Pilot Study on Quantitative Assessment of Muscle Imbalance: Differences of Muscle Synergies, Equilibrium-point Trajectories, and Endpoint Stiffness in Normal and Pathological Upper-limb Movements

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Abstract— **This paper proposes a novel method for assessment of muscle imbalance based on muscle synergy hypothesis and equilibrium point (EP) hypothesis of motor control. We explain in detail the method for extracting muscle synergies under the concept of agonist–antagonist (AA) muscle pairs and for estimating EP trajectories and endpoint stiffness of human upper limbs in a horizontal plane using an electromyogram. The results of applying this method to the reaching movement of one normal subject and one hemiplegic subject suggest that (1) muscle synergies (the balance among coactivation of AA muscle pairs), particularly the synergies that contributes to the angular directional kinematics of EP and the limb stiffness, are quite different between the normal subject and the hemiplegic subject; (2) the concomitant EP trajectory is also different between the normal and hemiplegic subjects, corresponding to the difference of muscle synergies; and (3) the endpoint (hand) stiffness ellipse of the hemiplegic subject becomes more elongated and orientation of the major axis rotates clockwise more than that of the normal subject. The level of motor impairment would be expected to be assessed from a comparison of these differences of muscle synergies, EP trajectories, and endpoint stiffness among normal and pathological subjects using the method.**

I. INTRODUCTION

Muscle imbalance, a symptom of hemiplegia, is motor impairment in which muscle activities are inadequately coordinated. The disorder of muscle group activities leads to a decline in motor ability and a lack of movement smoothness. Typical assessment methods of the motor function of hemiplegic patients such as the Fugl–Meyer assessment [1], Brunnstrom recovery stage [2] and stroke impairment assessment set [3] estimate the pathological level by determining whether the subject can perform some specific tasks. These methods are useful for assessing motor outcome but not necessarily enough for assessing the motor command of muscle coordination.

In the field of neuroscience, Bernstein pioneered the concept of synergy. His idea developed to the muscle synergy hypothesis which suggests that the central nervous system controls multiple muscles simultaneously using coordination among muscles to compress the redundant degrees of freedoms (DOFs) and avoid complexity [4]. Moreover, Feldman proposed the equilibrium point (EP) hypothesis of the λ model [5], another leading hypothesis of motor control, which suggests that body movement is produced by two types of motor command: reciprocal and coactivation commands. The former is considered to be associated with the EP of the joint angle (threshold angle) and the latter is considered to be associated with the joint stiffness. According to the muscle synergy hypothesis and EP hypothesis, damaged muscle synergies make it difficult to control EP trajectories and endpoint stiffness. Therefore, the assessment of muscle synergies, EP trajectories, and endpoint stiffness is expected to be a useful index of motor impairment.

To clarify the tacit representation of muscle group activities in voluntary/involuntary movements, we have analyzed the coordination between agonist-antagonist (AA) muscles and proposed the concepts of the ratio of the EMG levels of AA muscles (AA ratio) and the sum of the EMG levels of AA muscles (AA sum) [6]. On the basis of the statistical analysis of AA muscles' activities, we found that the upper-limb movements in a horizontal plane could be explained by two muscle synergies that respectively represent the bases for the radial and angular movements of an endpoint in the polar coordinates centered on the shoulder.

In this paper, we extend the knowledge derived from our statistical analysis and propose a novel method for extracting muscle synergies and estimating the EP trajectories and endpoint stiffness of human upper limbs using a physics analysis of the human musculoskeletal system. To verify the potential of this method for assessment of muscle imbalance, we discuss the differences of tacit motor representations during reaching movement between a normal subject and a hemiplegic subject. In the examination of the proposed method, we focus on the following points: (1) muscle synergies, particularly the synergy that contributes to the angular directional kinematics of EP and the joint stiffness, are quite different between the normal and the hemiplegic

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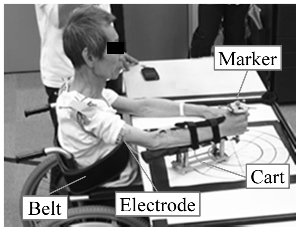

Fig. 1. Experimental setup

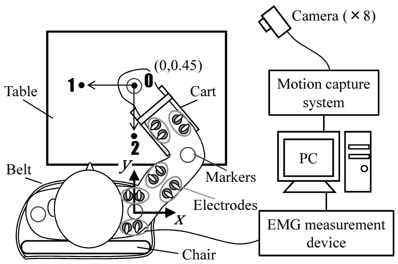

Fig. 2. Schematic illustration of system configuration

subject; (2) the concomitant EP trajectories of these subjects show different behaviors, corresponding to the difference of muscle synergies; and (3) the endpoint stiffness ellipse of the hemiplegic subject becomes more elongated and orientation of the major axis rotates clockwise more than that of the normal subject.

II. METHODS

A. Participants

A healthy subject (male, 61 years old, right-handed) and a hemiplegic subject (male, 74 years old, right-handed, mild-to-moderate right-side hemiplegia caused by stroke) volunteered for the experiment. All subjects gave informed consent and the Institutional Review Board of Osaka University and Senri Chuo Hospital approved the presented procedures.

B. Protocol

Subjects performed reaching movements in two directions in the horizontal plane. The base position of the hand is 0.45[m] front of the right shoulder (point 0). Subjects were instructed move in the orthogonal direction (center to left, and center to near side, with the directions defined as Direction 1 and 2, respectively) in 1.0 [s]. The distance of the reaching movement of normal subject was 0.15 [m], and that of hemiplegic subject was 0.10 [m]. The right forearm and wrist joint of the subjects were fixed on a cart that could move freely in the horizontal plane to compensate for gravity and limit the arm movements to the horizontal plane. The setup and configuration of the experiment are shown in **Fig.** 1 and 2. In the experiment, the following six muscles were measured: deltoid posterior (m_1), deltoid anterior (m_2), triceps long head (m_3), biceps (m_4), triceps lateral head (m_5), and brachioradialis (m_6). EMG signals of the upper limb muscles were measured using a multitelemetor systems (WEB-5000; Nihon Kohden Corp.) and a data acquisition system (Powerlab; AD-Instruments, Inc.) at 1000 [Hz]. EMG data were analyzed after band-pass filtering (10-450 [Hz]), full-wave rectification, smoothing, and normalization to maximum voluntary contraction (%MVC). Each joint position

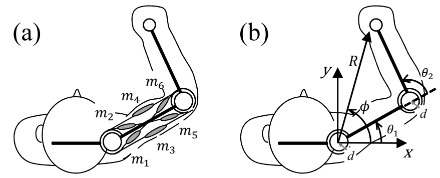

Fig. 3. Simplified model of human upper limb: (a) definition of six muscles; (b) definition of hand position and joint angles

(left shoulder, right shoulder, right elbow, and right hand) was also measured by an optical motion capture system with eight cameras (OptiTrack; Natural Point, Inc.) at 100 [Hz] synchronized with the EMG measurement.

C. Assessment Algorithm

1) Model: Human upper limbs on the horizontal plane were simplified as a two-link structure of three pairs of six muscles as shown in **Fig.** 3(a). The three muscle pairs are the shoulder joint's uniarticular muscle pair (m_1 and m_2), the biarticular muscle pair around the shoulder and elbow joint (m_3 and m_4), and the elbow joint's uniarticular muscle pair (m_5 and m_6). The definition of the hand position and joint angles are shown in **Fig.** 3(b). Here, we made the following three assumptions: (1) a muscle can be described as a spring system whose elastic coefficient and natural length are adjusted according to EMG signal [6]; (2) the same moment arm d of each joint is constant; and (3) the upper arm and forearm have same length L.

2) Muscle synergies: The AA muscle pair ratio (AA ratio) r_i and AA muscle pair sum (AA sum) s_i are defined using muscle activity m_i as [6]

$$r_i = \frac{m_{2i-1}}{m_{2i-1} + m_{2i}}, \quad s_i = m_{2i-1} + m_{2i} \quad (i = 1, 2, 3). \quad (1)$$

The change of joint angles under equilibrium condition are expressed as follows using the AA ratio and AA sum [6]:

$$\boldsymbol{q}_1 = \frac{1}{s_1 s_2 + s_2 s_3 + s_3 s_1} \left[\ s_1 s_2 + s_3 s_1, \quad s_2 s_3, \quad -s_2 s_3\ \right]^T, \quad (2)$$

$$\boldsymbol{q}_2 = \frac{1}{s_1 s_2 + s_2 s_3 + s_3 s_1} \left[\ -s_1 s_2, \quad s_1 s_2, \quad s_3 s_1 + s_2 s_3\ \right]^T, \quad (3)$$

$$\begin{bmatrix} \Delta\theta_1 \\ \Delta\theta_2 \end{bmatrix} = C_1 \begin{bmatrix} \boldsymbol{q}_1^T \\ \boldsymbol{q}_2^T \end{bmatrix} \left[\ r_1 - \tfrac{1}{2}, \quad r_2 - \tfrac{1}{2}, \quad r_3 - \tfrac{1}{2}\ \right]^T, \quad (4)$$

where C_1 is a coefficient determined by the muscle properties and moment arm. Then, we express the displacement of EP in polar coordinates by the AA ratio r_i and the AA sum s_i. As shown in **Fig.** 3(b), the hand position in polar coordinates $\boldsymbol{p} = (R, \phi)^T$ is expressed as follows by joint angles $(\theta_1, \theta_2)^T$:

$$\boldsymbol{p} = \begin{bmatrix} R \\ \phi \end{bmatrix} = \begin{bmatrix} 2L\cos\frac{\theta_2}{2} \\ \theta_1 + \frac{\theta_2}{2} \end{bmatrix}. \quad (5)$$

A small displacement of $\boldsymbol{p}$, $\Delta\boldsymbol{p} = (\Delta R, \Delta\phi)^T$, under the assumption that $\boldsymbol{q_1}$ and $\boldsymbol{q_2}$ are constant around EP, is

$$\Delta\boldsymbol{p} = \boldsymbol{J} \begin{bmatrix} \Delta\theta_1 \\ \Delta\theta_2 \end{bmatrix} = \begin{bmatrix} C_2(\theta_2) & 0 \\ 0 & C_1 \end{bmatrix} \begin{bmatrix} \boldsymbol{q}_2^T \\ (\boldsymbol{q}_1 + \frac{\boldsymbol{q}_2}{2})^T \end{bmatrix} \begin{bmatrix} \Delta r_1 \\ \Delta r_2 \\ \Delta r_3 \end{bmatrix}, \quad (6)$$

where $\boldsymbol{J}(= \frac{\partial(R,\phi)^T}{\partial(\theta_1,\theta_2)})$ is a Jacobian matrix, $C_2(\theta_2)(= -C_1 dL \sin\frac{\theta_2}{2})$ is a coefficient determined by the muscle properties, moment arm, length of link, and angle of elbow joint θ_2 and $[\Delta r_1, \Delta r_2, \Delta r_3]^T$ is $[r_1 - \frac{1}{2}, r_2 - \frac{1}{2}, r_3 - \frac{1}{2}]^T$. **Equation** 6 shows that the displacement of the EP can be estimated from the projection of the AA ratio vector $\Delta \boldsymbol{r}$ onto the subspace that composed of two vectors, $\boldsymbol{q}_2$ and $(\boldsymbol{q}_1 + \frac{1}{2}\boldsymbol{q}_2)$, that are determined by the AA sums. The base radial and angular vectors and orthogonal vector to both the radial and angular directions are as follows:

$$\boldsymbol{u}_R = \boldsymbol{q}_2 / |\boldsymbol{q}_2|, \tag{7}$$

$$\boldsymbol{u}_\phi = (\boldsymbol{q}_1 + \frac{\boldsymbol{q}_2}{2}) / |\boldsymbol{q}_1 + \frac{\boldsymbol{q}_2}{2}|, \tag{8}$$

$$\boldsymbol{u}_{R\times\phi} = (\boldsymbol{u}_R \times \boldsymbol{u}_\phi) / |\boldsymbol{u}_R \times \boldsymbol{u}_\phi|. \tag{9}$$

These basis vectors represent the distribution of the AA ratio vector in each direction. Therefore, $\boldsymbol{u}_R$ and $\boldsymbol{u}_\phi$ are defined as radius and angular directional muscle synergy vector, respectively, and $\boldsymbol{u}_{R\times\phi}$ is defined as null directional muscle synergy vector.

3) EP trajectories: The average of AA ratio is defined as $\bar{\boldsymbol{r}}$. The inner products of each synergy vector and the change in the AA ratio $d\boldsymbol{r}(= \boldsymbol{r} - \bar{\boldsymbol{r}})$, $w_R = \boldsymbol{u}_R.d\boldsymbol{r}$, $w_\phi = \boldsymbol{u}_\phi.d\boldsymbol{r}$, and $w_{R\times\phi} = \boldsymbol{u}_{R\times\phi}.d\boldsymbol{r}$, are defined as muscle synergy scores. Then, ΔR and $\Delta\phi$ are proportional to w_R and w_ϕ, respectively. EP trajectories in polar coordinates are estimated from a linear combination of muscle synergy scores as $R_{est} = k_R w_R + R_0$ and $\phi_{est} = k_\phi w_\phi + \phi_0$, where R_{est} and ϕ_{est} are the radial and angular components of EP trajectory. k_R and k_ϕ are gain constants for transforming muscle synergy scores into the EP trajectories, and R_0 and ϕ_0 are basis positions of EP in polar coordinates. Then, the EP trajectory in Cartesian coordinates $\boldsymbol{x}_{\text{est}}$ is calculated as $\boldsymbol{x}_{\text{est}} = (x_{\text{est}}, y_{\text{est}})^T = (R_{\text{est}}\cos(\phi_{\text{est}}), R_{\text{est}}\sin(\phi_{\text{est}}))^T$.

Here, the null directional muscle synergy does not contribute to the kinematics of the EP, but contributes to regulate the limb stiffness under a dynamic condition [7].

4) Endpoint stiffness: In this model, the stiffness of each muscle is proportional to its level of activity [6]. Here, we defined a constant for converting AA sum $\boldsymbol{s}$ to joint stiffness $\boldsymbol{K}_s$ as k_s[Nm/rad]; then, $\boldsymbol{K}_s$ is expressed as

$$\boldsymbol{K}_s = k_s \begin{bmatrix} s_1 + s_2 & s_2 \\ s_2 & s_2 + s_3 \end{bmatrix}. \tag{10}$$

Next, considering the effect of null directional muscle synergy score to joint stiffness, the absolute value of null directional muscle synergy score is added to each component of joint stiffness $\boldsymbol{K}_s$. We newly defined this new matrix as joint stiffness $\boldsymbol{K}_{s+n}$:

$$\boldsymbol{K}_{s+n} = \boldsymbol{K}_s + k_n \begin{bmatrix} |w_{R\times\phi}| & |w_{R\times\phi}| \\ |w_{R\times\phi}| & |w_{R\times\phi}| \end{bmatrix}, \tag{11}$$

where k_n is a constant for converting the null directional muscle synergy score to additional joint stiffness. The joint stiffness $\boldsymbol{K}_{s+n}$ is transformed by a Jacobian matrix $\boldsymbol{J}_x(= \frac{\partial(x,y)^T}{\partial(\theta_1,\theta_2)})$ to the endpoint stiffness $\boldsymbol{K}_x^{s+n}$:

$$\boldsymbol{K}_x^{s+n} = (\boldsymbol{J}_x^T)^{-1} \boldsymbol{K}_{s+n} \boldsymbol{J}_x^{-1}. \tag{12}$$

Please see [7] for more detail information including the validity of our method.

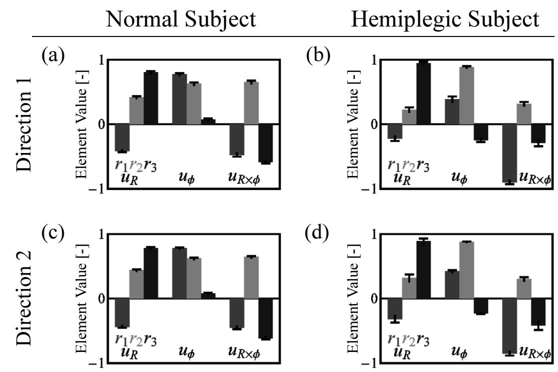

Fig. 4. Muscle synergy vectors during reaching movements in normal and hemiplegic subjects

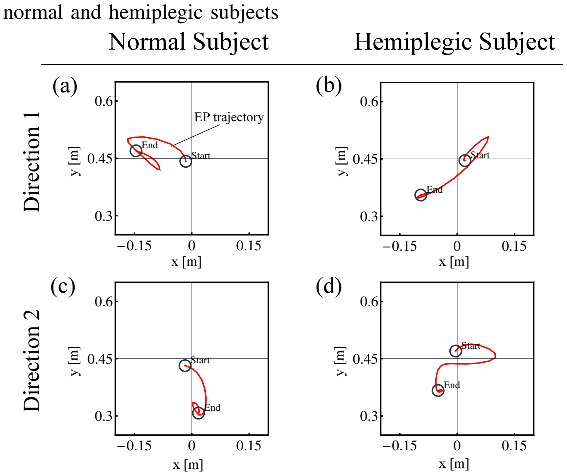

Fig. 5. EP trajectories during reaching movements in normal and hemiplegic subjects

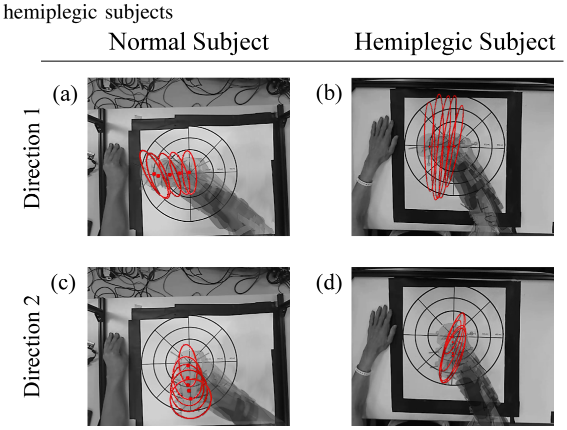

Fig. 6. Endpoint stiffness ellipses during reaching movements in normal and hemiplegic subjects

III. Results

Muscle synergy vectors during reaching movements in normal and hemiplegic subjects are shown in **Fig.** 4. The left group of three bars in each chart represents the radial directional muscle synergy vector $\boldsymbol{u}_R$, the central group represents the angular directional muscle synergy vector $\boldsymbol{u}_\phi$, and the right group represents the null directional muscle synergy vector $\boldsymbol{u}_{R\times\phi}$. Each bar indicates the contribution for each AA ratio. The left blocks are for the normal subject ((a) and (c)) and the right blocks are for the hemiplegic subject ((b) and (d)). EP trajectories are shown in **Fig.** 5. The red lines represent EP trajectories during reaching movements.

Gain constants (k_R and k_ϕ) and basis positions (R_0 and ϕ_0) for EP were regressed from the least squares method using the endpoint (hand) position and muscle synergy scores of the starting and ending points. Stiffness ellipses during reaching movements are shown in **Fig.** 6. Each ellipse was drawn at the starting point, at points 1/4, 1/2, and 3/4 of the distance, and at the ending point, respectively. Note that the values of k_s and k_n differ for each subject; thus, the magnitude of stiffness cannot be compared between subjects directly by the size of the ellipses in these images.

IV. Discussion

A. Validity of Assessment Results

We first verify the estimation results of the EP trajectory. The left blocks in **Fig.** 5 show that EP trajectories estimated from the EMG of the normal subject roughly correspond to the direction of reaching movement. The EP trajectories were, however, distorted from the actual endpoint trajectories. The similar distortion is reported in [8]. Next, we focus on the normal subject's endpoint stiffness. In the horizontal reaching movement (Direction 1), the major axis of the stiffness ellipse almost lay roughly along the direction to the shoulder; moreover, the size of the stiffness ellipse increased at the starting and ending points of the reaching movement and decreased at the mid points of movement as shown in **Fig.** 6(a). In the vertical reaching movement (Direction 2), the shape of the stiffness ellipse became short and thick, and the orientation of the major axis rotated counter clockwise, with the hand position coming closer to the body (**Fig.** 6(c)). These characteristics of the shape and direction of the stiffness ellipse are similar to those obtained in previous studies by mechanical perturbation [9].

B. Quantitative Assessment of Muscle Imbalance

In our experiment, the normal subject and the hemiplegic subject achieved similar endpoint trajectories. (See red points in **Fig.** 6.) However, the muscle synergies, EP trajectories and endpoint stiffness that realize the similar endpoint trajectories were quite different between these subjects.

1) Muscle synergies: The inner products of $\boldsymbol{u}_R$ in each directional movement (Direction 1 and 2) and those of $\boldsymbol{u}_\phi$ were approximately 1.0 in both the normal subject and the hemiplegic subject (**Fig.** 4). This indicates that each subject used same muscle coordination patterns in spite of different movement direction. However, these muscle synergy vectors between normal subject and hemiplegic subject are quite different. The average inner products between the normal and hemiplegic subjects were 0.958 for $\boldsymbol{u}_R$, 0.847 for $\boldsymbol{u}_\phi$, and 0.791 for $\boldsymbol{u}_{R\times\phi}$. The synergies that contribute to the angular directional movement of EP and the endpoint stiffness showed large differences.

2) EP trajectories: In the reaching movements in both Directions 1 and 2, the EP trajectories of the normal subject did not form the straight lines toward target positions but formed slightly distorted curves (**Fig.** 5(a) and (c)). The tendency corresponds to the result previously reported in [8]. The EP trajectories of the hemiplegic subject, however, showed quite different paths toward target positions (**Fig.** 5(b) and (d)). It seems that the EP at the initial stage of the movement particularly tends to fail to move to the target. This inadequate initial trajectory of EP may relate to the feedforward command planned in advance before the movement.

3) Endpoint stiffness: Overall, the stiffness ellipse of the hemiplegic subject became more elongated and orientation of the major axis rotated clockwise more than that of the normal subject. Taking notice of each movement direction, in Direction 1, the stiffness ellipse of the hemiplegic subject became larger at the mid points (**Fig.** 6(b)) whereas that of the normal subject became smaller at mid points (**Fig.** 6(a)). In Direction 2, the stiffness ellipse of the hemiplegic subject remain elongated and orientation of the major axis was almost same (**Fig.** 6(d)). In contrast, the stiffness ellipse of the normal subject became nearly circular and orientation of the major axis rotated counter clockwise when the hand position moved closer to the body (**Fig.** 6(c)).

These differences between the normal subject and the hemiplegic subject in the muscle synergies, EP trajectories, and endpoint stiffness are mainly caused by the differences in the balance/imbalance of muscle co-activations. Since muscle synergies are defined by the balance among AA sums that relate to joint stiffness, the abnormal muscle synergies mean the imbalance among joint stiffness and result in irregular endpoint stiffness. Moreover, the change in endpoint stiffness brings the distortion of concomitant EP trajectories. Thus, the proposed method based on the muscle synergy hypothesis and EP hypothesis has a potential to quantitatively assess the ability of motor control. It is expected that our approach will be applied to practical use for rehabilitation, such as the assessment, diagnosis and treatment for motor impairment.

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