Analysis of reaching movements in stroke patients using average variability of electromyogram value

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Abstract: The hypothesis in this study was tested by conducting EMG experiments comparing the variability in muscle activity during repetitive reaching movements in hemiplegic patients and healthy subjects. The present study investigated the characteristics of reaching movements in hemiplegic patients using the variability in average electromyogram (EMG) value. We studied 21 right-handed stroke patients with left-sided hemiparesis and 14 right-handed healthy control subjects. Post-stroke patients (hemiplegic group) and normal subjects (control group) repeated a reaching movement 10 times. The variability in average EMG value of each muscle was defined as the average standard deviation of the average rectified values (nARV-SDave). During the reaching movements, the nARV-SDave values was significantly higher in the hemiparesis group than in the control group for the biceps and triceps brachii (P < 0.05). In the hemiparesis group, significant negative correlations between the variability in nARV-SDave values and the Fugl-Meyer assessment scores were observed in all muscle types (rs = −0.46 to −0.76; P < 0.05, P < 0.01). This study identified a direct relationship between the variability in muscle activity and the severity of motor function deficit in post-stroke patients. The selective impact on the biceps and triceps were related to the nature of the reaching task.

Keywords: stroke, upper extremity, reaching movement, electromyography, hemiplegia

Introduction

A stroke is a medical emergency because a severe reduction or interruption of blood flow to the brain causes the cell death within minutes. The most common complication following a stroke is a transient or permanent impairment of upper extremity functions, limiting the patients' autonomy [1]. As many daily activities involve reaching for an object, it is important for physical and occupational therapists to understand the kinematic and kinetic characteristics of reaching movements in post-stroke patients.

Several kinematic studies revealed that reaching movements in stroke patients are characterized by enhanced variability, prolonged movements, and a lower range of motion in the shoulder and elbow joints, compared with healthy subjects or the non-affected side [2–7]. The higher movement variability suggests that stroke patients are not able to stably perform reaching movements when asked to repeat them several times. In other words, stroke patients assume kinematically unstable reaching patterns, and the trajectory varies during repetitive reaching movements. Electromyography (EMG) studies identified muscle activation abnormalities in stroke patients, such as prolonged agonist bursts associated with reduced speed during elbow flexion and extension [8], simultaneous co-contraction of agonist and antagonist muscles [9–13], and abnormal muscle tone [14]. Muscle synergy and spasticity in stroke patients generate specific movement patterns [15, 16]. Most studies characterized the patients using...
integral EMG data and the ratio of agonist/antagonist muscle contraction, which provided useful information on muscle combination, synergy, and spasticity. These approaches identified the relation of the muscle groups affected by a stroke during typical synergy patterns (e.g., co-contraction) [15, 16], but the characteristics of specific muscles remain unclear. It is important to clarify this point to enable physical and occupational therapists to target specific muscles when treating post-stroke patients for unstable reaching movements.

The aim of this kinetic study was to analyze the characteristics of reaching movements in stroke patients. This hypothesis was tested by conducting EMG experiments comparing the variability in muscle activity during repetitive reaching movements in hemiplegic patients and healthy subjects. We hypothesized that specific muscles contribute to the variability in reaching movements, and that their activity correlates with the severity of motor dysfunction.

Methods

Subjects

The subjects were patients treated at Rehabilitation Hospital (Saitama, Japan) for a stroke. Those included in the study (hemiplegic group) met the following criteria: (1) no serious cognitive deficit; (2) a Mini-Mental State Examination (MMSE) score > 24; (3) no marked contracture affecting performance during a reaching task; (4) the absence of paralysis that would prevent the subjects from completing a reaching task; and (5) right arm dominance. The patients with a lesion located in the cerebellum or brainstem were excluded because the symptoms produced by such lesions are atypical in comparison with those in other areas. Subjects were recruited in a rehabilitation hospital.

We studied 21 right-handed stroke patients with left-sided hemiparesis (hemiparesis group, mean age: 57.0 ± 0.8 years, 19 men, two women) and 14 right-handed healthy control subjects (control group, mean age: 53.7 ± 10.7, seven men, seven women). All subjects gave their written informed consent. The protocol was in accordance with the Declaration of Helsinki and approved by the Ethics Committee. Table 1 presents demographic data for participants.

Experimental Procedure

The experimental design is described in Fig. 1. Each subject was seated on a chair in front of a table, with the trunk immobilized by a set of straps. On the side affected by the stroke, the hand and forearm were immobilized using a splint device. An acrylic board was placed on the table underneath the arm and was coated with silicon spray to decrease friction between the board and the splint. Each reaching task was initiated from a starting point (30° of abduction, 10° of shoulder extension, and 100° of elbow flexion) to a target point (30° of elbow flexion on the sagittal-horizontal axis). A circular tag was placed at the start and target points. The data were collected using laser sensors (LV21-A, Keyence Corp., Japan) located at the start and target points on the other side of the table.

Each task consisted of the subject attempting to move from the start point to the target point, and back to the start point. The length of each task was determined

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### Table 1. Demographic data of all subjects and clinical score of the hemiplegic subjects.

| ID | Age | Sex | Duration of disease (Month) | MMSE | FM |
|----|-----|-----|-----------------------------|------|----|
| H1 | 47  | M   | 12                          | 30   | 13 |
| H2 | 57  | M   | 13                          | 30   | 25 |
| H3 | 57  | M   | 15                          | 30   | 23 |
| H4 | 48  | M   | 5                           | 30   | 34 |
| H5 | 35  | M   | 4                           | 30   | 34 |
| H6 | 64  | M   | 10                          | 25   | 25 |
| H7 | 67  | F   | 3                           | 25   | 15 |
| H8 | 63  | M   | 5                           | 30   | 29 |
| H9 | 70  | M   | 4                           | 25   | 10 |
| H10| 63  | M   | 4                           | 27   | 5  |
| H11| 43  | M   | 4                           | 30   | 21 |
| H12| 59  | M   | 3                           | 30   | 12 |
| H13| 51  | M   | 2                           | 29   | 36 |
| H14| 62  | M   | 7                           | 30   | 22 |
| H15| 43  | M   | 3                           | 27   | 6  |
| H16| 67  | M   | 5                           | 30   | 30 |
| H17| 70  | M   | 4                           | 30   | 5  |
| H18| 56  | M   | 6                           | 30   | 19 |
| H19| 49  | M   | 4                           | 28   | 27 |
| H20| 61  | M   | 4                           | 25   | 10 |
| H21| 65  | F   | 3                           | 30   | 33 |

| C1 | 42  | F   | -                           | -    | -  |
| C2 | 57  | M   | -                           | -    | -  |
| C3 | 56  | F   | -                           | -    | -  |
| C4 | 33  | M   | -                           | -    | -  |
| C5 | 34  | M   | -                           | -    | -  |
| C6 | 57  | F   | -                           | -    | -  |
| C7 | 63  | F   | -                           | -    | -  |
| C8 | 68  | M   | -                           | -    | -  |
| C9 | 61  | M   | -                           | -    | -  |
| C10| 51  | M   | -                           | -    | -  |
| C11| 52  | F   | -                           | -    | -  |
| C12| 61  | F   | -                           | -    | -  |
| C13| 64  | M   | -                           | -    | -  |
| C14| 53  | F   | -                           | -    | -  |

| Mean ± SD | 55.7 ± 10.2 | 5.7 ± 3.6 | 28.6 ± 2.0 | 20.7 ± 10.2 |

H: Hemiparesis group, C: Control group, M: Man, F: Female, MMSE: Mini-Mental-State Examination, FM: Fugl-Meyer Assessment of Sensorimotor Recovery After Stroke Score
by the signal received by the laser sensor positioned at the start point (Laser 1). The subject was confirmed to reach the target point by a signal from the laser sensor at that point (Laser 2). During the reaching movement, the subjects began to move their forearm slightly before the starting point, pass over the target point, pull back their forearm and pass over the starting point. At the starting and target point, the subjects were instructed to make the pass-over distance less than a few centimeters.

Previous studies on healthy subjects analyzed reaching tasks using a ballistic movement [4, 5]. However, daily life seldom requires one to reach for something quickly. Therefore, our subjects were asked to perform the reaching task at a comfortable speed that they determined during preliminary trials. They repeated the reaching task 10 times with a few minutes of rest after each task. This task was not heavy, but we decided the length of the muscle recovery period was about 2 minutes by subject’s subjectively opinions in our preliminary tests.

**EMG Recordings and Analysis**

Surface EMG recordings from the left upper extremity were obtained using active electrodes (DE-2.1, Delsys Inc., USA). The six muscles targeted were the pectoralis major, the anterior, middle, and posterior deltoid, as well as the brachii muscles of the biceps and triceps. The electrodes were placed at the center of the belly of each muscle. Before attaching the electrodes, the skin surface was abraded with Nuprep Skin Prep Gel (Weaver and Company, USA), and rubbed with alcohol. The position of the electrodes was verified by the examination of the EMG activity on a computer monitor during preliminary tasks [17].

The sampling frequency of the EMG signals was 1000 Hz. An EMG amplifier (Bagnoli2, Delsys Inc., USA) was used to record the EMG activity. The signals were digitized using a NR-2000 (Keyence Corp., Japan) and recorded on a computer. The signals from laser sensors were recorded to measure the analysis period.

The data were analyzed using the method described by Kaneko [18]. The EMG signals were filtered offline (bandwidth ranging from 10 to 500 Hz) using the Butterworth filter to calculate the average rectified value (ARV) using LabView version 7.1 (National Instruments Corp., USA; Fig. 2). For experiments comparing the stroke group to the control group, the ARV and analysis period needed to be normalized. We could not adapt the usual normalization method (e.g., Maximal Voluntary Contraction). Therefore, the ARV was normalized using the maximum ARV value of all 10 reaching tasks and the analysis periods. The EMG signals of each task were interpolated by spline transformation using MATLAB version 7.0.1 (MathWorks Inc., USA). Then, the number of representing data was fixed as 1000 points. Because all subjects took more than 1 second to complete the task, the method of interpolation for all trials was down sampling. The amplitude of the ARV and the time were normalized in this manner (normalized ARV; nARV). The standard deviation of the nARV was calculated at each point for a total of 10 tasks (nARV standard deviation; nARV-SD). The variability of the average EMG of each muscle was defined as the average nARV-SD (nARV-SDave) for the 10 normalized reaching periods recorded sequentially.

**Clinical Evaluation**

The motor function of the affected arm was evaluated using the Fugl-Meyer assessment method of sensorimotor recovery after the stroke test [19]. The scores ranged from 0 (severe deficit) to 66 (no detectable deficit). In this study, we used a variant of the Fugl-Meyer test (FM) designed for upper extremity functions.

**Statistical Analysis**

The unpaired t-test was used to compare the control group and hemiplegic group for the nARV-SDave values of each muscle. Spearman rank-order correlation was used to analyze the relationship between nARV-SDave values and FM score for each muscle. SPSS 22.0 was used for statistical analysis. The significance level of all statistical comparisons was set at $p < 0.05$. 

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**Fig. 1.** Illustration of the experimental setup: (A) horizontal plane view, (B) sagittal plane view.
Results

Typical Subjects

Typical nARV curves are presented for one subject of the control group (Fig. 3) and the hemiplegic group (Fig. 4). The superimposed nARV curves were processed from the raw EMG data recorded during each of the 10 reaching tasks to show the variability in EMG values (Figs. 3A and 4A). The nARV-SD calculated from each nARV are presented in Fig. 3B and 4B. FM scores for each subject are presented in Table 1. The nARV curves of the typical control subject (Fig. 3) were less variable than those of the typical hemiplegic subject (Fig. 4).

Comparison of nARV-SDave between the hemiplegic and control groups

The two groups were compared for the mean nARV-SDave values of the six muscles. Significant differences in nARV-SDave between the two groups were identified by two-way ANOVA. The multiple range tests indicated that the nARV-SDave values of the biceps and triceps brachii were significantly higher in the hemiplegic group than in the control group (Fig. 5, \( P < 0.05 \)). In contrast, no significant difference was observed between the groups for the other four muscles tested.
Correlation between nARV-SDave and FM scores

The hemiparesis group was further evaluated for the relationship between nARV-SDave and FM scores for each muscle group (Fig. 6). Strong negative correlations were observed in all muscles.

Discussion

We used EMG recordings to distinguish the muscle activities during kinematically unstable repetitive reaching tasks. It has been emphasized that EMG is the most appropriate method to measure motor function, because it has high clinical significance [9−13, 15, 16, 20]. Integral EMG (IEMG) [14] and co-contraction ratio (CCR) [16] have been suggested to determine the co-contraction ratio between muscles. In recent years, partially linear decomposition methods, such principal component analysis (PCA), linear independent component analysis (ICA) [21, 22], and nonnegative matrix factorization (NMF) [23], are often used to investigate the relation between cortical activation (electroencephalography) and movement (EMG). They are useful to detect interactions between the central nervous system (CNS) and muscles. Whereas these new methods are useful to study muscle–muscle (e.g., co-contraction and synergy) or CNS–muscle interactions, these studies could not compare the variability in activities of each muscle type during repetitive reaching task. Therefore, the selective increase in variability in brachii muscle activity during repetitive reaching movements, identified in the present

Fig. 3. Normalized average rectified value (nARV) for a typical subject of the normal group (ID number C2). (A) Superimposed nARV. (B) Averaged curve of the nARV (nARVave) with the standard deviation (nARV-SD) shown as the grey area.
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study, has high clinical significance.

The strong negative correlations between the nARV-SDave of all six muscle types and the FM score of the post-stroke patients clearly indicate that a severe deficit in motor function is associated with highly unstable muscle activities during repetitive reaching movements. Previous studies showed that the characteristics of reaching movements in stroke combine unstable trajectory and velocity [2−7]. These characteristics indicate that the continuous and smooth movement strategy used during reaching activities is lost in post-stroke patients [2]. The present study suggests that the variability in muscle activity may explain the unstable movement reported in previous kinematic studies [2]. Our results support the notion that the variability in muscle activity relates to unstable movement.
It should be emphasized that measurements of muscle activity using EMG have a high clinical significance from the viewpoint of variability. Because motor impairment in the upper extremity is the most frequent stroke complication, therapists make considerable efforts to target abnormal muscle activities. Furthermore, the present study proposes a promising method to objectively assess hemiplegic upper extremities to avoid unreliable assessments, such as the FM score, as pointed out by [16]. Despite these facts, such subjective assessment methods are the most widely used in clinical settings [19, 25]. Although these clinical assessments are very useful to roughly estimate motor disorders, they cannot clarify multiple muscle activities in detail. Consequently, the reliable EMG measurements presented herein clarify the characteristics of variability in muscle activity in post-stroke patients.

The selective impact of a stroke on the activities of biceps and triceps brachii is intriguing. Previous studies used reaching tasks that involved pointing a forward spatial target [4, 5]. Because these tasks required lifting the upper extremity, the deltoid played a major role to hold the arm up against gravity. However, our study adopted a reaching task requiring the subjects to slide their forearm on a table with reduced friction. Therefore, the subjects could complete the task even if they had serious upper extremity paresis limiting their ability to raise their arm against gravity. During our task, the prime mover muscles were likely the biceps and triceps brachii, rather than the deltoid. A previous study compared muscle activation patterns during reaching and retrieval movements with and without gravity compensation, and the data showed that the level of muscle activity was lower with gravity compensation [26]. These results are consistent with our reasoning that the sliding task would predominantly engage the bicep and tricep muscles.

The comparable deltoid and pectoralis major activities of the hemiplegic and control groups suggest that unstable muscle activity might exist in control subjects during repetitive reaching movements. These findings
may be related to Bernstein’s problem, whereby more than one motor signal can lead to the same trajectory of a given motor system and identical motor signals can lead to different movements under non-identical initial conditions or in the presence of variations in the eternal force field [27, 28]. The hypothesis supporting the concept of degrees of freedom to motor control is that the principal problem faced by the central nervous system is the large number of joints and muscles in the human body and the infinite combinations of muscle action [27, 29]. In stroke subjects, kinematic variability may be due to unstable muscle activity during a single reaching movement. In the post-stroke subjects, the trajectory was fluctuating during repetitive reaching movements owing to variability in muscle activity. In control subjects, kinematic variability may be due to difficulties in reproducing exactly repeated muscle activities. Although muscle activity remains stable during each reaching movement, the combination of muscle activity is not constant between repetitions. Normally, coordination between muscle types (synergy) decreases the kinematic variability even if the variability in muscle activity increases, a mechanism lost in hemiplegic subjects.

**Conclusion**

We report the existence of variability in muscle activity during repetitive reaching movements in hemiparesis subjects. A significant negative correlation was established between the variability in muscle activity and the clinical score. The use of EMG analysis may be useful to clinically assess the variability in muscle activity.

**Conflicts of Interest**

The author declares no conflict of interest.

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