35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Quantitative Evaluation of Cerebellar Ataxia based on Pathological Patterns of the Muscle Activities

J. Lee, Y. Kagamihara, and S. Kakei

Abstract— **Quantitative evaluation of cerebellar ataxia is crucial for precise evaluation of cerebellar diseases. In particular, it is essential to capture anomaly of the causal motor commands as well as the resultant movement for the ataxia. In this paper, we propose a new method to make a quantitative evaluation of the cerebellar ataxia based on EMG signals. As an experimental task, we asked subjects to perform step-tracking wrist movements with a manipulandum, and recorded wrist joint movements and muscle activities of four wrist prime movers with surface electrodes. The subjects included fourteen patients with cerebellar diseases and thirteen normal controls.**

We succeeded to extract two parameters from the EMG signals of the four wrist prime movers, which characterize the pathological patterns of muscle activities for the cerebellar ataxia, Total Co-contraction Level (TCL) and Directionality of Muscle Activity (DMA). We found that the two parameters were useful to characterize pathological patterns of muscle activities in cerebellar ataxia. Consequently, it is expected that our proposed method is useful not only in tracking condition of cerebellar patients but also in evaluating the effects of a treatment or neuro-rehabilitation aiming at the normalization of motor commands.

I. Introduction

Ataxia is a major sign of cerebellar dysfunction [1]. Clinical signs of ataxia for cerebellar patients are clearly evident in the execution for a goal-directed movement, such as 1) slow to start and slow movement, 2) inaccuracy in achieving a target (dysmetria), and so on [3, 4]. Conventional clinical evaluation for the clinical signs of ataxia mainly depends on a number of qualitative neurological tests, such as International Cooperative Ataxia Rating Scale (ICARS) [2]. However, its subjectivity and lack of quantitativeness (or semi-quantitative evaluation by pre-defined precision) lets researchers take an interest in developing the new tools for quantitative assessment of ataxia.

So far, some researchers tried to make quantitative evaluation of the cerebellar ataxia using the arm movement [3-4]. But, their evaluations were mostly limited to the 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 necessary to capture causal anomaly of the motor commands directly, rather than to observe the resultant movement indirectly [1, 5]. Recently, we developed a system to analyze the relationship between movement disorders and abnormal muscle activities for wrist movements, and identified causal relationship between wrist movement and activities of as few as four wrist prime movers [6]. With our method, it was possible to establish one-to-one relationship between cerebellar ataxia and causal activities of the muscles [7]. In this study, for the next step, we propose a novel method to evaluate cerebellar ataxia directly from a level of motor commands based on activities of the four wrist prime movers. In particular, we captured characteristic patterns of the muscle activities for patients with cerebellar ataxia. In other words, we extracted two parameters characterizing the co-contraction and the effectiveness of muscle activities. We then confirmed the effectiveness of these parameters for a quantitative evaluation of cerebellar ataxia.

* Manuscript received February 4, 2013. This work was supported by the Tokyo Metropolitan Institute of Medical Science (Kakei) and MEXT KAKENHI 24650304 (Lee).

J. Lee and S. Kakei are with the Motor disorders project, Tokyo Metropolitan Institute of Medical Science, 2-1-6 Kamikitazawa, Setagaya-ku, Tokyo 156-8506, Japan (e-mail: lee-jg@igakuken.or.jp, kakei-sj@igakuken.or.jp). Y. Kagamihara is with the Tokyo Metropolitan Tama Medical Center, 2-8-29 Musashidai, Fuchu-shi, Tokyo 183-8524, Japan (e-mail: yasuhiro_kagamihara@tmhp.jp)

II. Experimental Method

A. Subject and Experimental Setup

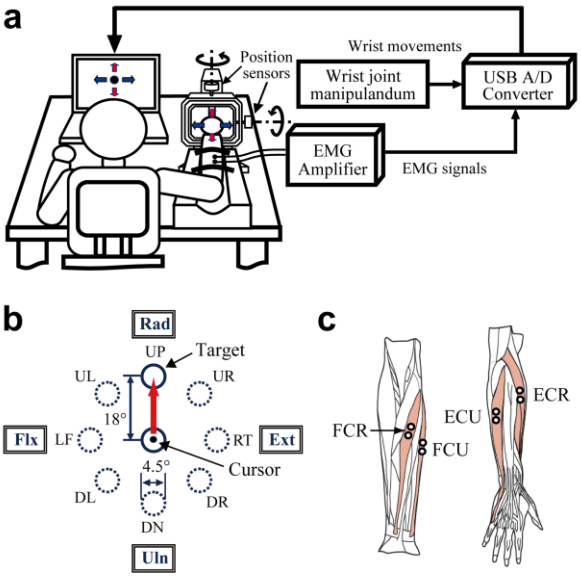

Figure 1. Outline of the experimental setup (a), step-tracking movement as the experimental task (b), and muscles related to the wrist joint (c)

Fourteen patients clinically diagnosed as cerebellar disorders (average age was 58.5, seven patients were diagnosed as spinocerebellar degeneration, six patients as multi-system atrophy and one patient as multiple sclerosis) and thirteen normal controls who didn't have any history of neurological disorders (average age was 52.1) participated as the subjects. All participants gave an informed written

consent, and the local ethical committees approved this study.

Fig. 1a shows the outline of the experimental setup. The subject sat on a chair and grasped a manipulandum with his/her right hand. The forearm was comfortably supported with an armrest. 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.

As an experimental task, we asked subjects to perform step-tracking wrist movements for 8 directions (Fig. 1b: UP, UR, RT, DR, DN, DL, LF, UL). When a target jumped from the center to one of 8 targets on the screen, the subject was required to move the cursor immediately from the center to the new target as rapidly and accurately as possible. The target was presented in clockwise order, starting with UP target of upward direction and ending with the UL target of upper-left direction. Each subject performed 3 cycles for 8 targets, resulting in a total of 24 trials. During the task, four channels of EMG signals and two degree of freedom wrist movements were sampled and recorded at 2 kHz. EMG signals were recorded with Ag-AgCl surface electrodes and amplified differentially. We recorded the EMG signals from four wrist prime movers: *extensor carpi radialis* (ECR), *extensor carpi ulnaris* (ECU), *flexor carpi ulnaris* (FCU) and *flexor carpi radialis* (FCR). Fig. 1c shows the approximate positions of the recording electrodes.

B. Preprocessing and Normalization of EMG Signals

The EMG signals recorded during task were digitally rectified and filtered with a second-order low-pass filter ([9], cut-off frequency: 2.2 Hz). This filter is sufficient to estimate muscle tensions from surface EMG signals [9, 10]. We then normalized the tensions of each muscle using muscle activities for isometric wrist joint torque of 0.78Nm. In other words, we first asked each subject to generate isometric wrist joint torque of 0.78Nm for the 8 directions in clockwise order, starting with UP target of upward direction and ending with the UL target of upper-left direction, and recorded EMG signals from the four wrist prime movers. In particular, for the relationship between the isometric wrist joint torque and four wrist primer, we assumed that the isometric wrist joint torque was proportional to the linear sum of the four muscle tensions as follows:

$$\tau_x(t) = \sum_{i=1}^{4} a_{ix} e_i(t) \quad (1)$$

$$\tau_y(t) = \sum_{i=1}^{4} a_{iy} e_i(t) \quad (2)$$

where, $\tau_x(t)$ and $\tau_y(t)$ represent X-axis component and Y-axis component of the isometric wrist joint torque, respectively. $e_i(t)$ represent the tensions of each muscle i (ECR, ECU, FCU, and FCR) for the isometric task. a_{ix} and a_{iy} denote X-axis component and Y-axis component of the moment arm of each muscle i, respectively. Here, the moment arm is defined as the distance between the joint axis and the force action line of the muscle. In this study, it was used as a normalized parameter converting tensions of each muscle into muscle torques. In particular, with consideration for the pulling direction of each muscle [8], we restricted a sign of the moment of each muscle as follows:

- ECR: $a_{1x} \geq 0$ and $a_{1y} \geq 0$, ECU: $a_{2x} \geq 0$ and $a_{2y} \leq 0$,
- FCU: $a_{3x} \leq 0$ and $a_{3y} \leq 0$, FCR: $a_{4x} \leq 0$ and $a_{4y} \geq 0$

Then, by optimizing match between the isometric wrist joint torque and the linear sum of four muscle tensions with the equation (1) and (2) using the least squares method, we obtained moment arms for X- and Y-axis for each muscle, $a_{1x\sim4x}$ and $a_{1y\sim4y}$ (Fig. 2b).

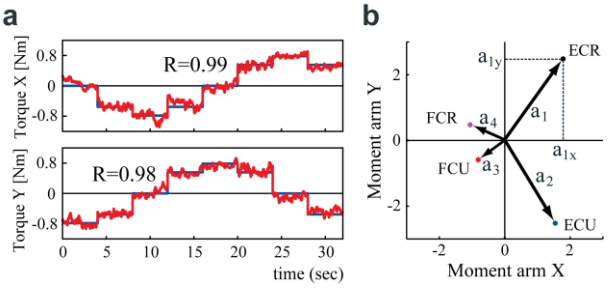

Figure 2. An example for match between the wrist joint torque and the linear sum of four muscle tensions (a) and moment arm for each muscle (b)

TABLE I. CORRELATION BETWEEN THE ISOMETRIC WRIST JOINT TORQUE AND THE LINEAR SUM OF FOUR MUSCLE TENSIONS

	Correlation *R* of normal control (n=13)	**Correlation *R* of cerebellar patient (n=14)**
Torque X	0.98±0.01	0.97±0.04
Torque Y	0.96±0.03	0.95±0.03

As is clearly shown in Fig. 2a, it was possible to establish a precise match between the isometric wrist joint torque (blue lines in the Fig. 2a) and the linear sum of the four muscle tensions (red lines in the Fig. 2a) with high correlation coefficient R (Fig. 2a, $R = 0.99$ for X-axis of torque, $R = 0.98$ for Y-axis of torque). In addition, the match was confirmed for both the normal control and the cerebellar patient with the high correlation coefficient R (Table 1). Finally, we normalized the tensions of each muscle by multiplying with the moment arms as follows:

$$T_i(t) = a_i E_i(t) = \sqrt{(a_{ix} E_i(t))^2 + (a_{iy} E_i(t))^2} \quad (3)$$

where, $T_i(t)$ represents normalized tension of each muscle i, and a_i denotes the moment arm of each muscle i. $E_i(t)$ represent the tensions of each muscle i for the step-tracking task.

III. RESULT

A. Cerebellar Ataxia and Causal Muscle Activity

Fig. 3 shows trajectories and EMG signals of the step-tracking movements for 8 directions recorded from a normal control and a cerebellar patient. As shown in *inset* of Fig. 3, the trajectories of the normal control were almost straight lines from the center to the targets, while the cerebellar patient frequently moved the wrist toward different directions against the target. First of all, we made quantitative

analysis for the movement kinematics of the cerebellar patients, in terms of movement time and accuracy of wrist movements, and compared with the normal controls (Fig. 4).

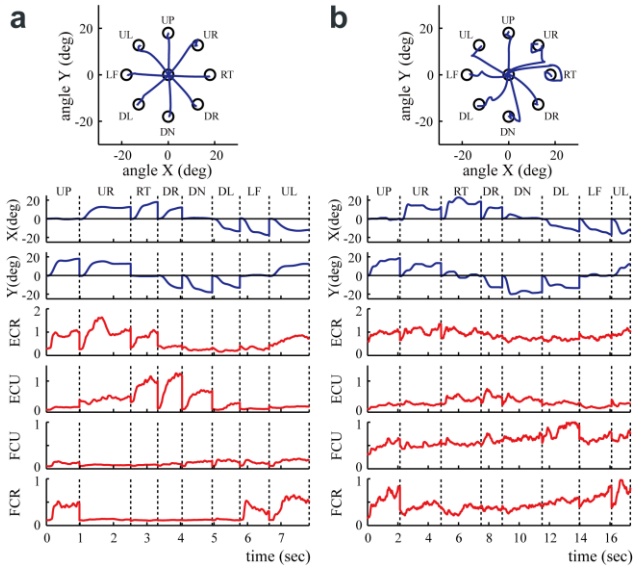

Figure 3. Trajectories and EMG signals for the step-tracking movement. (A) An example for a normal control. The inset demonstrates a trajectory of the wrist joint for a step-tracking movement. The top two traces show X-axis and Y-axis components of the wrist joint angle. The bottom four traces show EMG signals (= normalized muscle tensions) of ECR, ECU, FCU, FCR. (B) A corresponding example recorded from a cerebellar patient.

1) Movement time: As shown in Fig. 4a, the movement time for the cerebellar patients (mean value = 1.88s) was significantly longer than that for the normal controls (mean value = 1.08s)(p<0.001).

2) Accuracy of Movement: Accuracy of wrist movements was calculated as mean distance of the observed trajectory from the ideal straight trajectory from the center to the target [6]. As shown in Fig. 4b, the accuracy for the cerebellar patients (mean value = 1.81˚) were significantly different from that for the normal controls (mean value = 0.79˚)(p<0.001).

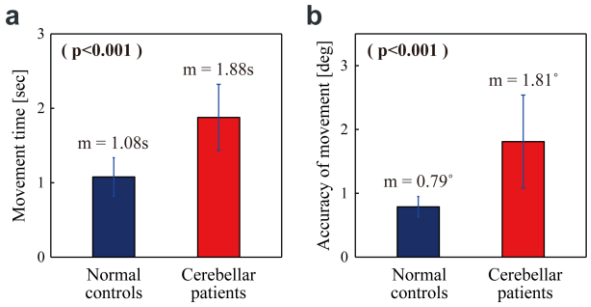

Figure 4. Analysis of the kinematics in the cerebellar patients and the normal control. (a) movement time, (b) accuracy of wrist movement.

Overall, for the step-tracking wrist movements, we confirmed the characteristic of the cerebellar ataxia demonstrated in previous studies, such as slower movements and loss of movement accuracy [3, 4]. In addition, as shown in Fig. 2 and Table 1, we also confirmed that there was enough information in the activities of the four prime movers to explain the wrist movement for 8 directions. In fact, Fig. 3a shows that the normal control moved the wrist into the targets by activating the proper muscle corresponding to the movement direction [8]. In contrast, the cerebellar patient demonstrated anomaly of muscle activities such as much lower contrasts between activities of agonists and antagonists, and eventually showed a difficulty to move the wrist toward the target (Fig. 3b).

B. Quantification of Pathological Patterns of Muscle Activities

From the EMG signals of the four wrist prime movers, we captured characteristic patterns of the muscle activities for patients with cerebellar ataxia. In other words, we extracted two parameters characterizing the co-contraction and the effectiveness of muscle activities: "Total Co-contraction Level (TCL)" and "Directionality of Muscle Activity (DMA)" in this study.

1) Total Co-contraction Level (TCL): A TCL parameter represents total activities of agonists and antagonists (Fig. 5a). As described in equation (4), the TCL was calculated by averaging the summation of normalized tensions for each muscle with movement duration t to normalize it for movement duration.

$$TCL = \frac{\int \left(\sum_{i=1}^{4} \vec{T}_i \right) dt}{t} \quad (4)$$

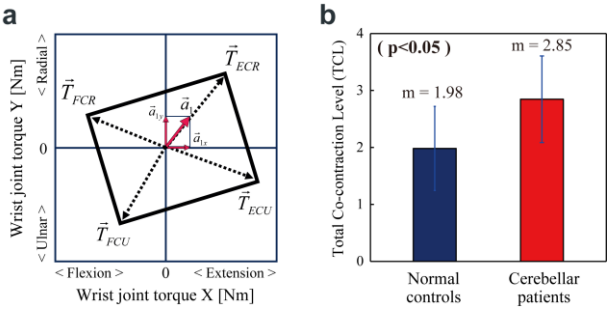

Figure 5. Illustration for Total Co-contraction Level (TCL) (a) and results of TCL parameter for normal controls and cerebellar patients (b)

As shown in Fig. 5b, the TCL for the cerebellar patients (mean value = 2.85) was higher than that for the normal controls (mean value = 1.98)(p<0.05). From this result, we found that cerebellar patients raised the co-contraction of both agonists and antagonists during task when compared to the normal controls.

2) Directionality of Muscle Activity (DMA): A DMA parameter means the effectiveness of muscle activities and was evaluated as the ratio of wrist joint torque to the total muscle torque (Fig. 6a). We first calculated the wrist joint torque from four muscle activities as follows:

$$\left| \vec{\tau}_{EMG} \right| = \sqrt{(\tau_x(t))^2 + (\tau_y(t))^2} \quad (5)$$

where, $\tau_x(t)$ and $\tau_y(t)$ represent X-axis component and Y-axis component of the wrist joint torque estimated from muscle activities using equation (1) and (2), respectively.

Then, as described in equation (6), we calculated the ratio of the wrist joint torque to the TCL, and finally, the DMA was calculated by averaging the ratio value for movement duration t for the normalization.

$$DMA = \frac{\int \left(\frac{|\vec{\tau}_{EMG}|}{TCL} \right) dt}{t} \quad (6)$$

As shown in Fig. 6b, the DMA for the cerebellar patients (mean value = 0.27) was significantly lower than that for the normal controls (mean value = 0.46)(p<0.001). The result indicates that almost muscle activities of the cerebellar patients failed to generate the wrist joint torque, that is, much lower contrasts between activities of agonists and antagonists.

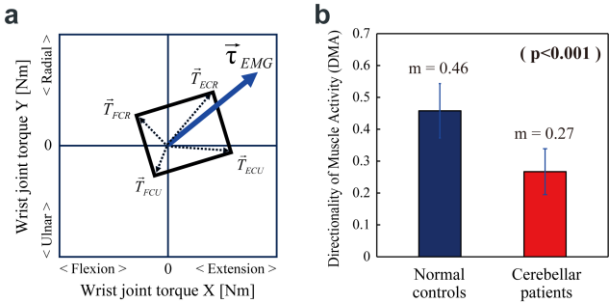

Figure 6. Illustration for Directionality of Muscle Activity (DMA) (a) and results of DMA parameter for normal controls and cerebellar patients (b)

IV. Discussion

In this study, based on the EMG signals, we made a quantitative evaluation of cerebellar ataxia at a level of motor commands. In particular, we captured characteristic patterns of the muscle activities with two parameters, Total Co-contraction Level (TCL) and Directionality of Muscle Activity (DMA). In the following discussion, we will discuss about functional significance of the two parameters and the relationship between the parameters and the cerebellar ataxia.

The TCL represents a co-contraction level of agonists and antagonists. A recent study about TCL reported that the TCL has a linear relationship to the joint stiffness [11]. Our result showed that, the cerebellar patients increased activities of both agonists and antagonists and maintained a high stiffness of the wrist joint (Fig. 5). On the other hand, it is well known that the cerebellar patients manifest muscular hypotonia [1]. Our seemingly contradictory observation may be explained a consequence of adaptation to minimize the impact of the cerebellar ataxia during the step-tracking movements with high stiffness. In other words, the increased TCL of the cerebellar patients may not be a primary deficit of the cerebellar ataxia, but a secondary resulting from the functional action (i.e. adaptation) against the cerebellar ataxia.

The hand is driven into the target by a wrist joint torque resulting from the difference between activities of agonists and antagonists. The DMA represents how effectively the causal muscle activities generated the resultant torque. To make DMA higher, it is desirable to maximize the contrast between activities of agonist and antagonist muscles as typically seen in triphasic EMG patterns [8]. Indeed, the control subjects showed higher values of DMA (Fig. 6b), while the cerebellar patients showed much lower DMA due to much lower contrasts between activities of agonists and antagonists. Consequently, the patients demonstrated much slower movements and dysmetria (Fig. 4). A number of clinical studies also suggested that the cerebellum is essential for a proper agonist selection and determining an appropriate timing and ratio of agonists and antagonists [1, 5]. In other words, DMA appears to parameterize effectiveness of agonist selection that represents the primary role of the cerebellum.

Overall, we found that TCL and DMA are useful parameters characterizing the pathological patterns of muscle activities in cerebellar ataxia. We believe that our proposed method is useful not only in tracking condition of cerebellar patients but also in evaluating the effects of a treatment or neuro-rehabilitation aiming at the normalization of motor commands.

Acknowledgment

We thank Dr. Yasuharu Koike for his invaluable advices for modeling of the wrist joint. We also thank Drs. Takahiro Ishikawa and Saeka Tomatsu for helpful discussions.

References

[1] HC. Diener and J. Dichgans, "Pathophysiology of cerebellar ataxia," Movement Disorders, Vol.7, No.2, 1992, pp. 95-109.

[2] Trouillas P et al., "International Cooperative Ataxia Rating Scale for pharmacological assessment of the cerebellar syndrome. The Ataxia Neuropharmacology Committee of the World Federation of Neurology," J. Neurol Sci., 1997, Vol. 145, No. 2, pp. 205-211.

[3] V. Sanguineti et al., "Cerebellar ataxia: Quantitative assessment and cybernetic interpretation," Hum Mov Sci., 2003, pp. 189-205.

[4] Menegoni F. et al., "Quantitative evaluation of functional limitation of upper limb movements in subjects affected by ataxia," Eur J Neurol. 2009, Vol. 16, No. 2, pp.232-239.

[5] M. Manto, "Pathoplysiology of Cerebellar dysmetria: The imbalance between the agonist and the antagonist electromyographic activities," European Neurology, 1996, pp. 333-337.

[6] J. Lee, Y. Kagamihara, and S. Kakei, "Development of a quantitative evaluation system for motor control using wrist movements—an analysis of movement disorders in patients with cerebellar diseases." *Rinsho Byori*, 2007, pp. 912-921.

[7] Jongho Lee, Yasuhiro Kagamihara and Shinji Kakei, "Quantitative Evaluation of Movement Disorders in Neurological Diseases based on EMG Signals", Conf Proc IEEE Eng Med Biol Soc., 2008, pp.181-184.

[8] DS. Hoffman and PL. Strick, "Step-tracking movements of the wrist. IV. Muscle activity associated with movements in different directions," *Journal of Neurophysiology*, 1999, pp. 319-333.

[9] Y. Koike and M. Kawato, "Estimation of dynamic joint torques and trajectory formation from surface electromyography signals using a neural network model," *Biological Cybernetics*, 1995, pp. 291-300.

[10] A. Mannard and R. Stein, "Determination of the frequency response of isometric soleus muscle in the cat using random nerve stimulation," Journal of Physiology, 1973, pp. 275-296.

[11] Osu R. et al., "Short- and long-term changes in joint co-contraction associated with motor learning as revealed from surface EMG," J Neurophysiol. 2002, Vol. 88, No. 2, pp.991-1004