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Estimation of Motor Recovery using Characteristics of EMG during Isometric Muscle Contraction in Hemiparetic Wrist

Ki Sik Tae[1], Sung Jae Song[2], Young Ho Kim[3]

[1]*Dept. of Biomedical Engineering, Konyang University,*
[2]*Dept. of Mechanical Engineering, Kangnung University,*
[3]*Dept. of Biomedical Engineering, Yonsei University*
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Abstract

The aim of this study was to evaluate the motor recovery in 4 chronic hemiparetic patients with Fugl-Meyer (FM) and EMG characteristics before and after the training program. The training was performed at 1 hr/day, 5 days/week during 6 weeks in 4 chronic stroke patients. Electromyographic activities of the affected hand were recorded during isometric wrist flexion/ extension movements. In all patients, FM was significantly improved after the 6-week training. Onset/offset delay of muscle contraction significantly decreased in the affected wrist after the training. The co-contraction ratio of flexor/extensor muscles decreased significantly. Also, onset/offset delay of muscle contraction and co-contraction ratio correlates significantly with upper limb motor impairment and motor recovery. This EMG technique allows an objective evaluation of changes in muscle activity in post-stroke patients, providing easily measurable, quantitative indices of muscle characteristics.

Key words : chronic stroke patients, Fugl-Meyer(FM), EMG, onset/offset delay, co-contraction ratio

Ⅰ. INTRODUCTION

Hemiparesis resulting from stroke is likely to be associated with a reduction in the numbers of functional corticospinal and corticobulbar fibers projection to the brainstem and spinal cord. Because these cortical projections carry instructions about voluntary movement to the cord, either loss of connectivity or reduced discharge in these pathways likely to limit the range of possible voluntary movement patterns on the affected side[1].

Spasticity is attributed to increased muscle tone associated with hyperreflxexia[1]. Previous efforts to quantify spastic hypertonia have concentrated on clinical scales[2,3], electromyographic analysis of limb resistance to passive or voluntary movements[4,5] and a host of electrophysiological reflex studies[1,6]. In spite of this broad range of techniques, no uniformly useful objective measurements have emerged in the clinical practice. An objective, quantitative measure would achieve widespread clinical acceptance only if its variations broadly paralleled an accepted clinical scale. An important criterion that objective parameters have to fulfill to gain everyday clinical acceptance is consistency and sensitivity[7]. Clinical scales, such as those proposed by Ashworth[2], offer qualitative information, but lack temporal reproducibility and suffer from a clustering effect in that most of the patients are grouped within the middle grades[7]. Nevertheless they have been and continue to be widely used in the study of spasticity [8] and are the present yardstick against which newer, more exact methods must be compared.

Many stroke survivors experience reasonable motor recovery of their proximal upper limb, but limitation distal recovery. For those with some hand function, evaluating their therapeutic methods such as constraint induced therapy[9] and electrical stimulation[10] may provide additional recovery. However, many stroke patients do not experience adequate distal recovery or are unresponsive to new therapeutic techniques.

In order to expand treatment strategies, the nature of hemiparesis and its relationship to motor recovery must to be further elucidated using quantifiable methods. Prior electomyographic (EMG) studies among stroke patients demonstrated significant delay in initiation[11-13] and termination of muscle

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Corresponding Author : Ki Sik Tae, Ph.D.
Dept. of Biomedical Engineering, Konyang University, 119 Daehangro, Nonsan, Chungnam, 320-711, Korea
Tel : +82-41-730-5316 / Fax : +82-41-730-5335
E-mail : tae@konyang.ac.kr

contraction[11,12], gaps in EMG interference patterns[14], abnormal co-contraction of agonist and antagonist muscles [15,16], and abnormal co-activation of synergistic muscles [17].

The purpose of this study is to describe the relationship between characteristics of muscle contraction and motor recovery in chronic hemiparetic subjects after rehabilitative training by designed arm trainer.

II. MATERIALS AND METHODS

A. Subjects

Totally ten subjects participated in this study. As a control group, six of them were right-handed healthy male subjects (age: 34±5, ranging 24~38 years) without any history of neurological or psychiatric disease. Other four were hemiparetic patients (age: 40.8±7 years) in chronic state, 24 months elapsed since hemiparesis; with no severe spasticity (modified Ashworth's Scale: MAS<3, Grade 0= no clearly, Grade 1= barely discernible repetitive movement or increase tone, Grade 2= either a slight but unsustained repetitive movement or a stronger but briefer repetitive movement, Grade 3= a strong and sustained repetitive movement, Grade 4= a movement equal to that expected of the intended hand) or tremor on affected upper extremity; and no serious cognitive problems, aphasia, attention deficits, or visual neglect. Two patients were left hemiparesis and the other right hemiparesis (Table 1).

B. Intervention

For the rehabilitative training of patients, we designed the arm trainer, which consists of 2 independent handles that move symmetrically. Both handles of the training system were connected to two serial spur gears. The system provides both handles with symmetric motions such as forearm pronation/supination or wrist flexion/extension. Therefore, the affected side can be passively controlled with the symmetrical movement according to the active motion of the unaffected side [18].

Each training with arm trainer was performed 5 times per week during 6 weeks. Each patient grasps the handles or the affected hand is strapped to the handle depending on the severity of the deficits.

Each training with BSAT takes at his/her home, and was performed 5 times per week during 6 weeks (30 sessions). In each session, patients were seated comfortably at a table with a custom-designed bilateral symmetric arm trainer in the following limb poison: ankle in neutral dorsiflexion, knee and hip placed at 90, shoulders in 30 flexion, elbows in 30, and wrist in neural position of flexion/extension. The apparatus consists of two independent handles that move symmetrically. Each patient grasps the handles or the affected hand is strapped to the handle depending on the severity of the deficits. Patients trained both forearm pronation/supination or wrist flexion/extension each 30 minutes, respectively. The whole training program consisted of four 15 minute session with BSAT and 10 minute rest was given at every session. Periods consisted of bilateral repetitive movements that were simultaneous for 1 and 3 and alternating for period 2 and 4. Movements were timed to a metronome set at the participant's preferred speed that was established at the first session by asking patients to assume a self-selected speed (Speed 1) and the other session was slow speed (Speed 2).

C. Fugl-Meyer (FM) Assessment

Fugl-Meyer (FM) assessment has been shown to be valid and reliable and it correlates well with inter-joint upper-limb coordination measurements in the upper-limb of patients after stroke[19]. During the 6-week training, FM in participated patients was measured every two weeks. All tests were measured by a physical therapist. The initial analyses were one-way t-test to compare measures on the dependent reliables before and after training at 6 weeks of training. In FM score, significant results were further investigated post hoc (Tukey honestly significant difference). An alpha level of <0.05 was used as the level of significance. All statistical analyses were performed by SPSS 10.0 (SPSS, Chicago, USA).

Table 1. Demographics and pathology of 4 patients with stroke

Patient No.	Age/Sex	Lesson type	Paretic hand	Time of stroke (months)
1	44/M	ICH in right BG, TH	Lt.	38
2	37/M	ICH in right BG, TH	Lt.	58
3	49/M	ICH in left BG, IC	Rt.	24
4	33/M	ICH in left TH, IC	Rt.	58

ICH=Intracerebral hemorrhage, BG=basal ganglia, TH=thalamus, IC=internal capsule

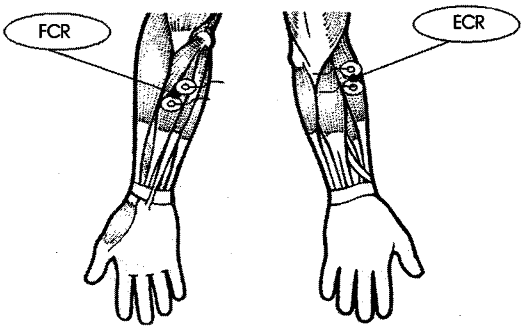

Fig. 1. Electrode displacement for the FCR and ECR with forearm supine (left) and prone (right)

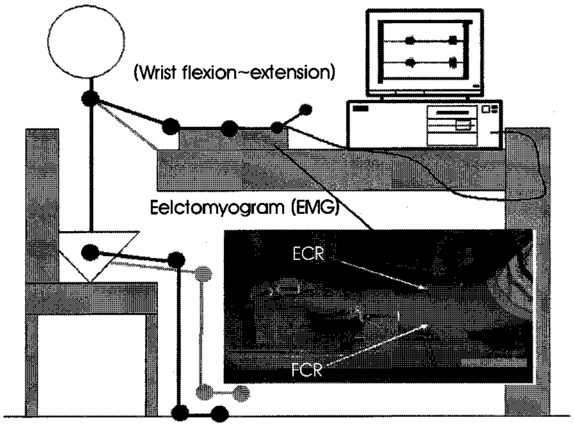

Fig. 2. The setting for positioning of the arm and forearm for EMG recording during isometric wrist flexion and extension

D. EMG Measurement

EMG activities were recorded from conductive solid-gel disposable Ag/AgCl transcutaneous recording electrodes (Noraxon, AZ, USA). Surface EMGs were recorded from the flexor carpi radialis (FCR) and the extensor carpi radialis (ECR) muscles. Active electrodes were placed over the muscle belly and the reference electrode over the muscle tendon (Fig. 1).

During the experiment, the subject's arm was placed on an apparatus that stabilized the wrist in a neutral position (Fig. 2).

Each subject was instructed to contract the wrist flexor or extensor as forcefully and quickly as possible against the confinement of the apparatus in response to an audible beep, and relax the muscle as quickly as possible as soon as the beep terminated. For wrist flexion, all subjects were asked to response to seven audible beeps consisting of five trials of 3s contraction. The trials were presented in a balanced random order to minimize subject anticipation. The procedure was repeated for wrist extension.

Onset/Offset Delay

Onset delay of the EMG signals was defined at the time interval between onset of the audible beep and onset the of the EMG signal. Delay in termination of the EMG signal was defined as the time interval between termination of the audible beep and termination of the EMG signal (Fig. 3).

Data acquisition hardware included MP 150 system (Biopac system, Inc., CA, USA). Amplifier gain was set at 1,000 with sampling frequency of 1,080 Hz was used. For determination of the delay of muscle contraction, EMG signals were band-pass filtered (10-1000Hz) and full-wave rectified. The baseline of the EMG signal was defined as the average activation level for 3 seconds prior to muscle contraction and maintained the above baseline at least during 25 milliseconds. Then, the onset was defined when the rectified signals first exceeded the baseline plus two standard deviations.

Co-Contraction Ratio

In addition, the co-contraction ratio of flexor and extensor muscles was quantified during isometric wrist flexion/extension. Since the muscle force is almost proportional to the integrated EMG (IEMG), we first measured muscle activations in agonist and antagonist during wrist movements.

$$EMG_N = \frac{EMG_m}{EMG_{m\_rest}} \quad (1)$$

where EMG_N represents a normalized value of EMG signals during wrist movements. EMG_m indicates muscle activations during wrist movements; and EMG_{m_rest} indicates a value of EMG_m measured during relaxation.

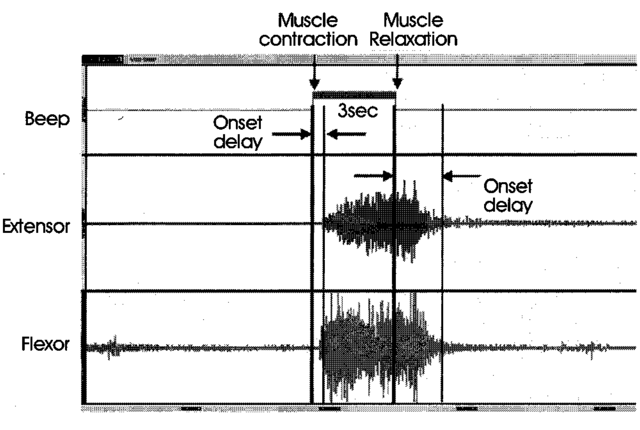

Fig. 3. Representative EMG raw data during isometric wrist contraction

Table 2. Changes in clinical score of FM

Patient	FM 0-2-4-6 (week)	dFM
1	25 - 29 - 33 - 34	9
2	35 - 49 - 54 - 56	21
3	20 - 25 - 27 - 32	12
4	26 - 27 - 37 - 38	12

dFM = last FM score−initial FM score

$$IEMG= \sum_{n=0}^{N} \left(\overline{EMG_{Nn}}\right) \triangle t \qquad (2)$$

where N indicates the number of sampled data in experimental trials and t is a wrist contraction time.

$$Co-contraction\ ratio= \frac{IEMG_n^{ANTA}}{IEMG_n^{AGO}} \qquad (3)$$

where $IEMG_n^{AGO}$ indicates a IEMG of agonist and $IEMG_n^{ANTA}$ is a IEMG of antagonist during wrist movements. During the 6-week training, we measured EMG parameters in patients were measured every two weeks.

E. Data Analysis

EMG data was analyzed using two separate *t*-tests. The first test determined the effects of three experiment-specific factors on delay in onset/offset and co-contraction ratio, which included arm side (control, unaffected and affected), direction of wrist movement (flexion and extension) with unpired *t*-test. The second test determined the differences between delay in onset/offset included arm side (control, unaffected and affected), direction of wrist movement (flexion and extension) using in paired *t*-test. One-way repeated ANOVA was used to compare before and after training. Finally, Spearman's correlation coefficients describing the relationship between EMG parameters and motor recoveries, were obtained. We used the nonparametric test of the ordinal nature of FM score. An alpha level of <0.05 was used as the level of significance. All statistical analyses were performed with SPSS 10.0 (SPSS, Chicago, USA).

III. RESULTS

A. Fugl-Meyer (FM) Assessment

Table 2 shows changes in motor function such as FM score during the 6-week training. In all four patients, FM (range: 0-66) of the affected hands were significantly improved after the 6-week training program ($p<0.05$).

B. Change of Onset/Offset Delay

Table 3 shows onset/offst delay for wrist flexion/extension movements during the 6-week training. As shown in Table 3,

Table 3. Changes in EMG onset/offset delay

Side	No.	Wrist flexion 0-2-4-6 (week)		Wrist extension 0-2-4-6 (week)	
		$Delay_{on}$ (s)	$Delay_{off}$ (s)	$Delay_{on}$ (s)	$Delay_{off}$ (s)
Control		0.17±0.11	0.31±0.13	0.22±0.17	0.21±0.07
Unaffeced	1	0.43−0.30−0.34−0.30	0.45−0.41−0.64−0.41	0.46−0.32−0.33−0.33	0.53−0.49−0.59−0.42
	2	0.30−0.35−0.29−0.26	0.34−0.44−0.29−0.29	0.22−0.23−0.31−0.38	0.60−0.38−0.49−0.68
	3	0.30−0.27−0.29−0.28	1.13−0.59−0.79−0.64	0.24−0.26−0.24−0.20	0.70−0.45−0.47−0.23
	4	0.48−0.51−0.37−0.32	0.65−0.58−0.54−0.47	0.34−0.32−0.41−0.30	0.79−0.55−0.56−0.55
Average		0.38−0.34−0.32−0.37	0.64−0.51−0.52−0.46	0.32−0.28−0.32−0.28	0.65−0.46−0.52−0.47
Affected	1	0.51−0.41−0.37−0.33	0.71−0.64−0.60−0.58	0.78−0.50−0.44−0.40	1.05−0.64−0.62−0.60
	2	0.56−0.50−0.36−0.37	1.87−0.95−0.92−0.76	0.68−0.44−0.33−0.32	0.86−0.81−0.69−0.57
	3	0.76−0.73−0.52−0.50	1.80−1.26−0.86−0.74	1.04−0.55−0.74−0.49	1.19−1.15−0.93−0.72
	4	0.65−0.60−0.49−0.40	1.67−0.86−0.74−0.77	1.16−0.72−0.57−0.52	1.67−1.14−1.18−1.07
Average		0.62−0.57−0.44−0.40	1.51−0.93−0.78−0.76	0.92−0.56−0.52−0.44	1.19−0.94−0.86−0.75

$Delay_{on}$: Onset delay on muscle contraction, $Delay_{off}$: Offset delay on muscle contraction

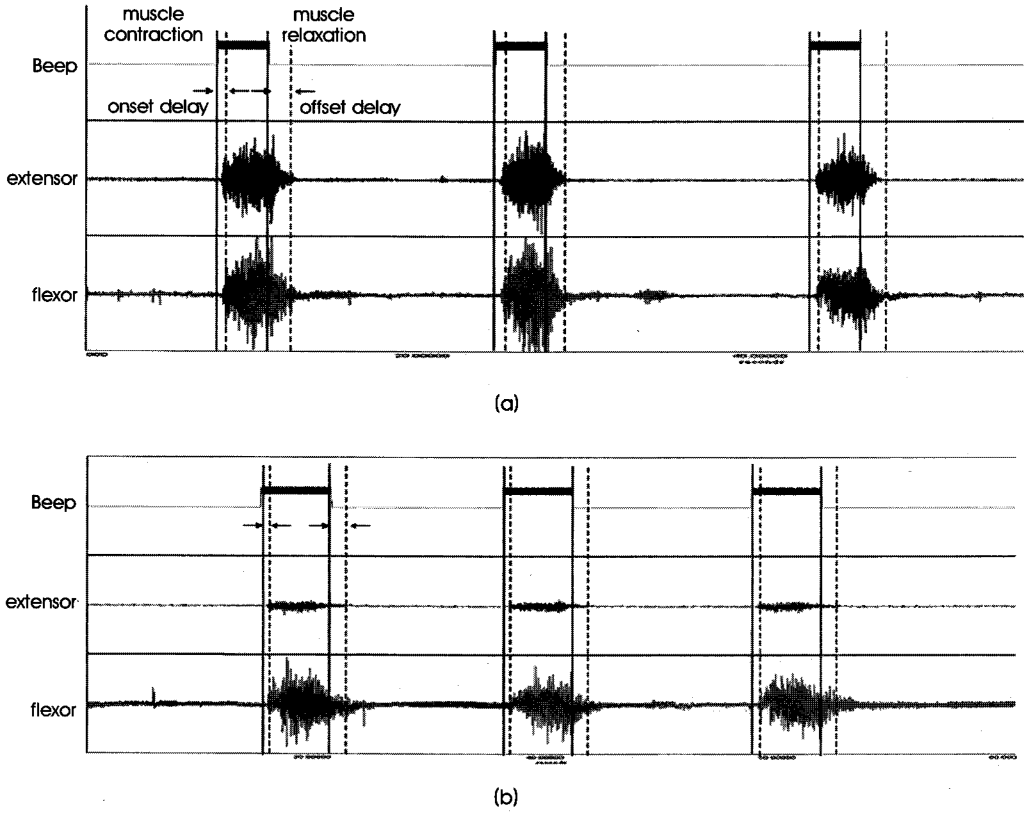

Fig. 4. EMG data of different muscles during isometric affected wrist flexion in Patient 1. (a) EMG signal before the training, (b) EMG signal after the training

after the 6-week training, the unaffected hands, as well as the control group, did not show significant changes in onset/offset delays for wrist flexion/extension. However, affected hands showed significantly decreased onset/offset delays in muscle contraction after the 6-week training in both wrist flexion and extension ($p<0.05$).

Fig. 4 show the EMG onset/offset delay of different muscles during affected wrist flexion.

Table 4 shows the effects of three experiment-specific factors on onset/offset delay in control, unaffected and affected before training. Before the training, onset/offset delay on the affected side were significantly larger than those in the control group and unaffected side. Onset/offset delay in the unaffected side were significantly larger than those on the control group.

Fig. 5 show the EMG onset/offset delay of different muscles during three side (control, unaffected, affected side) wrist flexion before the training.

Fig. 6 shows the differences between onset/offset delay included control, unaffected and affected before training. Offset delay of affected sides was significantly larger than onset delay in both wrist flexion and extension ($p<0005$). In unaffected side, offset delay was significantly larger than onset time in wrist extension (Fig. 6(b)).

C. Co-Contraction Ratio

Table 5 shows changes of the co-contraction ratio for wrist flexion/extension movements during the 6-week training. Co-contraction ratio of muscle contraction in the affected side

Table 4. Differences of onset/offset delay before training

Sides	Wrist flexion		Wrist extension	
	$Delay_{on}$	$Delay_{off}$	$Delay_{on}$	$Delay_{off}$
Control	0.170.11	0.310.13	0.220.17	0.210.07
Unaffected	0.380.09	0.640.34*	0.320.11	0.650.11*
Affected	0.620.10^{*+}	1.510.54^{*+}	0.920.22^{*+}	1.190.34^{*+}

* Significantly different from control sides with independent t−test ($p<0.05$)
+ Significantly different from unaffected sides with independent t−test ($p<0.05$)

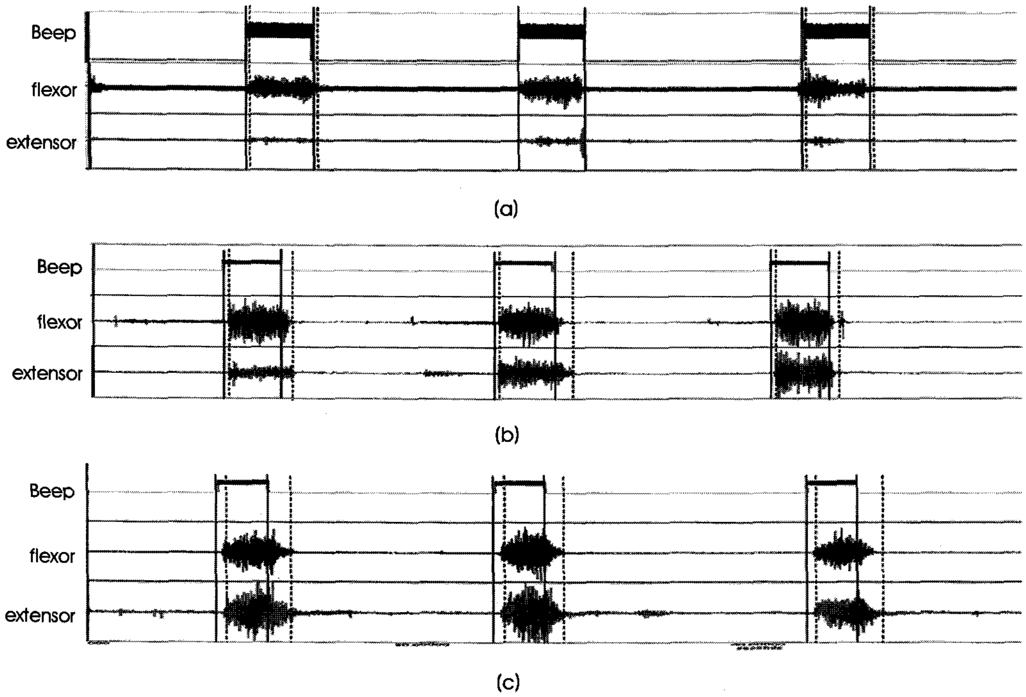

Fig. 5. EMG onset/offset delay of different muscles during three side (control, unaffected, affected side) wrist flexion before the training. (a)control side, (b)unaffeced side, (c)affected side

was significantly larger than those in the control group ($p<0.05$). As shown in Table 5, after the training, the unaffected hands, as well as the control group, did not show significant changes in co-contraction ratio for wrist flexion/extension. However, affected hands showed significantly decreased co-contraction ratio in muscle contraction ($p<0.05$).

D. Correlations with EMG Parameters and Motor Recoveries

Spearman's correlation coefficients were determined, relating each EMG parameter from wrist flexion and extension of the affected hand to FM scores. Representative scatter diagrams of in onset/offset delay during 3s wrist flexion and extension versus FM scores are shown in Fig. 7. Onset/offset delays in muscle contraction correlated well with FM scores, except for offset delay in wrist flexion.

In addition, as shown in Fig. 8, the co-contraction ratio in wrist movements correlated well with FM scores.

Ⅳ. DISCUSSION

Most quantitative EMG studies performed on impaired limbs of hemiparetic patients have dealt with temporal

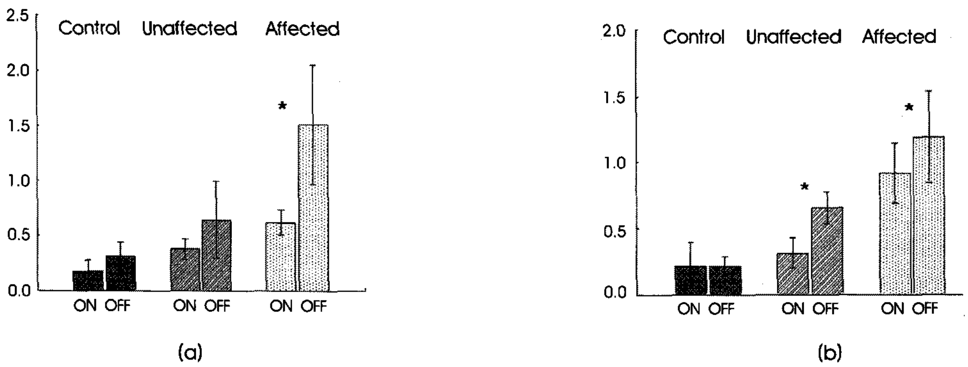

Fig. 6. Comparison of delay in contraction onset and offset of the wrist flexor (a) and extensor muscle (b). Values of the bar are mean SD. ON: onset delay, OFF: offset delay * Significant difference between onset and offset delay ($p<0.05$)

Table 5. Changes of the co-contraction

Side	No.	Co-contraction ratio (CCR)	
		Wrist flexion 0-2-4-6 (week)	Wrist extension 0-2-4-6 (week)
Control		0.15±0.04	0.15±0.08
Unaffeced	1	0.34 - 0.35 - 0.35 - 0.19	0.40 - 0.30 - 0.26 - 0.19
	2	0.25 - 0.23 - 0.30 - 0.16	0.30 - 0.34 - 0.33 - 0.17
	3	0.41 - 0.44 - 0.35 - 0.20	1.30 - 0.80 - 0.50 - 0.27
	4	0.30 - 0.25 - 0.25 - 0.18	0.38 - 0.35 - 0.23 - 0.18
Average		0.33 - 0.32 - 0.31 - 0.18	0.60 - 0.45 - 0.33 - 0.20
Affected	1	1.20 - 0.70 - 0.43 - 0.26	0.66 - 0.45 - 0.23 - 0.20
	2	0.92 - 0.29 - 0.19 - 0.12	0.44 - 0.41 - 0.21 - 0.19
	3	4.09 - 2.94 - 0.45 - 0.36	2.13 - 0.75 - 0.49 - 0.31
	4	1.18 - 0.87 - 0.40 - 0.23	0.58 - 0.39 - 0.20 - 0.20
Average		1.85 - 1.20 - 0.37 - 0.24	0.95 - 0.50 - 0.28 - 0.23

analyses of EMG patterns during arm movements[13]. Consistent with prior studies[11,12], we found a significant onset/offset delay of muscle contraction of the hemiparetic wrist compared to the control and unaffected side. We observed a difference of approximately 0.8s in the onset delay of muscle contraction between the affected and unaffected wrist. How much of this difference was due to the impairment in motor processing rather than efferent mechanisms is cause hyperexcitability of the spinal motor pool and lead to loss of the orderly recruitment of motor units[20]. However, Heald et al.[21] reported difference in latency of no more than 0.1s between the affected and unaffected limbs after activating the motor cortex with transcortical magnetic stimulation and recording thenar muscle responses. Dewald et al.[17] examined spatio-temporal abnormalities in the flexor reflex response in the impaired upper limb of hemiparetic subjects.

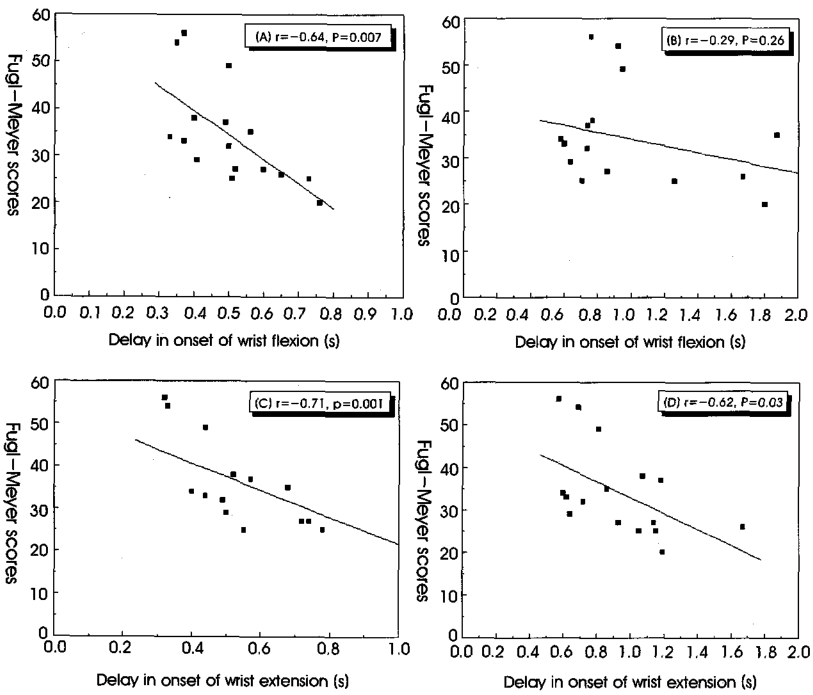

Fig. 7. Correlations between delay of EMG responses of wrist movement and FM score.
(A) Delay in onset of wrist flexion versus FM scores, (B) Delay in offset of wrist flexion versus FM scores, (C) Delay in onset of wrist extension versus FM scores, (D) Delay in offset of wrist extension versus FM scores

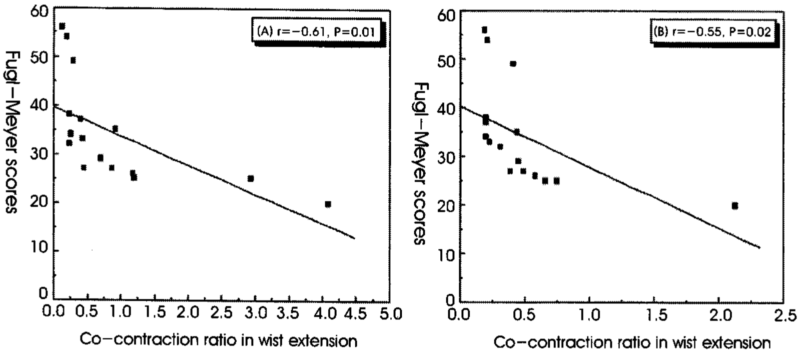

Fig. 8. Correlations between co-contraction ratio of wrist movement and FM score.
(A) Co-contraction ratio of wrist flexion versus FM scores, (B) Co-contraction ratio of wrist extension versus FM scores

The difference in delay in the reflex response between affected and unaffected limbs ranged between 0.1 and 0.4s. The delay, which is attributable to deficits in the efferent mechanism, would account for only a small portion of the delay observed in this study. Consistent with prior studies[12,17], we found a significant delay in termination of muscle contraction of the hemiparetic upper limb compared to the unaffected upper limb. Hammond et al.[13] evaluated the difference in delay in termination of muscle contraction using a similar experimental design.

The co-activation of agonist and antagonist muscles is an important component of motor control in normal individuals. An abnormal co-activation pattern, consisting of massive and synergistic activation of many muscles, has been reported on the affected side of hemiparetic patients during movement [22]. In the present study, we observed that co-contraction ratio, which was defined by the ratio between agonist and antagonist using IEMG, significantly decreased after the 6-week training.

The second objective of this study was to describe the statistical relationship between a fundamental neural deficit manifested by onset/offset delay of muscle contraction and co-contraction ratio of hemiparetic upper limb, and clinical motor recovery, as measured by the FM score. In this study, we found a statistical relationship between the degree of the EMG responses and FM. In this study, we found that onset/offset delay and co-contraction ratio correlates significantly with motor recovery.

Many stroke survivors achieve the hand closure by isolated movements or by volitionally activating a flexor synergy pattern. Dewald et al.[17] demonstrated a similar statistical relationship between muscle co-activation patterns of synergistic muscles in the paretic upper limb and FM scores. Thus, it is possible that subjects with more prolonged onset/offset delays of muscle contraction also have greater degree of muscle weakness, fatigue, abnormal co-contraction of antagonist and agonist muscles, and abnormal co-activation of synergetic muscles, all of which may have more direct impact on functional activity.

The strong correlation of EMG characteristics with the motor recovery allows their application in clinical practice, in particular to objectively evaluate changes to physical therapy for hemiparetic patients. Further studies with long-term follow up and optimal EMG data analysis for hamiparetic patients give more insight.

V. CONCLUSION

Major findings in this paper are: (1) there is a significant difference in onset/offset delay of muscles contraction between the affected and unaffected upper limbs; (2) there is a significant decrease in co-contraction ratio of affected hand of chronic stroke patients after 6-week training program; and (3) onset/offset delay and co-contraction ratio correlates significantly with upper limb motor impairment and motor recovery.

In this study, EMG technique allows an objective evaluation of changes in muscle activity in post-stroke patients, providing easily measurable, quantitative indices of muscle characteristics.

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