall three point increase in the Fugl Meyer score from 22 to 25 and a decrease in the ARAT score of two points from 21 to 19. The decrease in the ARAT score was in the grasp and grip sections of the test. In the flexor synergy section of the Fugl-Meyer improvements were seen in shoulder retraction (1 to 2) and external rotation (0 to 1). Improvements were also seen in volitional movement of shoulder flexion (1 to 2) and forearm supination-pronation (0 to 1). In the hand, mass flexion ability increased (1 to 2) as did grasp A (distal finger grasp, 0 to 1), while cylindrical grasp ability decreased (1 to 0). The reflexes in biceps and finger flexors could not be elicited at post training, resulting in a 2 point decrease in the reflex section.

Kinematic analysis was preformed with the Motion Monitor miniBirds system to access changes in movement ability. The start and end position of each movement was always the same and a strap was used to prevent compensation through trunk movement during reaching movements but was removed for object manipulation tasks. The subject was asked to perform two self-paced reaches toward an out of reach target that required shoulder elevation and elbow extension. Both pre and post analysis of hand position showed a relatively straight movement of the hand through the reaching pattern as shown in Figure 4a. The range of motion of the hand remained relatively similar with a max increase of only 5.0 cm vertically and 3.2 cm laterally after training. A linear fit of the horizontal vs. vertical hand movement provided an R^2=0.89 before training and R^2=0.96 after training, implying some increase in linearity of the movement. However, although end point position data did not produce large changes, Figure 4b shows a dramatic change in inter-joint coordination of the shoulder elevation and elbow extension during the reaching movement. The instability of movement at the elbow before therapeutic intervention can be seen from the large variability from a linear path with a R^2=0.68 before training, which improved to R^2=0.88 after training. This increase in R^2 value implies an increase in movement smoothness and arm joint coordination during the reaching movement.

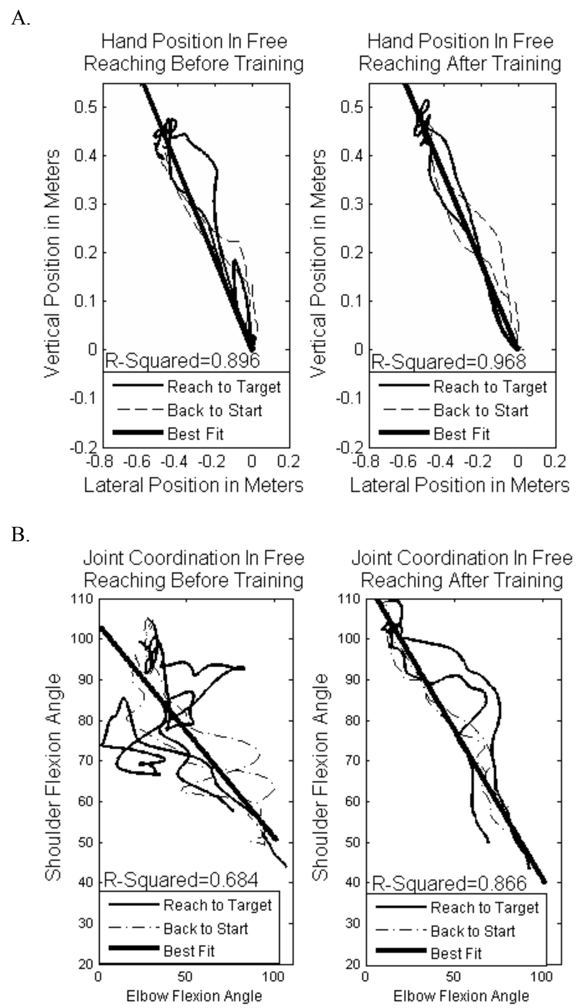

Fig. 4. The top image, Fig 4a shows the similar trajectories of the hand between the pre and post trial with a better range of motion and straightness of movement after training. Figure 4b shows the change in coordination of the elbow and shoulder during this movement pre and post therapeutic intervention.

The most extended coordinated posture in the pre-training reaching trial was 105° of elevation at the shoulder and 27.75° at the elbow, where 0° is full elbow extension. After training, the position was 109° at the shoulder and 9.83° at the elbow showing a definitive increase in coordinated shoulder elevation and elbow extension after training. The average increase in elbow extension angle between the two sessions was 17.5^{o} while the maximum shoulder elevation angle was relatively consistent between sessions. Self-selected outward reaching movement time decreased from an average of 4.82s to 3.59s. A paired T-test showed that this change was not statistically significant (p=0.37). Mean peak velocity was slightly reduced between sessions from 12 mm/s to 10 mm/s. However, this change was also not statistically significant (p=0.24).

The subject showed a dramatic increase in supination range of motion at the wrist, which, as noted in the pouring task training analysis, was very difficult before therapeutic intervention. In attempting to move her arm to lift a water bottle on the table, the subject had very little volitional wrist supination-pronation prior to intervention with a recorded average range of motion of 22.8$^{o}\pm$ 3.38^{o}. After intervention range of motion was increased to 60.7$^{o}\pm$ 4.24^{o}. The subject remained unable to grasp the water bottle or a bolt nut in kinematic analysis after training. Index finger-thumb aperture in combined kinematic analysis of attempts to lift a water bottle and a bolt nut off the table was only 1.93 cm before training and 3.06 cm in post training analysis with a standard deviation of 1 cm for both sessions.

VI. Conclusions

The TIFT method of training for rehabilitation has shown generally positive results in a single stroke subject trial. In training, the subject showed decreasing reliance on the TIFT walls as well as faster self paced movements through the task implying that the tasks became easier. In kinematic analysis the subject showed a dramatic increase in smooth coordination in the side reaching task as well as an increase elbow extension and supination range of motion. This is fairly consistent with the gains in the Fugl-Meyer test, where improvements were seen in shoulder retraction, external rotation, shoulder flexion, and supinationn-pronation. There was some concern that the subject might develop abnormal movement timing due to the time independent training. However, the general reduction in self-selected movement time in training and reaching movements as well as the similar peak velocities in pre and post training kinematic reach implies that abnormal timing strategies were not adopted from training.

It is unfortunate that gains were not seen in functional grasp as she was unable to lift objects in the kinematic analysis and in fact showed a decrease in ARAT score in grasp and grip. Although grasp was not a main goal of the therapeutic intervention, as joint coordination was, it was expected that the training with the HandSOME device would elicit some improvements in grasp control outside of the robot as it did inside the robot. While there were some improvements in mass flexion and distal finger grasp ability on the Fugl-Meyer scale, it was clear that finger extension did not improve with training. It is possible that the number of grasping movements (660 total) was simply not sufficient to improve finger extension ability outside of the device. Another possibility is that the hand training changed the resting posture of the subject's hand, leading to decreased effectiveness in the compensation methods used during performance of the ARAT. General increase in flexor tone may have also played a role in the ARAT. Subject tone was highly variable during training sessions and the number of elastic cords used with the HandSOME device occasionally had to be changed in the middle of task training to adequately compensate for finger flexor hypertonia.

We argue that the decrease in flexor reflex score on the Fugl-Meyer from 2 to 0 after training is unlikely to be a negative sign. This chronic subject had good volitional control of biceps and finger flexors, and generally showed no decreased on the performance-based sections of the Fugl-Meyer related to these muscle groups. In fact the inability to elicit reflexes in the flexors may be a sign of decreased hypertonia.

Further testing with other stroke subjects of varying levels of impairment will help expand this research and show if this modality will be helpful for improving ability in activities of daily living.

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References

[1] K.M. Zackowski, W. Dromerick, S. Sahrmann, W.T. Thach, and J. Bastian, "How do strength, sensation, spasticity and joint individuation relate to the reaching deficits of people with chronic hemiparesis?," *Brain : a journal of neurology*, vol. 127, May. 2004, pp. 1035-46.

[2] T.M. Sukal, M.D. Ellis, J.P. Dewald. "Shoulder abduction-induced reductions in reaching work area following hemiparetic stroke: neuroscientific implications," *Exp Brain Res*. 2007 Nov;183(2):215-23.

[3] J.P. Dewald, R.F. Beer. "Abnormal joint torque patterns in the paretic upper limb of subjects with hemiparesis," *Muscle Nerve*. 2001 Feb;24(2):273-83.

[4] J.W. Krakauer. "Motor learning: its relevance to stroke recovery and neurorehabilitation," *Curr Opin Neurol*. Feb 2006;19(1):84-90.

[5] M.D. Ellis, B.G. Holubar, A.M. Acosta, R.F. Beer, J.P. Dewald. "Modifiability of abnormal isometricelbow and shoulder joint torque coupling after stroke," *Muscle Nerve*. 2005 Aug;32(2):170.

[6] P.S. Lum, S. Mulroy , R.L. Amdur, P. Requejo, B.I. Prilutsky, A.W. Dromerick. "Gains in upperextremity function after stroke via recovery or compensation: Potential differential effects on amount of real-world limb use," *Top Stroke Rehabil.* 2009 Jul-Aug;16(4):237-53.

[7] M.L. Aisen, H.I. Krebs, N. Hogan, F. McDowell, B.T. Volpe. "The effect of robot-assisted therapy and rehabilitative training on motor recovery following stroke," *Arch Neurol*. 1997 Apr;54(4):443-6.

[8] H.I. Krebs, N. Hogan , B.T. Volpe , M.L. Aisen ,L. Edelstein , C. Diels. "Overview of clinical trials with MIT-MANUS: a robot-aided neuro-rehabilitation facility," *Technol Health Care*. 1999;7(6):419-23.

[9] G.B. Prange, M.J. Jannink, C.G. Groothuis-Oudshoorn, H.J. Hermens , M.J. Ijzerman. "Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke," *J Rehabil Res Dev*. 2006 Mar-Apr;43(2):171-84.

[10] J. Mehrholtz, T. Platz, J. Kugler, M. Pohl. "Electromechanical and robot-assisted arm training for improved arm function and activities of daily living after stroke," *Cochrane Database of Systematic Reviews*. 2008; 4:CD006876.

[11] S. Hesse, G. Schulte-Tigges, M. Konrad, A. Bardeleben, C. Werner. 2003. "Robot-assisted arm trainer for the passive and active practice of bilateral forearm and wrist movments in hemiparetic subjects," *Arch. Phy. Med Rehabil.* 84:915-20.

[12] M. Lorenzo, C. Maura, G. Psiche, S. Giulio, and M. Pietro, “Performance adaptive training control strategy for recovering wrist movements in stroke patients: a preliminary, feasibility study,” *Journal of NeuroEngineering*, vol. 6, 2009, pp. 1-11.

[13] A. Waldner, C. Tomelleri, and S. Hesse, “Transfer of scientific concepts to clinical practice : recent robot-assisted training studies,” *Functional Neurology*, vol. 24, 2009, pp. 173-178.

[14] D. Lynch, M. Ferraro, J. Krol, C.M. Trudell, P. Christos, B.T. Volpe . “Continuous passive motion improves shoulder joint integrity following stroke,” *Clin Rehabilitation* 2005, 19(6):594-599.

[15] L. Marchal-Crespo, D.J. Reinkensmeyer. “Review of control strategies for robotic movement training after neurologic injury,” *Journal of NeuroEngineering and Rehabilitation*. 2009 Jun16; 6:20

[16] R. Schmidt, and R. Bjork, “New conceptualizations of practice: common principles in three paradigms suggest new concepts for training,” *Psychological Science*, vol. 3 (4), pp. 207-217, 1992.

[17] L.E. Kahn, P.S. Lum, W.Z. Rymer, D.J. Reinkensmeyer. “Robot-assisted movement training for the stroke-impaired arm: Does it matter what the robot does?,” *J Rehabil Res Dev*. 2006 Aug-Sep;43(5):619-30.

[18] C.G. Burgar, P.S. Lum, P.C. Shor, H.F. Machiel Van der Loos. “Development of robots for rehabilitation therapy: the Palo Alto VA/Stanford experience,” *J Rehabil Res Dev*. 2000 Nov-Dec;37(6):663-73.

[19] S.K. Banala,S.H. Kim, S.K. Agrawal, J.P. Scholz. “Robot assisted gait training with active leg exoskeleton (ALEX),” *IEEE Trans Neural Syst Rehabil Eng*. 2009 Feb;17(1):2-8.

[20] A. Duschau-Wicke, J. von Zitzewitz, A. Caprez, L. Lunenburger, R. Riener. “Path control: a method for patient-cooperative robot-aided gait rehabilitation,” *IEEE Trans Neural Syst Rehabil Eng.* 2010 Feb;18(1):38-48.

[21] T. Nef, M. Guidali, and R. Riener, "ARMin III - arm therapy exoskeleton with an ergonomic shoulder actuation," *Applied Bionics and Biomechanics*, vol. 6, 2009, pp. 127-142.

[22] E.B. Brokaw, R. Holley, P.S. Lum. Hand Spring Operated Movement Enhancer (HandSOME) Device for Hand Rehabilitation after Stroke. *IEEE Engineering in Medicine and Biology Conference*, Buenos Aires, 2010.

[23] T. Nef , P.S. Lum. “Improving backdrivability in geared rehabilitation robots,” *Med Biol Eng Comput*. 2009 Apr;47(4):441-7.

[24] E.B. Brokaw, T.M. Murray, T. Nef, P.S. Lum. “Retraining of inter-joint arm coordination after stroke using robot-assisted time-independent functional training,” *Journal of Rehabilitation Research & Development*. Accepted Dec 14, 2010. Publication Pending.

[25] J. Brazier, R. Harper, N. Jones, A. O’cathain, K. Thomas, T. Usherwood, and L. Westlake, “Validating the SF-36 health survey questionnaire: new outcome measure for primary care.,” *British Medical Journal*, vol. 305, 1992, p. 160.

[26] A. Fugl-Meyer, L. Jääskö, I. Leyman, S. Olsson, and S. Steglind, “The post-stroke hemiplegic patient. 1. a method for evaluation of physical performance,” *Scand J Rehabil Med,* 1975. 7(1):13-31.

[27] N. Yozbatiran, L. Der-Yeghiaian, S.C. Cramer. “A standardized approach to performing the Action Research Arm Test,” *Neurorehabil Neural Repair*. 2008;22:78-90.

[28] P. Staubli, T. Nef, V. Klamroth-Marganska, and R. Riener, “Effects of intensive arm training with the rehabilitation robot ARMin II in chronic stroke patients: four single-cases.,” *Journal of neuroengineering and rehabilitation*, vol. 6, Jan. 2009, p. 46.