Proceedings of the 2nd Biennial IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics
Scottsdale, AZ, USA, October 19-22, 2008

Combined Electromyography(EMG)-Driven System with Functional Electrical Stimulation (FES) for Poststroke Rehabilitation

R. Li, X. L. Hu, K. Y. Tong*, *Senior Member, IEEE*

Abstract—**Robot and functional electrical stimulation (FES) techniques have been used for improving motor functions after stroke respectively. In this work, we aimed to examine the combined effects from Robot and FES in post-stroke wrist rehabilitation. We developed a new electromyography (EMG)-driven FES-robot system with a control algorithm, which was interactive to the voluntary motor inputs from persons after stroke. Two hemiplegic subjects with chronic stroke were recruited to test the EMG-driven FES-robot system. The results demonstrated that the integrated system was effective in improving the tracking performance represented by root mean squared error (RMSE) and root mean squared jerk (RMSJ) of tracking trajectories in programmed wrist tracking tasks assisted with different proportions of the interactive supports from the FES and robot parts respectively. This combined system may have the potential to be applied in stroke rehabilitation.**

INTRODUCTION

STROKE can cause morbidity and invalidity in the paretic limbs, and about 80%-90% persons after stroke have permanent motor function weakness or sensory dysfunction [1]. Although, most patients can recover parts of the function through long-term and intensive post-stroke physical training, post-stroke treatment always requires huge human resource and large financial expense.

In comparison with the post-stroke rehabilitation programs conducted by human physical therapists, post-stroke trainings assisted with rehabilitation robot showed their advantages in aspects of well-controlled training setup and saving the human resources [2][3]. It has been reported that robot-assisted therapy could significantly improve the upper limb motor functions after stroke [4-7]. The most commonly reported motion types provided by developed rehabilitation robots are: 1) continuous passive motion, 2) active-assisted movement (for interactive treatment), and 3) active-resisted movement [5]. Due to the effectiveness in motor improvement by active-assisted robotic treatment, the recent developments involving rehabilitation robots has been worked towards the active-assisted control strategies for interactive rehabilitation treatment, which allows the robotic system to react to patient's voluntary intention.

Functional electrical stimulation (FES) is a common technique used for the rehabilitation of people with neurological disabilities. FES has been used to generate motions of upper limbs in quadriplegic patients [8] and the motions of lower limbs in paraplegic patients [9][10]. It has been found that by using FES at the paretic muscles, muscle strength may be improved by the regular electrical stimulation on the target muscles [11]. There are many FES systems available for clinical use. For example, the bionic glove [25][26] from the University of Alberta, Canada, is a hybrid system consisting of a garment with FES electrodes that use a mechanical measurement of wrist extension to trigger stimulation of finger flexion. There are also other commercially available FES products, such as the Handmaster [12], an orthosis in which stimulation electrodes are fitted for upper limbs.

Comparing the training effects of using rehabilitation robot and using FES devices, we may find their own advantages and disadvantages. Rehabilitation robotic systems usually have mechanical components to support body parts to finish a programmed motion task [13]. In a physical training assisted by a rehabilitation robot, subjects may practice whole limbs, which are related to the activities of several groups of muscles. [21-24]. However, physical trainings assisted with robot usually cannot target on a specific muscle as in the treatments with FES. Treatments with FES may precisely activate each target muscle. However, the main disadvantages of the physical treatments with FES are that the physical training on muscle groups usually requires a number of FES electrodes to stimulate muscles, and mechanical limb supports usually are lacking in FES devices. In our previous works, a robotic system driven by electromyography (EMG) has been developed for post-stroke training on both the wrist and elbow joints [14][15][29]. Although significant motor improvements obtained after the training, muscle weakness still existed, especially in the wrist and elbow extensors [16]. We also developed a four-channel FES system for gait training on persons after stroke [17]. With this FES system, gait speeds were improved [18].

In this work, we developed a new system for stroke rehabilitation by combining EMG-driven robot system with

Manuscript received April 22, 2008. This work was supported by the Research Grants Council of the Hong Kong Special Administrative Region, China. (Grant No. PolyU 5284/06E)
R. Li is with the Department of Health Technology and informatics, The Hong Kong Polytechnic University, Hong Kong, China, SAR.
X. L. Hu is with the Department of Health Technology and informatics, The Hong Kong Polytechnic University, Hong Kong, China, SAR.
*K. Y. Tong (corresponding author) is with the Department of Health Technology and informatics, The Hong Kong Polytechnic University, Hong Kong, China, SAR (Tel: 852-2766 7669; Fax: 852-2334 2429; E-mail: K.y.tong@polyu.edu.hk).

EMG-driven FES system; and the performance of using this system by persons after stroke were analyzed.

I. METHODS

A. The FES-Robot System

Fig 1 shows the diagram of the FES-robot system for post-stroke rehabilitation. The FES-robot system was composed of a robot part and FES part, which were both driven by voluntary EMG signals detected from the flexor carpi radialis (FCR), and extensor carpi radialis (ECR). When using this system, a subject would be seated with the affected upper limb mounted horizontally on the system to conduct wrist extension and flexion by tracking a target cursor on a computer screen (Fig 2), moving with an angular velocity at 10^o/sec from -45^o (extended position) to 60^o (flexed position).

The hardware of the system consists of a Robot system and an FES system which are controlled by a computer. The computer sampled the amplified EMG signals from the FCR and ECR muscles with a sampling frequency of 1000 Hz , also the angle feedbacks of the wrist through a digital-to-analogue device. Then sent out the control signals to the Robot system and the FES system respectively. The software of the system was developed by LABVIEW program which processed the incoming signals, sent out the control signals, and provided a screen interface to the subject as shown in Fig 2. Furthermore, the electrical stimulation from the FES was given on the surface FCR and ECR muscles.

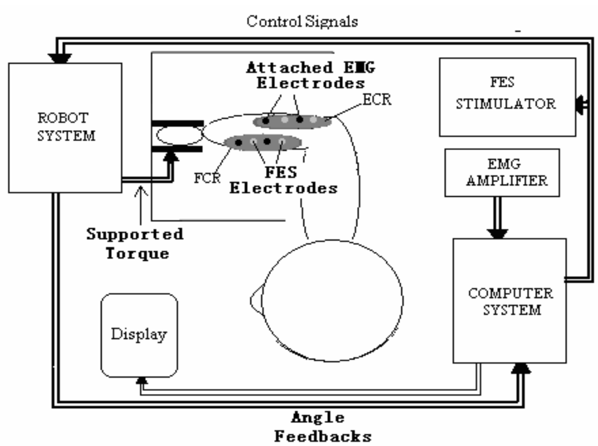


Fig 1. The diagram of the FES-robot system

The control algorithm for the FES-robot system could be described as follows:

1) The EMG signals were processed by band-pass filter from 10Hz to 500Hz. The stimulation artifacts in the EMG signals were deleted by method of sample and hold principle, as did in stimulus removal study of Minzly [27]. The envelope of an EMG signal trial was then obtained by full-wave rectification and filtering with a moving average window (100ms). The processed ECR and FCR EMG at this step was named as, EMG_i, where i represented the respective muscles.

2) The processed EMG_i, was then sent to the robot and FES parts. For the robot part, the assistive torque from the motor was formulated as:

$$T_a = G \cdot T_{IMVC} \cdot M_i \quad (1)$$

where, G is a constant gain used to adjust the magnitude of the assistive torque; and T_{IMVC} is the maximal value of the torques during IMVF when doing flexion, or IMVE when doing extension. M_i is defined as

$$M_i = \frac{EMG_i - EMG_{irest}}{EMG_{iIMVC} - EMG_{irest}} \quad (2)$$

where, EMG_i is the EMG of the agonist muscle i (ECR during the extension, or FCR during the flexion). EMG_{irest} is the averaged EMG of muscle i during the resting state, and EMG_{iIMVC} is the maximal value of muscle i during its maximal isometric contractions at wrist angle of 0^o. Robot-assisted post-stroke rehabilitation with proportional EMG control has been applied in our previous study on elbow and wrist training [15] [16] [28].

For the FES part, the stimulation intensity to a target muscle was defined as:

$$I_a = K \cdot I_{\max,i} \cdot M_i \quad (3)$$

where, K is a constant gain used to adjust the magnitude of the stimulation voltage intensity; $I_{max,i}$, is the stimulation intensity which can evoke the maximum flexion or extension torque when the wrist joint is positioned at 0^o; M_i bears the same meaning as in Eq 2.

B. System Evaluation with Persons after Stroke

After obtaining approval from the Human Subjects Ethics Sub-Committee of the Hong Kong Polytechnic University, we recruited two subjects with chronic stroke (at least 1 yr postonset of stroke, right hemiplegia, ages of 52 yrs and 38 yrs respectively) to evaluate the system. The motor disabilities at the wrist joint of these two subjects were measured by the modified Ashworth score for the wrist (1 and 1+ respectively) [19] and Fugl-Meyer score at the forearm/hand (14 and 9 respectively) [20].

In the experiment, each subject was firstly required to conduct the isometric voluntary flexion and extension at 0^o with a repetition of 3 times. Then, the stimulation intensities of $I_{max,i}$ (Eq 3) for the ECR and FCR muscles at the wrist joint of 0^o were started to output. After that, the subject were asked to carry out wrist tracking tasks by following a target cursor moving with the angular velocity of 10^o/sec on the computer screen (Fig 2). There were 5 cycles of wrist extension/flexion in each tracking trial, and seven combinations between the supports from the FES and robot parts during the tracking task were examined, as illustrated in Table 1. Tracking accuracy was evaluated by the root mean squared error (RMSE) between the target and actual angles during the tracking, as shown in Eq 4.

$$RMSE = \sqrt{\frac{1}{N}\sum(\theta_0(i) - \theta(i))^2} \quad (4)$$

where $\theta_o(i)$ was the target wrist angle at i^{th} sampling instant and $\theta(i)$ was the actual wrist angle at i^{th} sampling. N was the total number of samples.

The smoothness of the tracking was measured by the root mean squared jerk (RMSJ), as shown in Eq 5

$$RMSJ = \sqrt{\frac{1}{N}\sum j(i)^2} \qquad (5)$$

J(i) was jerk of wrist movement at i^{th} sampling instant which could be calculated from the third derivatives of the angle .

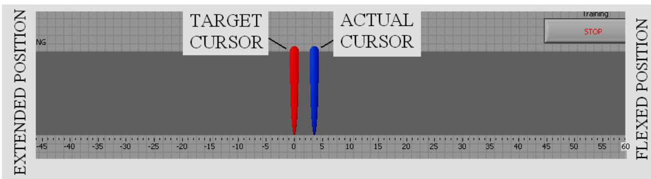


Fig. 2 The display of the screen interface for the subjects when doing the tracking tasks.

TABLE I
THE PROPORTION OF THE FES OR ROBOT INVOLVED.

Combinations	FES support, K	Robot support, G
1	0%	0%
2	50%	0%
3	100%	0%
4	50%	50%
5	100%	100%
6	0%	100%
7	0%	50%

K and G are the gain values defined in Eq 1 and 3.

II. RESULTS

Three tested results were examined in this paper: a) the hardware performance (Fig 3) to make sure if the system works as EMG driven Robot-FES system; b) tracking trajectories with and without supports from the system to compare if the system can bring the stroke patient significant moving improvement; c) difference performance with different combinations of the supports from the FES and robot.

Fig.3 shows the representative EMG trials of the ECR, FCR muscles and FES intensity in a tracking task, which was with 50% motor and 50% FES supports. The former two graphs were the normalized EMG signals (ECR and FCR), which are defined as energy, used to driven the Robot and FES. In the last panel in Fig.3, it shows the stimulation intensity driven by the former two signals. Also, the stimulating time is 180 seconds.

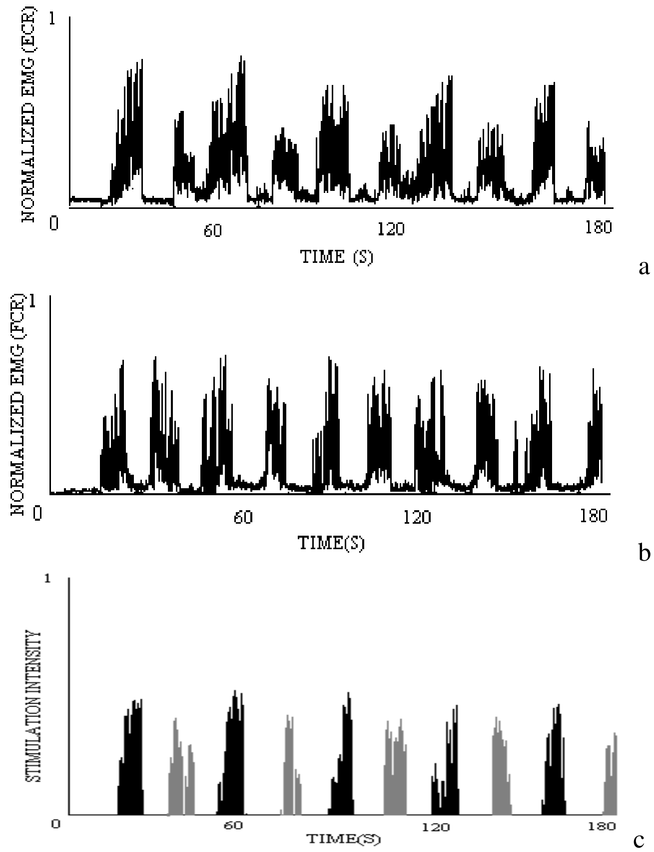


Fig.3 The representative EMG energies for the ECR and FCR muscles (a and b) and the corresponding stimulation intensities (c) with 50% robot and 50% FES supports. In c, the dark line is the stimulation for ECR and the gray line is for FCR, the scale of the y axis ranges from 0 to 1, reflecting the stimulating intensity to these two muscles during a tracking task.

In Fig 3, we can see two properties of the system. Firstly, the support from the FES part was interactive and related to the EMG amplitudes of the agonist muscles during the tracking. Secondly, the stimulation intensity from the system was calculated by the gain, K in Eq 3. The FES and Robot parts were controlled in real time by the subjects' own EMG signals.

Fig.4 shows two tracking trajectories represented by the tracking angles, with and without the support from the system. The first trial was conducted without any assistance (Fig 4.a), and the second trial (Fig 4.b) was the movement supported by the system with the combination of G=50% and K=50%.

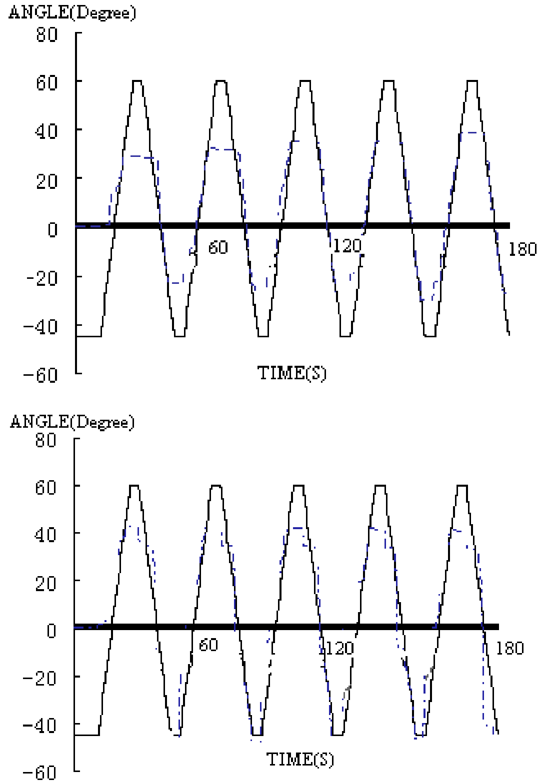
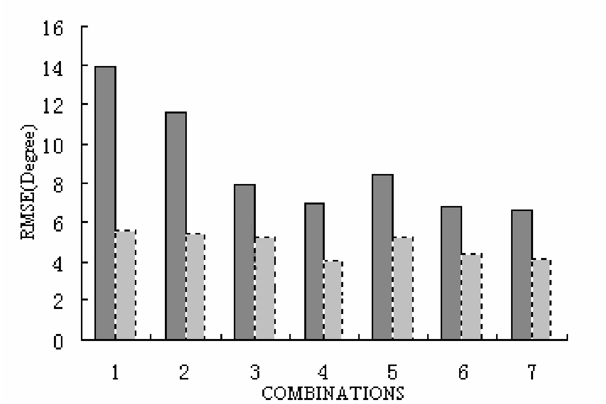


Fig.4The representative tracking trajectories of the target angle (thick lines) and the actual angle (dashed lines) during two tracking tasks with different supportive combinations from the system. In a, there was no support from the system. In b, the supports from the robot and FES parts are 50% and 50%.

In Fig 4, It shows that the range of motion (flexion or extension) for wrist was apparently increased with the assistive force from the system. The stroke patient cannot reach -20° and 30° in the direction of flexion and extension respectively without the assistive force (as Fig 4. a), but can get to the full range up to -45° at the flexion direction and significant improvement in extension tracking task, up to 43 ° with the system's assistance.

In Fig 5, the performances of the tracking for the two subjects with different combinations of the supports from the FES and robot parts were summarized by the parameters of RMSE and RMSJ, which showed the tracking accuracy and the tracking stability respectively. The different FES and robot combinations were numbered as specified in Table 1.



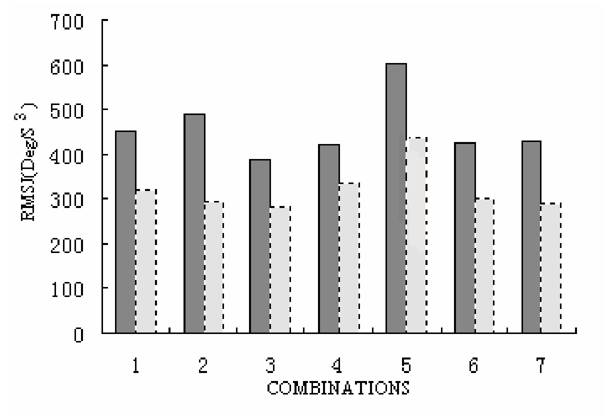


Fig. 5 The RMSE and RMSJ in seven different combinations (as numbered in Table 1), calculated from two patients (the black bars are for patient 1 and the grey bars are for patient 2). The upper graph is the RMSE. The lower graph is the RMSJ calculated based on the same data.

In the Fig 5.a, the largest tracking error was observed when there was no support from either the robot or the FES part in subject 1. The lower tracking error was observed when the support combinations are: 50% robot and 50% FES, 0% FES and 100% robot, and 0% FES and 50% robot, but the lowest are 50% robot and 50% FES . The variation in the tracking error in subject 2 was not as large as that in subject 1, and the lower tracking error was observed in the support combination of 50% FES and 50% robot, 0% FES and 100% robot, 0% FES and 50% robot, but the lowest are 50% robot and 50% FES. In conclusion, 50% FES and 50% robot combination is the best proportion on improving the tracking error in this system.

When evaluating the tracking smoothness by RMSJ (Fig 5.b), the largest RMSJ value happened when 100% FES and 100% robot were applied.

Overall, there were three FES and robot support combinations with smaller RMSE and RMSJ found in the two subjects attended the experiment, i.e., [50% FES and 50% Robot], [50% Robot], and [100% Robot] but the most efficient one is [50% FES and 50% Robot].

III. CONCLUSION

In our paper, we developed a new FES-robot rehabilitation system. The robot and FES sub-systems were driven by ECR and FCR EMG signals, which reflected the voluntary intention of the subjects. The assistance from the system was only given to the agonist muscle during the tracking in the same movement direction (i.e., in the flexion, only FCR was stimulated; while in the extension, only ECR was stimulated), which may suppress the over excitation from the antagonist muscle.

The system evaluation results from the two hemiplegic subjects after stroke suggested that with the adequate supports (e.g. 50% robot and 50% FES) from the robot and FES, the

RMSE of the tracking performance improved. However, if the gain of the supports from the system was too large (e.g. 100% robot and 100% FES), the control abilities of the subjects on the robotic system were not stable enough to conduct smooth tracking, which resulted in high RMSJ. The different combination of the supports from the robot and FES parts should be studied on more subjects in the future work.

REFERENCES

[1] J. Bogousslavsky, G. Van Melle, and F. Regli, "The Lausanne Stroke Registry: analysis of 1,000 consecutive patients with first stroke," *Stroke*, vol. 19, pp. 1083-92, 1988.

[2] J. V. Basmajian, C. A. Gowland, M. A. Finlayson, "Stroke treatment: comparison of integrated behavioural-physical therapy vs traditional physical therapy programs," Arch Phys Med Rehabil, vol. 68, pp. 267–272, 1987.

[3] R. Dickstein, S. Hocherman, T. Pillar, R. Shaham, "Stroke rehabilitation. Three exercise therapy approaches," Phys Ther, vol. 66, pp. 1233–1238. 1986.

[4] 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, vol. 54, pp. 443–6, 1997.

[5] B. T. Volpe, H. I. Krebs, N. Hogan, L. Edelsteinn, C. M. Diels, M. L. Aisen, "Robot training enhanced motor outcome in patients with stroke maintained over 3 years," Neurology, vol. 53, pp. 1874–6, 1999,

[6] H. I. Krebs, B. T. Volpe, M. Ferraro, S. Fasoli, J. Palazzolo, B. Rohrer, "Robot-aided neurorehabilitation: from evidence-based to science-based rehabilitation," Top Stroke Rehabil, vol. 8, pp.54–70, 2002.

[7] S. E. Fasoli, H. I. Krebs, J. Stein, W. R. Frontera, N. Hogan, S. H. Jang, "Effects of robotic therapy on motor impairment and recovery in chronic stroke," Arch Phys Med Rehabil, vol. 84, pp. 477–82, 2003.

[8] K. L. Kilgore, P. H. Peckham, G. B. Thrope, M. W. Keith, and K. A. G. Stone, "Synthesis of hand grasp using functional neuromuscular stimulation," IEEE Trans. Biomed. Eng., vol. 36, pp. 761–769, 1989.

[9] H. J. Chizeck, R. Kobetic, E. B. Marsolais, J. J. Abbas, I. H. Donner, and E. Simon, "Control of functional neuromuscular stimulation system for standing and locomotion in paraplegics," Proc. IEEE, vol. 76, pp.1155–1165, 1988.

[10] A. Kralj and T. Bajd, "Functional Electrical Stimulation, Standing and Walking after Spinal Cord Injury," Boca Raton, FL: CRC Press, 1989.

[11] P. T. Baker, D. R. McNeal, L. A. Benton, R. L. Bowman, L. L. Waters, "Neuromuscular electrical stimulation: A practical guide," 3rd ed. Downey (CA): Rancho Los Amigos Medical Center, 1993, p. 135–40.

[12] M. J. Ijzerman, T. S. Stoffers, and F. Groen, "The NESS Handmaster orthosis: Restoration of hand function in C5 and stroke patients by means of electrical stimulation," J. Rehab. Sci., vol. 9, pp. 86–89,

[13] R. Kamnik, T. Bajd, "Standing-up robot: an assistive rehabilitative device for training and assessment," J Med Eng Technol, vol. 28(2), pp. 74–80. 2004.

[14] X. L. Hu, K. Y. Tong and L. Li, "The Mechanomyography of Persons after Stroke during Isometric Voluntary Contractions," Journal of Electromyography and Kinesiology, vol. 17(4), pp. 473-83, 2007.

[15] X. L. Hu, K. Y. Tong, R. Song, V. S. Tsang, P. O. Leung and L. Li, "Variation of Muscle Coactivation Patterns in Chronic Stroke During Robot-Assisted Elbow Training" Archives of Physical Medicine and Rehabilitation, vol. 88, pp. 1022-29, 2007,

[16] R. Song, K. Y. Tong, X. L. Hu, "Evaluation of Velocity-dependent Performance of the Spastic Elbow during Voluntary Movements" Archives of Physical Medicine and Rehabilitation, 2007

[17] K. Y. Tong and M. H. Granat "Gait control system for functional electrical stimulation using neural networks" Medical & Biological Engineering & Computing vol. 37, no.1, pp35-41,1999.

[18] R.K.Y. Tong, M.F.W. Ng, L.S.W. Li, and E.F.M. So, "Gait Training of Patients After Stroke Using an Electromechanical Gait Trainer Combined With Simultaneous Functional Electrical Stimulation ," Physical Therapy, vol. 86, pp. 1282-1294, 2006.

[19] B. Ashworth, "Preliminary trial of carisoprodal in multiple sclerosis," Practitioner, vol. 192, pp. 540–42, 1964.

[20] A. R. Fugl-Meyer, L. Jaasko, I. Leyman, "The post-stroke hemiplegic patient, I: a method for evaluation of physical performance," Scand J Rehabil Med, vol. 7, pp. 13-31, 1975.

[21] L. E. Kahn, M. L. Zygman, W. Z. Rymer, D. J. Reinkensmeyer, "Robot-assisted reaching exercise promotes arm movement recovery in chronic hemiparetic stroke: a randomized controlled pilot study," J Neuroengineering Rehabil, vol. 3, pp. 12, 2006.

[22] C. D. Takahashi, D. J. Reinkensmeyer, "Hemiparetic stroke impairs anticipatory control of arm movement," Exp Brain Res, vol. 149, pp. 131–40, 2003.

[23] C. G. Burgar, P. S. Lum, P. C. Shor, "Development of robots for rehabilitation therapy: the Palo Alto VA/Stanford experience," J Rehabil Res, vol. 37, pp. 663–73, 2000

[24] D. Reinkensmeyer, J. Emken, S. Cramer, "Robotics, motor learning, and neurologic recovery," Annu Rev Biomed Eng, vol. 6, pp. 497–525, 2004.

[25] M.G. Prochazka, M. Wieler, and Z. Kenwell, "The bionic glove: An electrical stimulator garment that provides controlled grasp and hand opening in quadriplegia," Arch. Phys. Med. Rehab., vol. 78, pp. 608–614, 1997.

[26] D. Popovic, A. Stojanovic, A. Pjanovic, S.Radosavljevic, M. Popovic, S. Jovic, and D. Vulovic, "Clinical evaluation of the bionic glove," Arch.Phys. Med. Rehabil., vol. 80, pp. 299–304, 1999.

[27] J. Minzly, J. Mizrahi and N.Hakim, "Stimulus artifact suppressor for EMG recording during FES by a constant-current stimulator," Med. Bio. Eng. Comput, vol. 31, pp72-5, 1993

[28] X. L. Hu, K. Y. Tong, R. Song, X. J. Zheng, K. H. Lui, W. W. F. Leung, S. Ng, and S. S. Y. Au-Yeung, "Quantitative Evaluation of Motor Functional Recovery Process in Chronic Stroke Patients during Robot-Assisted Wrist Training," *Journal of Electromyography and Kinesiology*, in press, 2008.

[29] R. Song, "A Robotic System Using Myuoelectrical Control at the Elbow Joint for the Rehabilitation of Persons after Stroke," Ph.D. dissertation, Dept. HTI., Polyu., 2005.