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A New Method for Quantitative Evaluation of Neurological Disorders based on EMG signals

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1. Introduction

In this chapter, we propose a novel method to make a quantitative evaluation of neurological disorders based on EMG signals from multiple muslces. So far, some researchers tried to evaluate arm movements in various conditions (Nakanishi et al., 1992; Nakanishi et al., 2000; Sanguineti et al., 2003). They captured some features of movement disorders in patients with neurological diseases such as Parkinson's disease or cerebellar atrophy. However, the scope of these analyses was limited to movement kinematics. The problem here is that the movement kinematics, in general, cannot specify its causal muscle activities (i.e. motor commands) due to the well-known redundancy of the musculo-skeletal system. Thus, in order to understand central mechanisms for generation of pathological movements, it is essential to capture causal anomaly of the motor commands directly, rather than to observe the resultant movement indirectly (Manto, 1996; Brown et al., 1997). It should be also emphasized that the new method must be simple and noninvasive for wider clinical application.

To address these issues, we developed a novel method to identify causal muscle activities for movement disorders of the wrist joint. In order to determine causal relationship between muscle activities and movement disorders, we approximated the relationship between the wrist joint torque calculated from the movement kinematics and the four EMG signals using a dynamics model of the wrist joint (see Section 3.2). Consequently, we found that the correlation between the wrist joint torque and the EMG signals were surprisingly high for cerebellar patients as well as for normal controls (see Section 3.3). These results demonstrated a causal relationship between the activities of the selected muscles and the movement kinematics. In fact, we confirmed the effectiveness of our method, identifying the causal abnormality of muscle activities for the cerebellar ataxia in detail (see Section 3.4).

Finally, we further extended our analysis to calculate parameters that characterize pathological patterns of the muscle activities (see Section 4.1). We will conclude this chapter by discussing the application and clinical value of these parameters (see Section 4.2).

2. Materials and Methods

2.1 Experimental apparatus

In order to make a quantitative evaluation of neurological disorders, we developed a system for quantitative evaluation of motor command using wrist movements (Lee et al, 2007). Specifically, we intended to analyze the causal relationship between movement disorders and abnormal muscle activities. In addition, the system was also designed to be non-invasive and used handily at the bedside.

An outline of the system is shown in Figure 1. It consists of four components, a wrist joint manipulandum, a notebook computer, a small Universal Serial Bus (USB) analog-to-digital (A/D) converter interface and a multi-channel amplifier for surface electromyogram (EMG) signal. Movement of the wrist joint is measured with 2 position sensors of the manipulandum at 2 kHz sampling rate, and the wrist position is linked to the position of the cursor on the computer display. In other words, the manipulandum worked as a mouse for the wrist joint. Consequently, we can analyze the relationship between movement disorders and muscle activities, while subjects perform various wrist movement tasks using the manipulandum.

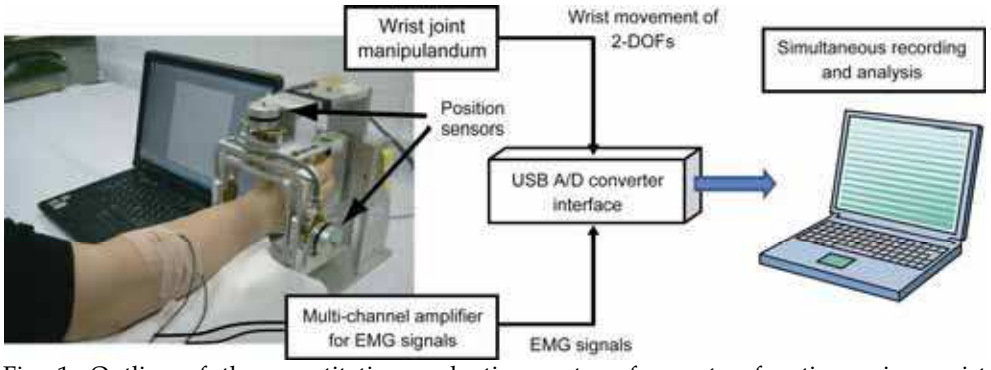

Fig. 1. Outline of the quantitative evaluation system for motor function using wrist movement

2.2 Experimental task

Subjects sat on a chair and grasped the manipulandum with his/her right hand. The forearm was comfortably supported by an armrest. As the experimental task, we asked subjects to perform step-tracking wrist movements (Figure 2A) and pursuit wrist movements (Figure 2B).

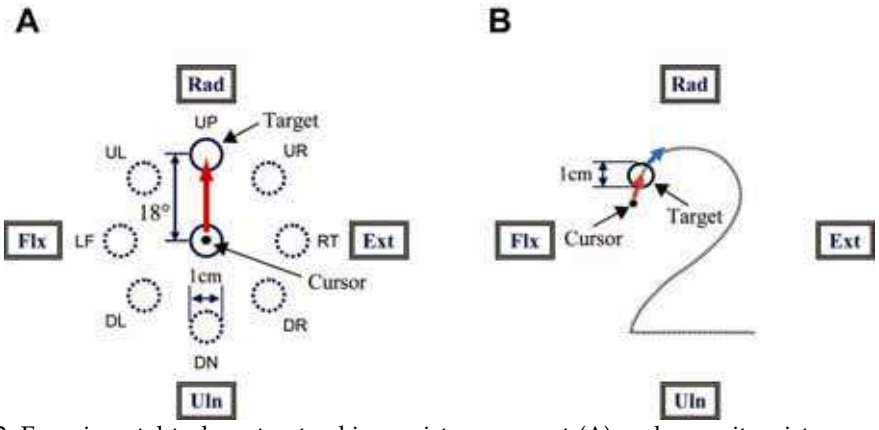

Fig. 2. Experimental tasks : step-tracking wrist movement (A) and pursuit wrist movement (B). To make these wrist movement tasks, the subject holds the forearm in the neutral position, midway between full pronation and full supination.

1. Step-tracking wrist movement
When a circular target, whose diameter was 1 cm, was displayed at the center of the monitor, the subject was required to move the cursor into the target. When a new target was shown at a place equivalent to 18 degrees of the wrist joint movement, the subjects had to move the cursor immediately to the new target as rapidly and accurately as possible. The subject performed the step-tracking wrist movement for the target of 8 directions (UP, UR, RT, DR, DN, DL, LF, UL). For this task, eight patients clinically diagnosed as cerebellar disorders and eight normal controls participated as subjects. Each subject performed this task 3 times.

2. Pursuit wrist movement
When a circular target, whose diameter was 1 cm, was displayed at the upper left of the monitor (X=-10° , Y=8°), the subject was required to move and hold the cursor into the target. After 3 seconds, the target moves by making the path of the figure 2 at the constant speed (mean velocity = 4.97deg/sec). At that time, the subjects had to enter the cursor into the moving target continuously. For this task, eight patients clinically diagnosed as cerebellar disorders, four patients clinically diagnosed as Parkinson's disease and eight normal controls participated as the subjects. Each subject performed this task 5 times.

During the task, four channels of EMG signals and two degree of freedom wrist movements were sampled and recorded at 2 kHz.

2.3 Recording muscle activities

We recorded surface EMG signals from four wrist prime movers: extensor carpi radialis (ECR), extensor carpi ulnaris (ECU), flexor carpi ulnaris (FCU) and flexor carpi radialis (FCR). The EMG signals were recorded with Ag-AgCl electrodes, amplified and sampled at 2 kHz. Typical locations of the surface electrodes for these four muscles are shown in Figure 3A. The position of each electrode was adjusted for each subject to maximize EMG signals of each muscle for a specific movement. In a few healthy control volunteers, we confirmed

effectiveness of the adjustment with high correlation between the surface EMG signals and the corresponding EMG signals recorded with needle electrodes from the same muscles identified with evoked-twitches.

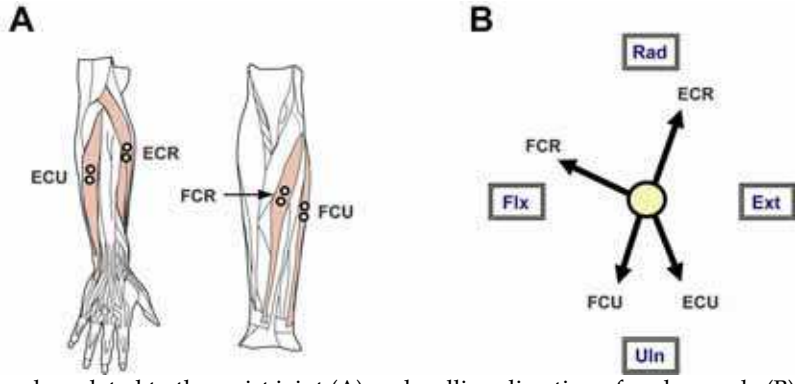

Fig. 3. Muscles related to the wrist joint (A) and pulling direction of each muscle (B). (A) The four wrist prime movers whose activities were recorded: extensor carpi radialis (ECR), extensor carpi ulnaris (ECU), flexor carpi ulnaris (FCU) and flexor carpi radialis (FCR). We did not distinguish extensor carpi radialis longus (ECRL) and extensor carpi radialis brevis (ECRB), because they have quite similar actions on the wrist and their activities are indistinguishable with surface electrodes. (B) The arrow indicates the pulling direction of each muscle. Muscle pulling directions for ECR, ECU, FCU, FCR were 18.4, 159.5, 198.3, and 304.5° clockwise from UP target.

There are two reasons why we chose these four muscles. First, the mechanical actions of these muscles are evenly distributed to cover the wrist movement for any direction (Figure 3B). Second, it is easy to record their activities with surface electrodes (Figure 3A). This is an essential clinical benefit to record muscle activities without pain, sparing use of invasive needle or wire electrodes. It should be also noted that use of no more than four surface electrodes contributes greatly to minimize time needed to set up recording.

2.4 Normalization of EMG Signals

It is well known that EMG signals are closely correlated with activities of α-motoneurons, which represent the final motor commands from the CNS. These motor commands generate muscle contraction, which results in muscle tension. It is established that a second order, low-pass filter is sufficient for estimating muscle tension from the raw EMG signal (Mannard & Stein, 1973). However, although the low-pass filtered EMG signal is proportional to muscle tension, the proportional constant varies due to variability of skin resistance or relative position of the electrode on a muscle for each recording. Therefore, for a quantitative analysis, it is necessary to normalize the EMG signals. For this purpose, we asked each subject to generate isometric wrist joint torque for the PD of each muscle. Namely, for each muscle, we set the amplitude of the EMG signals for 0.8 Nm of isometric wrist joint torque as 1. Then, the normalized EMG signals were digitally rectified and then filtered with a low-pass filter of a second order.

In this study, we used a Butterworth low-pass filter of a second order with cut-off frequency of 4Hz. Most critically, we considered the filtered EMG signals as muscle tensions, and used them to estimate the wrist joint torque (Mannard & Stein, 1973; Koike & Kawato, 1995). In this study, we called the filtered EMG signals as muscle tension shortly.

3. Identification of causal muscle activities for movement disorders

In this section, we will describe the results of identification for the step-tracking movement of the wrist for various directions. Specifically, we identified causal abnormality of muscle activities for movement disorders of cerebellar patients, confirming effectiveness of our method for analysis of movement disorders at the level of the motor command.

3.1 Movement disorders and causal anomaly in the muscle activities

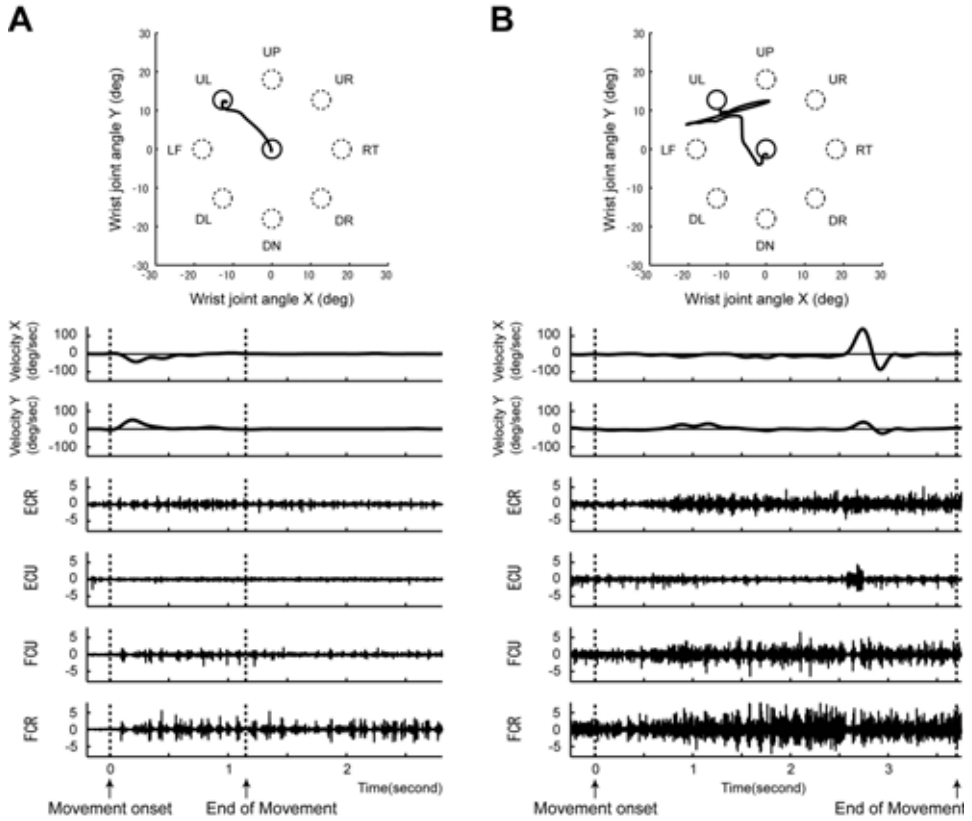

Fig. 4. Wrist joint kinematics and EMG signals for UL target. (A) An example of step-tracking movement for UL target in a normal control. The inset demonstrates a trajectory of the wrist joint. The top two traces show X-axis and Y-axis components of the angular velocity. The bottom four traces show EMG signals of ECR, ECU, FCU, FCR. (B) A corresponding example recorded from a cerebellar patient.

Figure 4 shows a trajectory, velocity profiles and EMG signals for a movement toward UL target. As shown in Figure 4A, the trajectory of a normal control was almost straight, and the angular velocity of a wrist joint showed a typical bell-shape profile for both X- and Y-components. In terms of EMG signals, FCR whose pulling direction (see Figure 3B) was directed to the UL target was active from the movement onset to the end. In addition, the activity of FCR lasted while a wrist was maintained in the UL target. ECR and FCU that had minor contribution for the direction also demonstrated moderate and probably cooperative activities. In contrast, ECU whose pulling direction was directed opposite to UL target, was inactive throughout the movement. Overall, the muscle activities and the mechanical actions of the four muscles can explain the movement quite reasonably in the normal control. The same was true for the cerebellar patients. Even the complex trajectory can be explained with the muscle activities as follows. As shown in Figure 4B, the initial downward movement was lead by inadvertent dominance of activities of FCU. Then simultaneous recruitment of FCR and ECR lifted the wrist upward. However, as the activities of FCR exceeded that of ECR, the wrist was pulled leftward. But a sudden burst of ECU and simultaneous shut-down of FCR and FCU ignited a diddling of the wrist.

3.2 A dynamics model of the wrist joint

In order to determine causal muscle activities for movement disorders quantitatively, we approximated the relationship between the wrist joint torque calculated from the movement kinematics and the four EMG signals using a dynamics model of the wrist joint.

The equations of the wrist joint torque calculated from the wrist joint kinematics (angle, angular velocity, angular acceleration) can be decomposed into the X-axis component and Y-axis component as follows.

$$M\ddot{\theta}_x(t) + B\dot{\theta}_x(t) + K\theta_x(t) = f_x(t) \tag{1}$$

$$M\ddot{\theta}_y(t) + B\dot{\theta}_y(t) + K\theta_y(t) + mgc\cos\theta_y(t) = f_y(t) \tag{2}$$

Where, $\theta_x(t)$ and $\theta_y(t)$ represent X-axis component and Y-axis component of the wrist joint angle. $\dot{\theta}_x(t)$, $\dot{\theta}_y(t)$, $\ddot{\theta}_x(t)$ and $\ddot{\theta}_y(t)$ indicate X-axis component and Y-axis component for angular velocity and angular acceleration of the wrist joint respectively. *M* is an inertial parameter and we calculated this parameter for each subject by measuring volume of the hand. *B* and *K* represent viscous coefficient and elastic coefficient. We set these coefficients as 0.03Nms/rad and 0.2Nm/rad for the step-tracking movement, based on the previous studies (Gielen & Houk, 1984; Haruno & Wolpert 2005). *m* and *c* are the mass and center of mass for the hand, and we calculated these parameters for each subject by measuring volume of the hand. *g* is acceleration of gravity (g=9.8m/s2). $f_x(t)$ and $f_y(t)$ denote X-axis component and Y-axis component of the wrist joint torque calculated from the wrist movement.

We assumed that the wrist joint torque were proportional to the linear sum of the four EMG signals. That is, considering the pulling direction of each muscle shown in Figure 3B, the relationship between the wrist joint torque and the muscle tension of four muscles are formalized as follows:

$$a_{1x}e_1(t) + a_{2x}e_2(t) - a_{3x}e_3(t) - a_{4x}e_4(t) = g_x(t) \quad (3)$$

$$a_{1y}e_1(t) - a_{2y}e_2(t) - a_{3y}e_3(t) + a_{4y}e_4(t) = g_y(t) \quad (4)$$

Where, $e_1(t)$, $e_2(t)$, e_3 (t), and $e_4(t)$ represent the muscle tension of ECR, ECU, FCU, and FCR, respectively. $g_x(t)$ and $g_y(t)$ represent X-axis component and Y-axis component of the wrist joint torque estimated from the four muscle tensions, respectively. a_{1x}~a_{4x} ($\geqq 0$) and a_{1y}~a_{4y} ($\geqq 0$) denote the parameters for the musculo-skeletal system of the wrist joint that convert the muscle tension into the wrist joint torque. It should be noted that the sign of each parameter works as a constraint to limit the pulling direction of each muscle.

In our previous study, we calculated the parameters a_{1x}~a_{4x} and a_{1y}~a_{4y} using the simple relationship between the wrist joint torque and the muscle tension for isometric contraction (Lee et al., 2007). However, there was no guarantee that these parameters obtained for an isometric condition were suitable to estimate dynamic wrist joint torques during movement. In fact, estimation of the dynamic wrist joint torques with these parameters was relatively poor for extreme movements, such as jerky movements of the cerebellar patients. Therefore, it is desirable to introduce alternative parameters obtained for movement conditions. In this study, we directly calculated these parameters from the relationship between the wrist joint torque and the muscle tension during movement, by optimizing a match between the wrist joint torque (equation (1) and (2)) and the linear sum of four muscle tensions (equation (3) and (4)) using the least squares method.

3.3 Performance of the model

Figure 5 shows an example of the match between the wrist joint torque calculated from the wrist movement (blue line) and the linear sum of the four muscle tensions (red line) for a normal control (A) and a cerebellar patient (B). As clearly seen in Figure 5 and Table 1, there were very high correlations between the wrist joint torque and the four muscle activities for both the cerebellar patients and the normal controls (R for normal controls = 0.81±0.08 (X-axis), 0.84±0.05 (Y-axis); R for cerebellar patients = 0.81±0.09 (X-axis), 0.81±0.05 (Y-axis)). The result strongly suggested that it is possible to identify causal anomaly of the muscle activities for each abnormal movement. Therefore, it should be possible to analyze central mechanisms for generation of pathological movements at the level of the motor command with high accuracy.

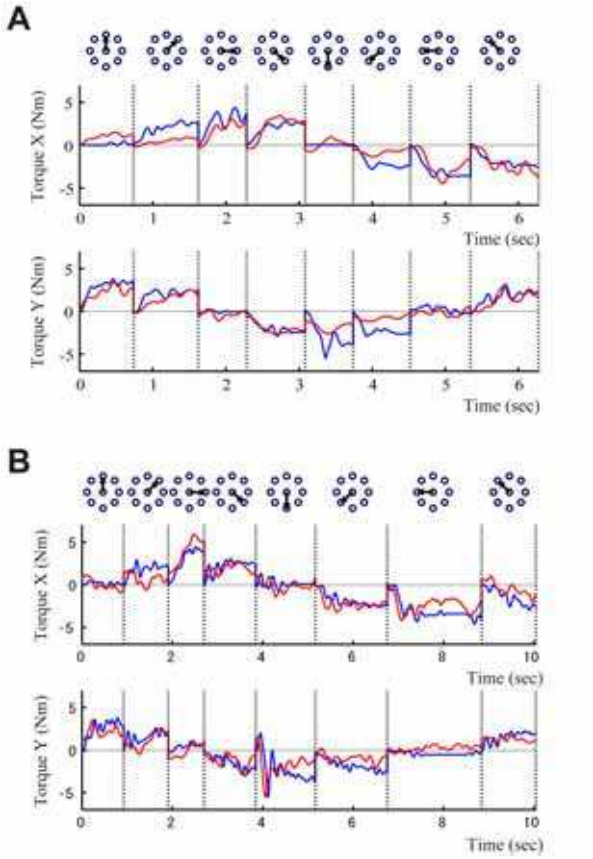

Fig. 5. Relationship between the wrist joint torque calculated from the wrist movement (blue line) and the linear sum of four muscle tensions (red line) for a normal control (A) and a cerebellar patient (B). Figures of top trace indicate the direction of wrist movement.

	Correlation R of normal control (n=8)	Correlation R of cerebellar patient (n=8)
Torque X	0.81±0.08	0.81±0.09
Torque Y	0.84±0.05	0.81±0.05

Table 1. Correlation between the wrist joint torque and the muscle activities.

3.4 Analysis of Causal Motor Commands for the Cerebellar Ataxia

In fact, we identified causal abnormality of muscle activities for cerebellar ataxia, confirming effectiveness of our method to analyze pathological movements at the level of the motor command.

Figure 6 demonstrates a typical example of one-to-one correlation between the muscle activities and the concomitant movement for the downward movement in Figure 5B. This figure summarizes relationship between the muscle activities (i.e.motor commands) and a

jerky wrist movement of a cerebellar patient for every 100msec. For instance, the initial movement (0msec) was away from the down target (i.e. upward) due to the excess activities of ECR that pulls the wrist upward. Then the wrist was redirected toward the down target due to the desirable predominance of the activities of FCU (100-300msec). However, 400msec after the onset, inadvertent activities of FCR pulled the wrist leftward, again, away from the target. In this way, it is possible with our system to determine the anomalous motor command for the cerebellar ataxia in further detail.

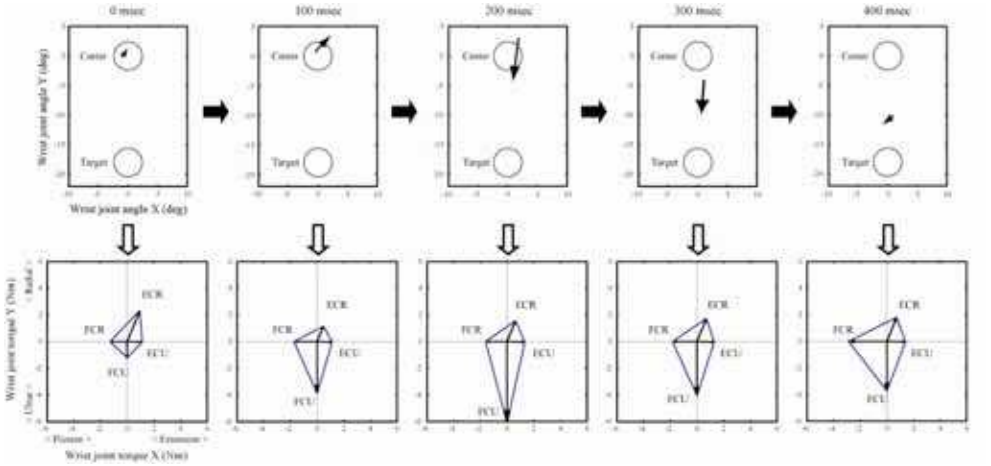

Fig. 6. Causal relationship between muscle activities and a jerky wrist movement of a cerebellar patient. Top panels show directions of the wrist movement for every 100msec. 0msec indicates the movement onset. Bottom panels show averaged activities of the four muscles for the corresponding time window. Muscle activities are represented as vectors.

4. Quantification of pathological patterns of muscle activities

Overall, it is possible to identify abnormal components of agonist selection for wrist movements by recording activities of as few as four (out of twenty-four) forearm muscles. We further extended our analysis to quantify the pathological patterns of muscle activities. In this section, we will describe two parameters that summarize variability and efficacy of muscle activities for the pursuit movement.

4.1 Parameters characterizing pathological patterns of muscle activities

To make a pursuit wrist movement, it is desirable to change muscle activities smoothly, because the target moves smoothly. On the other hand, it is also desirable to maximize contrast between activities of agonist and antagonist muscles to minimize energy consumption for a movement. As parameters characterizing the variability and the effectiveness of muscle activities, we defined "Variability of Total Contraction" (VTC) and "Directionality of Muscle Activity" (DMA) as follows. Indeed, we found these parameters were very different between control subjects and patients with neurological disorders, and therefore, were useful to quantify movement disorders.

4.1.1 Variability of Total Contraction (VTC)

VTC represents temporal variability of muscle activitites, as illustrated in Figure 6A. We first calculated amplitude of torque for each muscle using equation (5).

$$|\vec{T}_{Muscle}| = \sqrt{(a_x^{Muscle})^2 + (a_y^{Muscle})^2} \times e_{Muscle}(t) \tag{5}$$

Where, a_x^{Muscle} ($\geqq 0$) and a_y^{Muscle} ($\geqq 0$) denote the parameters for the musculo-skeletal system of the wrist joint, which convert muscle tension into the X-axis component and the Y-axis component of the wrist joint torque respectively. $e_{Muscle}(t)$ represents the muscle tension of each muscle.

$$VTC = \frac{\int \left(\sum_{Muscle=1}^{4} \left| \frac{d(|\vec{T}_{Muscle}|)}{dt} \right| \right) dt}{t} \tag{6}$$

Then, as described in equation (6), we calculated the instantaneous variability of the torque for the four muscles. Finally, the VTC was calculated by averaging the absolute value of the variation with movement duration *t* to normalize it for movement duration.

4.1.2 Directionality of Muscle Activity (DMA)

DMA was evaluted as the ratio of wrist joint torque to the total muscle torque as shown in Figure 6B and equation (8). We first calculated the wrist joint torque from four muscle activities as follows:

$$|\vec{\tau}_{EMG}| = \sqrt{(g_x(t))^2 + (g_y(t))^2} \tag{7}$$

Where, $g_x(t)$ and $g_y(t)$ represent X-axis component and Y-axis component of the wrist joint torque estimated from the four muscle tensions (see equations (3) and (4)).

$$DMA = \frac{\int \frac{|\vec{\tau}_{EMG}|}{\sum_{Muscle=1}^{4} |\vec{T}_{Muscle}|} dt}{t} \tag{8}$$

Then, as described in equation (8), we calculated the ratio of the wrist joint torque to the sum of the torque of the individual muscles, and finally, the DMA was calculated by averaging the ratio for movement duration *t* as a nomalization.

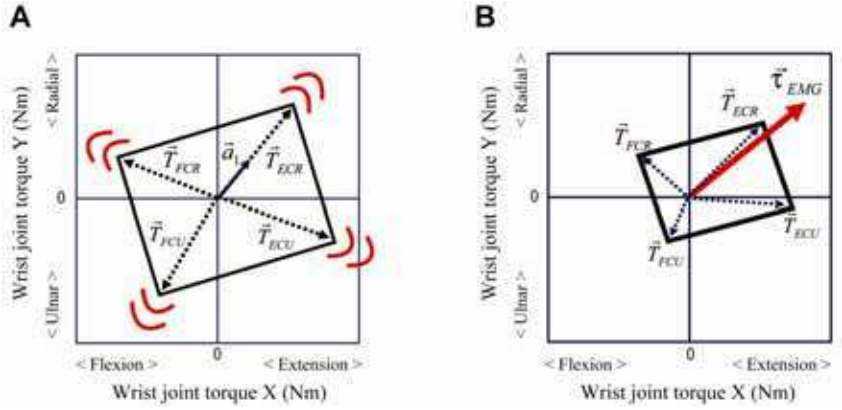

Fig. 6. Explanation of Variability of Total Contraction (VTC) (A) and Directionality of Muscle Activity (DMA) (B).

4.2 VTC and DMA in neurological disorders

In order to evaluate usefulness of VTC and DMA, we calculated these parametes for patients with cerebellar atrophy and patients with Parkinson's disease, as well as for normal control subjects. Figure 7 summarizes the results. The VTC indicates variability of muscle activities. Therefore, if there are a number of abrupt changes in the muscle activities, the VTC gets higher. For instance, in case of cerebellar patients, muscle activities keep fluctuating intensely due to the cerebellar ataxia. As a result, VTCs for the cerebellar patients tend to be higher than control subjects with much smoother muscle activities, as shown in Figure 7A. In contrast, VTCs for patients with Parkinson's disease tend to be smaller due to faint modulation of muscle activities (Figure 7A).

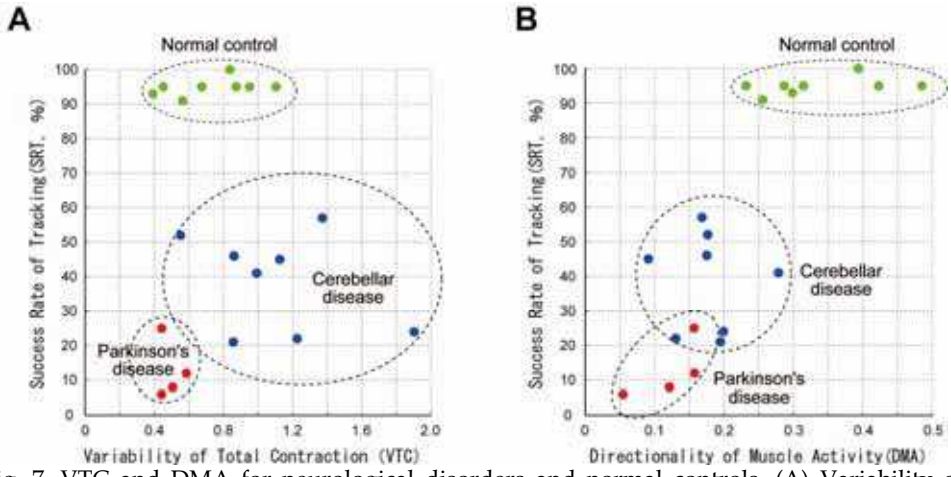

Fig. 7. VTC and DMA for neurological disorders and normal controls. (A) Variability of Total Contraction (VTC), (B) Directionality of Muscle Activity (DMA). SRT indicates the rate (%) of the cursor within the target for the pursuit movement.

The DMA represents directionality of muscle activities, and thereby indicating contrast between activities of agonist and the antagonist muscles. By definition, if agonists are activated selectively with complete suppression of antagonists, DMA gets highest. In contrast, DMA is low in case of co-contraction with comparable activities for agonists and antagonists. As a result, DMAs for cerebellar patients are usually very low due to significant co-contraction (see Figure 4B for example) as shown in Figure 7B. On the other hand, in case of patients with Parkinson's diseases, DMAs are also low due to poor modulation of agonist activities.

Overall, VTC or DMA captures characteristic patterns of the muscle activities for patients with cerebellar disorders and patients with Parkinson's disease. Moreover, it is possible to make more detailed characterization of pathological muscle activities by combining these parameters (Figure 8). If we use more useful parameters in combination with VTC and DMA, it will be possible to make more sophisticated evaluation of movement disorders in a high dimensional space of parameters that quantify patterns of muscle activities. Consequently, it could be possible to evaluate effects of newly developed treatments for neurological diseases in the parameter space.

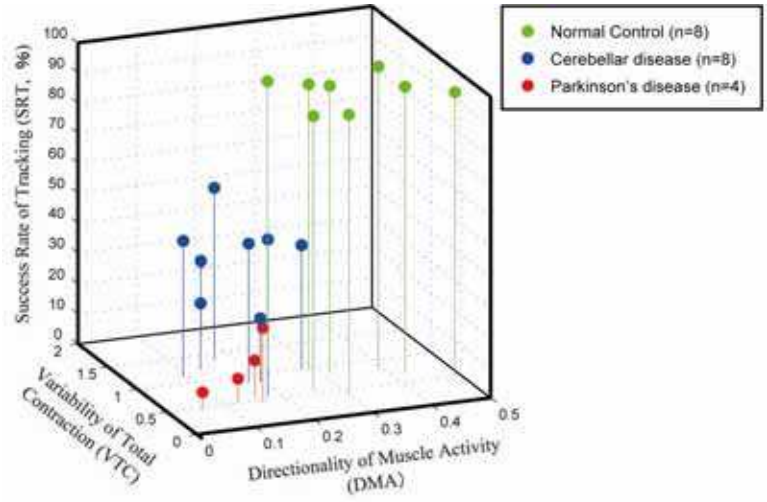

Fig. 8. Comprehensive assessment of muscle activities (i.e. motor commands) for neurological disorders and normal control. Green spheres, blue spheres and red spheres indicate normal controls, cerebellar patients and Parkinson's patients, respectively.

5. Discussion and conclusion

In this chapter, we proposed a new method to make a quantitative evaluation for movement disorders based on the EMG signals. In the following discussion, we will focus on three points: 1) Why it is essential to analyze muscle activities for evaluation of neurological disorders; 2) How effective our proposed method is. 3) Application of our proposed method.

Some researchers tried to make quantitative evaluation of the motor function for the arm movement (Nakanishi et al., 1992; Nakanishi et al., 2000; Sanguineti et al., 2003). For example, by analyzing the position, velocity and acceleration of arm during a circular movement on the digitizer, Nakanishi et al. evaluated the motor function of the arm in patients with neurological disorders including cerebellar deficits and Parkinson's disease. However, their analysis was limited to the movement kinematics. Unfortunately, the movement kinematics cannot specify its causal muscle activities due to the well-known redundancy of the musculo-skeletal system. In other words, completely different sets of muscle activities (causes) end up with the same kinematics (result). Thus, in order to understand central mechanisms for generation of pathological movements, it is essential to capture causal anomaly of the motor commands directly, rather than to observe the resultant movement indirectly (Manto, 1996; Brown et al., 1997). In addition, the movement kinematics provides no information about muscle tonus that is a crucial factor to diagnose movement disorders. Overall, it is essential to examine muscle activities to make more fundamental evaluation of neurological disorders.

In this study, we proposed a new method to identify causal muscle activities for movement disorders of the wrist joint. However, there are twenty-four muscles in the forearm that have significant effects on the wrist joint. If we had to record activities of all these muscles to reconstruct the movement kinematics, we would have to use a number of (i.e. twenty-four pairs of needle electrodes and it would take painful hours for just placing the electrodes. In this chapter, we proposed a new method to determine abnormal components of agonist selection for various wrist movements by recording activities of as few as four forearm muscles without pain. Consequently, with our proposed method, it is easy to analyze central mechanisms for generation of pathological movement. In fact, we confirmed the effectiveness of our proposed method, identifying the causal abnormality of muscle activities for the cerebellar ataxia with high accuracy.

So far, our method is limited to examine the wrist movement, rather than the whole arm. Nevertheless, the wrist joint is suitable to examine important motor functions of the arm. Basically, not only six wrist muscles but also eighteen finger muscles are relevant to control the two degrees of freedom of the wrist joint (Brand, 1985). This anatomical setup allows the wrist joint a uniquely wide variety of motor repertoires. For instance, the wrist joint plays an essential role in hand writing which requires the finest precision of all the motor repertoires. It should be emphasized that its role is not just a support for finger movements. On the other hand, the wrist is also capable to generate and/or transmit considerable torque as seen in the arm wrestling. Overall, our method is capable to examine wide range of natural or disordered movements by the wrist joint. However, in future, it is desirable to expand our method to analyze movements of any body part including the whole arm or gait.

Our proposed method is not limited to analysis of motor deficits. We will further apply this method to evaluation of rehabilitation or guidance of treatment for neurological diseases. As a first step, we examined parameters characterizing pathological patterns of muscle activities and demonstrated their usefulness to evaluate pathological muscle activities. These parameters, if combined appropriately, are useful to characterize complex patterns of muscle activities in a way easy to recognize visually. The high-dimensional parameter space

is also useful to evaluate effects of a medical treatment as a shift toward or away from the normal control in the parameter space. In other words, this system is potentially a navigation system for medical treatments based on the motor commands.

We are now preparing to use this system for evaluation and navigation of rehabilitation. We expect that an earliest sign of favorable or infavorable effects of rehabilitation emerges as subtle changes in muscle activities long before *visible* changes in movement kinematics. Our method may be also useful for evaluation of treatments currently available like the deep brain stimulation therapy or available in a near future, such as gene therapies whose targets are in the central nervous system and whose effects appear as, probably, slow renormalization of the motor commands.

6. Acknowledgement

We thank Dr. Yasuharu Koike for his invaluable advices on the approximation of the wrist joint model. We also thank Drs. Yoshiaki Tsunoda and Seaka Tomatsu for helpful discussions.

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Recent Advances in Biomedical Engineering

Edited by Ganesh R Naik

ISBN 978-953-307-004-9
Hard cover, 660 pages
Publisher InTech
Published online 01, October, 2009
Published in print edition October, 2009

The field of biomedical engineering has expanded markedly in the past ten years. This growth is supported by advances in biological science, which have created new opportunities for development of tools for diagnosis and therapy for human disease. The discipline focuses both on development of new biomaterials, analytical methodologies and on the application of concepts drawn from engineering, computing, mathematics, chemical and physical sciences to advance biomedical knowledge while improving the effectiveness and delivery of clinical medicine. Biomedical engineering now encompasses a range of fields of specialization including bioinstrumentation, bioimaging, biomechanics, biomaterials, and biomolecular engineering. Biomedical engineering covers recent advances in the growing field of biomedical technology, instrumentation, and administration. Contributions focus on theoretical and practical problems associated with the development of medical technology; the introduction of new engineering methods into public health; hospitals and patient care; the improvement of diagnosis and therapy; and biomedical information storage and retrieval. The book is directed at engineering students in their final year of undergraduate studies or in their graduate studies. Most undergraduate students majoring in biomedical engineering are faced with a decision, early in their program of study, regarding the field in which they would like to specialize. Each chosen specialty has a specific set of course requirements and is supplemented by wise selection of elective and supporting coursework. Also, many young students of biomedical engineering use independent research projects as a source of inspiration and preparation but have difficulty identifying research areas that are right for them. Therefore, a second goal of this book is to link knowledge of basic science and engineering to fields of specialization and current research. The editor would like to thank the authors, who have committed so much effort to the publication of this work.

How to reference

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Jongho Lee, Yasuhiro Kagamihara and Shinji Kakei (2009). A New Method for Quantitative Evaluation of Neurological Disorders based on EMG signals, Recent Advances in Biomedical Engineering, Ganesh R Naik (Ed.), ISBN: 978-953-307-004-9, InTech, Available from: http://www.intechopen.com/books/recent-advances-in-biomedical-engineering/a-new-method-for-quantitative-evaluation-of-neurological-disorders-based-on-emg-signals

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