2014 5th IEEE RAS & EMBS International Conference on
Biomedical Robotics and Biomechatronics (BioRob)
August 12-15, 2014. São Paulo, Brazil

Tacit Representation of Muscle Activities during Coordination Training: Muscle Synergy Analysis to Visualize Motor Enhancement in Virtual Trajectory of Multi-Joint Arm Movement

Keitaro Koba, Kenta Murakami, Takanori Oku, Kanna Uno, Pipatthana Phatiwuttipat, Yuto Yamashita, Mitsunori Uemura, Hiroaki Hirai, and Fumio Miyazaki

Abstract— **The tacit representation of muscle coordination has been a major topic of research on motor control since Bernstein's pioneering work. To unravel the mechanisms underlying voluntary movements, we investigated the electromyography signals of six muscles in a non-dominant upper limb during fast spiral movements on a horizontal plane. We considered muscle synergy to be a coordination index that we defined as the balance among co-activations of agonist-antagonist muscle pairs; it is a composite unit related to adjusting the impedance across joints. The virtual trajectory is a time series and is a succession of equilibrium points at the endpoint; it can be represented by the weights for the muscle synergies. Muscle synergy analysis was performed for three healthy subjects before and after voluntary training for eight days. The results revealed that (1) the six muscle activities in a non-dominant upper limb during spiral tracing are explained by three muscle synergies representing the bases for the radial, argumental, and null movements, respectively, of a hand according to polar coordinates centered on the shoulder; (2) the three muscle synergy bases for movements hardly changed with voluntary training kinematics, whereas the kinematics assessment scores for all subjects greatly improved; and (3) the virtual trajectory drastically changed with motor enhancement, especially in the argument direction. When the subjects were asked to perform fast spiral tracing, the polished virtual trajectory formed a beautiful but slightly distorted spiral curve that rotated in the opposite direction of the kinematic trajectory. This may originate from dynamic compensation by the central nervous system. A central factor in motor skill acquisition must be learning a virtual trajectory by considering the dynamic effect of movement especially in the argument direction. Our results imply that virtual trajectories for movements can be learned with invariant bases using polar coordinates, i.e., muscle synergies.**

I. INTRODUCTION

Motor synergy is a tacit representation of coordinated movement in the central nervous system (CNS) to govern and generalize multiple muscle activities with fewer meta-parameters. The hypotheses that coordinated movement may be explained by combining motor synergies or that motor synergies may be building blocks or composite units of motor control have attracted attention in the neuroscience field since Bernstein pioneered the idea of *engrams* [1]. However, the substance of motor synergies is still not well understood. One of the reasons is that it is not under conscious control; although, some researchers have reported that the neuronal population activities in the cortex directly encode the endpoint movement [2]. The most popular approach to investigate motor synergies is based on statistical analysis of state variables such as joint angles and electromyography (EMG) signals, which may be the set of motor states resulting from CNS motor commands based on motor synergies [3][4]. However, the results of statistical factor decomposition are not necessarily interpretable with such explanatory variables even though the factors successfully reduce the dimensionality of movement; therefore, the physical meaning of motor synergies, especially with regard to the equilibrium point (EP) and mechanical impedance, is unclear in most cases. Hogan and Sternad recently showed that kinematic synergies may be an emergent consequence of neuromuscular impedance [5]. To gain deeper insight into the physical meaning of motor synergies, this study examined the agonist-antagonist muscle pair (A-A) concept using the following explanatory variables: the A-A ratio, which is related to the EP, and the A-A sum, which is associated with the mechanical stiffness [6], [7]. The A-A concept can be regarded as comparable to the EP hypothesis (EPH, λ model) [8] and can be extended to the novel concept of EP-based synergies. Since the A-A concept originates from the control of a musculoskeletal robot with agonist-antagonist muscles, the muscle synergy extracted under the A-A concept has a clear physical meaning. The muscle synergy is expressed solely by the A-A sum, which is related to the mechanical stiffness. Based on the A-A concept, we especially focused on enhancing of motor coordination through voluntary training. We used EP-based muscle synergy analysis to investigate (1) how voluntary movement is associated with muscle synergies if muscle synergy is the functional representation of motor control and (2) how voluntary training improves motor skills with motor synergies and a concomitant virtual trajectory (i.e., time series of EP). A motor skill is a set of action units acquired by motor learning, which is a process of enhancing motor commands in order to reproduce a movement with high accuracy, efficiency, and smoothness. Since motor learning is accomplished with

This work was performed at Osaka University. All of the authors are with the Department of Mechanical Science and Bioengineering, Graduate School of Engineering Science, Osaka University. The authors' email addresses are
koba@robotics.me.es.osaka-u.ac.jp
murakami@robotics.me.es.osaka-u.ac.jp
oku@robotics.me.es.osaka-u.ac.jp
uno@robotics.me.es.osaka-u.ac.jp
phatiwuttipat@robotics.me.es.osaka-u.ac.jp
yamashita@robotics.me.es.osaka-u.ac.jp
uemura-m@me.es.osaka-u.ac.jp
hirai@me.es.osaka-u.ac.jp
miyazaki@me.es.osaka-u.ac.jp

978-1-4799-3127-9/6/14/$31.00 ©2014 IEEE

functional and structural changes in the neural system, the muscle synergies and concomitant virtual trajectory may be strongly influenced by such changes. This study focused on the EMG signals of upper limb muscles in the non-dominant arm during fast spiral movement on a horizontal plane before and after repetitive training for eight days and assessed the motor enhancement through the results of EP-based muscle synergy analysis in addition to conventional kinematics assessments such as the spiral test and one-third power law. The coordination training results are expected to contribute to sensorimotor control research [9] in fields such as neuroscience, rehabilitation, and robotics.

II. METHODS

A. Participants

Three healthy voluntary participants (male, 23 ± 1 years old, 1.7 ± 0.1 m, 64 ± 14 kg, right-handed) were enrolled in this study. The protocol conformed to the Declaration of Helsinki, and informed consent was obtained from the subjects as per the Ethics Committee of the Graduate School of Engineering Science, Osaka University.

B. Apparatus

Figure 1 shows the experimental setup, which consisted of a table, chair with harnesses, arm-support cart with low-friction ball wheels, display, motion capture system and EMG measurement device. The non-dominant upper limb (i.e., left upper limb) of a subject was placed on the cart at shoulder height to compensate for gravity and restrict limb motion on the horizontal plane. Both of the right and left shoulders of the subject were fixed to the chair with harnesses.

C. Procedure

Each subject was asked to trace a trajectory between the boundary lines as quickly as possible without touching the lines with his non-dominant arm while monitoring the display showing the ideal trajectory. In this study, the trajectory was a spiral, and the movement direction was clockwise from outside to inside. The spiral on the monitor had a spacing of 1.0 cm between the lines, which was equivalent to 3.5 cm in the task space, and the winding number of the spiral was 5.75. The center position of the spiral was set to correspond to the subject's hand position in his natural posture. The subjects repeated this task twenty times for measurement before voluntary training. The subjects were then asked to practice the spiral tracing fifty times per day for eight days, and the improved spiral tracing was measured twenty times after the voluntary training.

The kinematic data and EMG activity during movements were recorded at the same time. The positions at the shoulder, elbow, and hand of the left upper limb and at the right shoulder were measured with a motion capture system (OptiTrack; NaturalPoint, Inc.) at 100 Hz. The EMG activity of six muscles, which is shown in Fig. 2, were also measured with a multi-telemeter system (WEB5000; Nihon Kohden

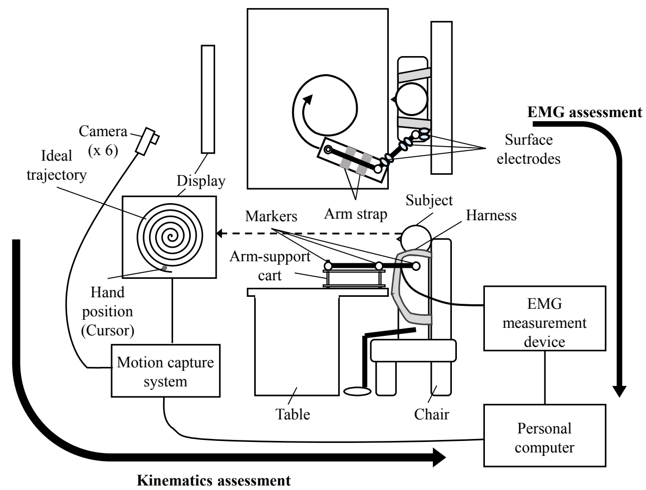

Fig. 1. Experimental setup. The subject traced a spiral trajectory as quickly as possible with his non-dominant arm while monitoring the display showing the ideal trajectory. The performance was evaluated by using both of the kinematics and EMG assessments.

Corp.) that sent EMG data to a personal computer after band-pass filtering (0.03 to 450 Hz), hum filtering (60 Hz) and amplification (x2000). The surface EMG measurement was performed after skin-cleansing (skin resistance was below 10 kΩ). The obtained raw EMG data were then preprocessed by the following procedures: band-pass filtering (10-150Hz), full-wave rectification, low-pass filtering (5Hz), and normalization to maximum voluntary contraction (% MVC).

D. Kinematics Assessment of Motor Learning

We used the following two indices to assess the kinematics before and after training.

1) *Spiral test.* The spiral test is a kinematic measure of coordination for the upper limb function; it is used in rehabilitation as a qualitative assessment to provide feedback to patients with coordination disorders such as Parkinson's disease or cerebellar disorders [10]. Although the subjects in this paper were neurologically and physically whole, we adopted this measure as an index that reflects the evolution of smooth movements with a non-dominant hand through voluntary training. Similar to the way the spiral test is used in rehabilitation, the subjects were scored on the time spent to complete the task the penalty time added for touching or crossing the lines. The score was defined as the sum of the time spent (from start to goal), the number of times the spiral line was touched multiplied by 3, and the number of times the spiral line was crossed multiplied by 5.

2) *One-third power law.* As another evaluation for the hand's trajectory, we computed the relationship between the tangential velocity and curvature radius of the hand's trajectory. Numerous studies have supported the empirical relationship called the one-third power law, which indicates that the hand's tangential velocity in smooth arm movements is proportional to the one-third power of the radius of the

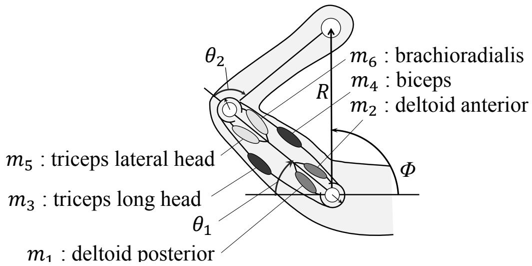

Fig. 2. Human upper limb model. Three agonist-antagonist pairs of muscles are arranged around the shoulder and elbow joints whose lever arms are simply modeled as constants. The kinematic position of the hand is described in polar coordinates centered on the shoulder.

TABLE I

DEFINITIONS AND FUNCTIONS OF A-A RATIO AND A-A SUM.

Symbol	Definition	Function
r_1	$\frac{m_1}{m_1+m_2}$	shoulder-joint angle extension
r_2	$\frac{m_3}{m_3+m_4}$	shoulder- and elbow-joint angle extension
r_3	$\frac{m_5}{m_5+m_6}$	elbow-joint angle extension
s_1	m_1+m_2	shoulder-joint stiffness increase
s_2	m_3+m_4	shoulder- and elbow-joint stiffness increase
s_3	m_5+m_6	elbow-joint stiffness increase

curvature [11]. The systematic relationship between the tangential velocity and curvature radius of the hand's trajectory during planar drawing movements is formulated as

$$v(t) = k\rho(t)^{\frac{1}{3}} \tag{1}$$

where $v(t)$ is the tangential velocity of the hand at time t and $\rho(t)$ is the curvature radius of the hand's trajectory. The parameter k is a gain factor that is related to the movement speed. By taking the logarithm of both sides of (1), the power-law relationship with a constant exponent of 1/3 can be rewritten as the following linear equation:

$$\log v(t) = \log k + \frac{1}{3}\log\rho(t). \tag{2}$$

This relationship may be an index of smoothness of the hand's trajectories [12].

E. EMG Assessment of Motor Learning

Muscle synergy analysis is useful for understanding how the CNS organizes multiple muscles for generating smooth movements [6][7]. The following explains the details of the muscle synergy extraction algorithm for the EMG signals.

Figure 2 shows a simplified human upper limb as a two-link structure with three pairs of muscles: a mono-articular muscle pair around the shoulder joint, bi-articular muscle pair around the shoulder and elbow joints, and mono-articular muscle pair around the elbow joint. These six muscles are described as m_i $(i = 1, 2, \cdots, 6)$. Each A-A muscle pair is a functional unit for characterizing joint movements. Table I lists the motor functions of the A-A muscle pair, which are defined by the following meta-parameters:

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

$$s_i = m_{2i-1} + m_{2i}(i = 1, 2, 3) \tag{4}$$

where m_i indicates the i-th muscle's EMG signal. The A-A ratio r_i contributes to the joint equilibrium angle, and the A-A sum s_i contributes to the joint stiffness [6][7]. For the sake of simplicity, we made the following assumptions: (1) the i-th muscle can be described as a spring system whose elastic coefficient and natural length are adjusted according to EMG signal m_i, as presented in [6][7]; (2) the lever arm of each joint is constant; and (3) the lengths of the upper arm (from shoulder joint to elbow joint) and forearm (from elbow to center of fist) are the same. Then, by using the A-A ratio and A-A sum, the equilibrium displacement of the joint angles can be described by the following equation:

$$\begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} = C\boldsymbol{S}\begin{bmatrix} r_1 - \frac{1}{2} \\ r_2 - \frac{1}{2} \\ r_3 - \frac{1}{2} \end{bmatrix} \tag{5}$$

where C is the coefficient determined by the muscle characteristics and the length of the lever arm and $\boldsymbol{S}$ is a matrix composed of the A-A sum only:

$$\boldsymbol{S} = \frac{1}{A}\begin{bmatrix} s_1s_2 + s_3s_1 & s_2s_3 & -s_2s_3 \\ -s_1s_2 & s_1s_2 & s_2s_3 + s_3s_1 \end{bmatrix} \tag{6}$$

$$A = s_1s_2 + s_2s_3 + s_3s_1$$

As shown in (5), the relationship between the joint angle and A-A ratio means that the latter controls the equilibrium joint angle linearly if the matrix $\boldsymbol{S}$ satisfies the condition of being a constant. However, one problem is motor redundancy: the joint angle vector is two-dimensional, whereas the A-A ratio vector is three-dimensional. The muscle synergy hypothesis has been influential in solving this motor problem [1][13]. We used this hypothesis to introduce a method to extract the muscle synergies from the human musculoskeletal model. As shown in Fig. 2, we defined the endpoint position by using the radius and argument in polar coordinates centered on the left shoulder. The joint angles and endpoint polar coordinates $\boldsymbol{p} = (R, \Phi)^{\mathrm{T}}$ are expressed as follows:

$$\begin{bmatrix} R \\ \Phi \end{bmatrix} = \begin{bmatrix} 2L\cos\frac{\theta_2}{2} \\ \pi - \theta_1 - \frac{\theta_2}{2} \end{bmatrix} \tag{7}$$

where L is the constant length of the upper arm/forearm. If both sides of (5) and (7) are differentiated with respect to time and (6) is assumed to be constant around equilibrium joint angles, the relationship between the hand's EP, A-A ratio, and A-A sum is given as

$$\dot{\boldsymbol{p}} = \boldsymbol{J_r}\dot{\boldsymbol{r}} \tag{8}$$

where

$$\dot{\boldsymbol{p}} = (\dot{R}, \dot{\Phi})^{\mathrm{T}} \tag{9}$$

$$\dot{\boldsymbol{r}} = (\dot{r_1}, \dot{r_2}, \dot{r_3})^{\mathrm{T}} \tag{10}$$

$$\begin{aligned} \boldsymbol{J_r} &= \begin{bmatrix} C_1(\theta_2) & 0 \\ 0 & C_2 \end{bmatrix}\begin{bmatrix} \boldsymbol{q_2}^{\mathrm{T}} \\ (\boldsymbol{q_1} + \frac{1}{2}\boldsymbol{q_2})^{\mathrm{T}} \end{bmatrix} \\ &\cong \begin{bmatrix} C_1 & 0 \\ 0 & C_2 \end{bmatrix}\begin{bmatrix} \boldsymbol{q_2}^{\mathrm{T}} \\ (\boldsymbol{q_1} + \frac{1}{2}\boldsymbol{q_2})^{\mathrm{T}} \end{bmatrix} \end{aligned} \tag{11}$$

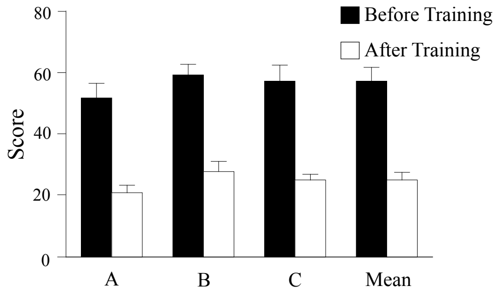

Fig. 3. Change in score of kinematics assessment (spiral test) before and after training

$$q_1 = \frac{1}{s_1s_2 + s_2s_3 + s_3s_1}\begin{bmatrix} s_1s_2 + s_3s_1 \\ s_2s_3 \\ -s_2s_3 \end{bmatrix} \tag{12}$$

$$q_2 = \frac{1}{s_1s_2 + s_2s_3 + s_3s_1}\begin{bmatrix} -s_1s_2 \\ s_1s_2 \\ s_2s_3 + s_3s_1 \end{bmatrix} \tag{13}$$

where $C_1(\theta_2), C_2$ are values determined by the muscle characteristics, link length L, and angle of the elbow joint θ_2; C_2 is a constant and $C_1(\theta_2)$ can be approximated as a constant C_1 in most cases. Note that these have an effect when $\boldsymbol{q_1}$ and $\boldsymbol{q_2}$ are constant. The above equations indicate that the velocity of the hand's EP can be estimated by projecting the velocity vector of the A-A ratio on the vector space made by $\boldsymbol{q_2}$ and $\boldsymbol{q_1}$+1/2 $\boldsymbol{q_2}$. Based on this informative relationship, we defined the synergy vectors as

$$\boldsymbol{u_R} = \frac{\boldsymbol{q_2}}{|\boldsymbol{q_2}|} \tag{14}$$

$$\boldsymbol{u_\Phi} = \frac{\boldsymbol{q_1} + \frac{1}{2}\boldsymbol{q_2}}{|\boldsymbol{q_1} + \frac{1}{2}\boldsymbol{q_2}|} \tag{15}$$

$$\boldsymbol{u_{R\times\Phi}} = \frac{\boldsymbol{u_R} \times \boldsymbol{u_\Phi}}{|\boldsymbol{u_R} \times \boldsymbol{u_\Phi}|}. \tag{16}$$

$\boldsymbol{u_R}$ and $\boldsymbol{u_\Phi}$ indicate the distributions of the A-A ratio vector in the radial and argument directions when centered on the left shoulder. $\boldsymbol{u_{R\times\Phi}}$ is defined as the null vector. It is notable that the synergy vectors consist of the A-A sum only. The inner products of the synergy vectors and the variation in the A-A ratio $w_R = \boldsymbol{u_R} \cdot \dot{\boldsymbol{r}}$ and $w_\Phi = \boldsymbol{u_\Phi} \cdot \dot{\boldsymbol{r}}$ are defined as the synergy scores. According to (8), the velocity of the hand's EP is taken by transforming the synergy score (w_R/w_Φ) in each direction to polar coordinates. The hand's EP (or virtual trajectory) is finally obtained by integrating the velocity over time (see [7] for more details).

III. RESULTS

Figure 3 shows the change in the score of the spiral test before and after training; the line bars on the top of the blocks indicate the standard deviation.

Figure 4 shows the natural logarithmic relationship between the tangential velocity and curvature radius of the hand's trajectory before and after training, where the red line is the approximate straight line.

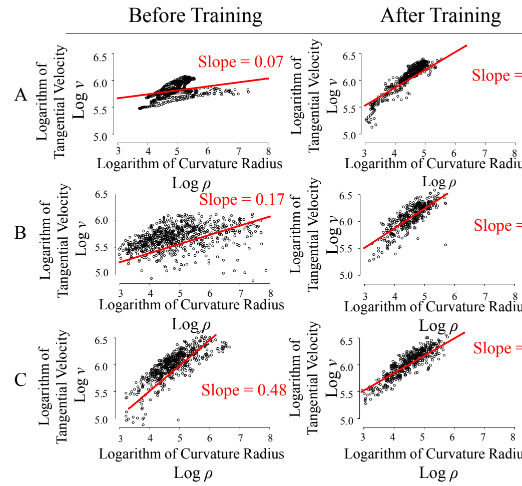

Fig. 4. Change in relationship between tangential velocity and curvature radius (one-third power law) before and after training

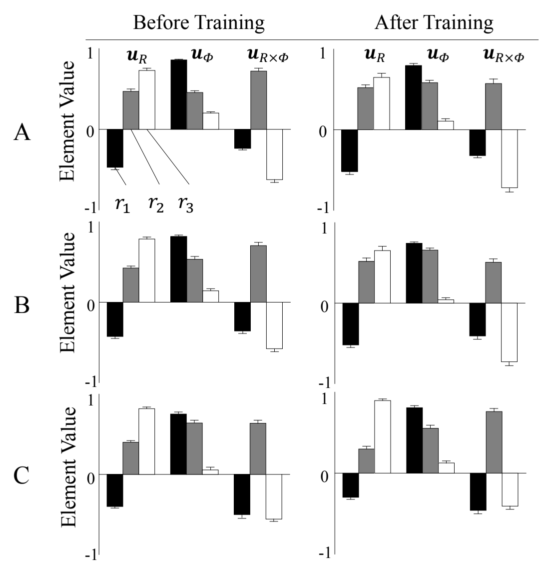

Fig. 5. Synergy vectors. The common coordination patterns were extracted from EMG signals. The synergy vectors hardly changed before and after training.

Figure 5 shows the synergy vectors and the standard deviation of all subjects; the left three blocks indicate the vector of the radius direction $\boldsymbol{u_R}$, the center three blocks indicate the vector of the argument direction $\boldsymbol{u_\Phi}$, and the right three blocks indicate the vector of the null direction $\boldsymbol{u_{R\times\Phi}}$. Figure 6 shows the actual hand trajectory and the virtual trajectory formed by the hand's EP before and after training, where the white and black circles are the start and end points, respectively. Figure 7 shows the trajectories of the radius and argument in polar coordinates centered on a shoulder, where the abscissa is time, the vertical axis are R

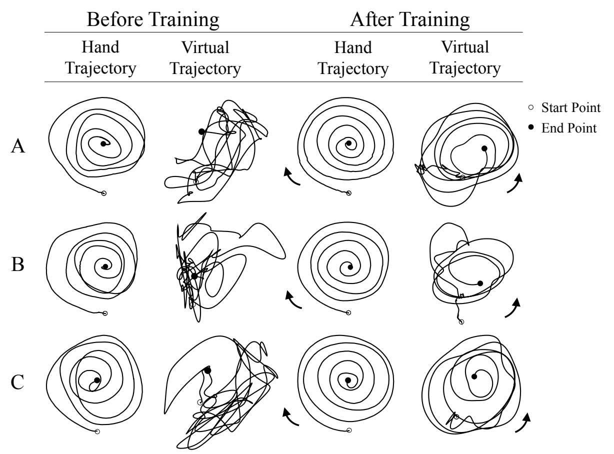

Fig. 6. Changes in hand and virtual trajectories before and after training. The virtual trajectories after training formed spirals whose rotation direction was opposite to that of the kinematic hand trajectories.

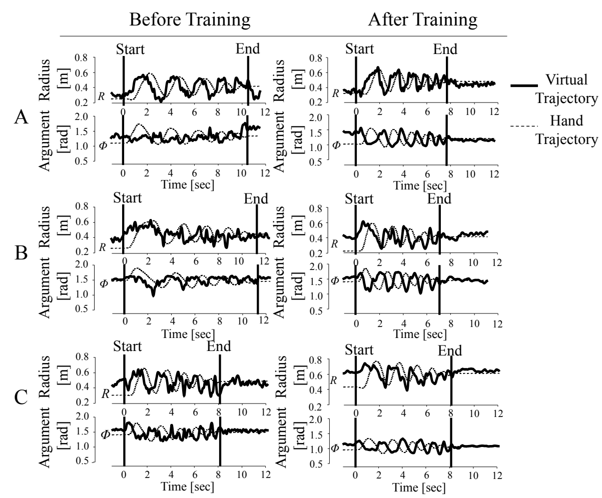

Fig. 7. Transition of hand and virtual trajectories in radius and argument directions before and after training. A drastic change in the virtual trajectories was observed in the argument direction.

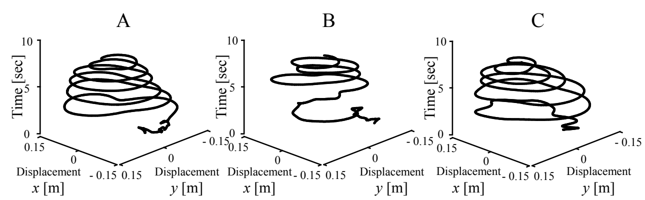

Fig. 8. Virtual trajectories after training (in time and space). A tacit representation based on muscle synergies demonstrated a spiral relating to the kinematic hand trajectories. The results visualize the motor (muscle) representation of hand trajectory. It is interesting to compare with the cortical representation shown in [2].

[m] and Φ [rad], the solid line is the virtual trajectory, and the dashed line is the actual hand's trajectory. Figure 8 shows the virtual trajectories in time and space. The transition of virtual trajectories after training is plotted in Cartesian coordinates.

IV. DISCUSSION

In motor learning research, it is important to present participants with tasks they have not seen outside the lab [14]. The task of tracing a spiral curve displayed on a monitor with a cursor does not usually exist in real life, and the participants were asked to perform this task as quickly as possible with their non-dominant hand. In this section, we discuss how the participants acquired or improved their motor skills through voluntary training in the special environment prepared for motor learning studies.

A. Score of Spiral Test

As shown in Fig. 3, the spiral test of all subjects scores greatly decreased after voluntary training. The average scores were 57.16$\pm$4.17 (mean$\pm$s.d.) before training, and 25.00$\pm$2.53 after training. The decrease in standard deviation also means that the twenty trials after training were more reproducible than those before training. The columns of the hand trajectory in Fig. 6 show the kinematic trajectories of the endpoint; they clearly indicate that the movement skills of the subjects improved with voluntary training. The results are consistent with the scores of the spiral test.

B. One-Third Power Law

In the smooth drawing movements, the slope of the logarithm form of the power-law relationship tends to be 1/3 (or 0.33). The right-side graphs in Fig. 4 illustrate the validity of the one-third power law for the "skilled" spiral tracing after voluntary training. All subjects clearly satisfied this kinematic constraint, which may be related to the smooth trajectory or kinematic structure of the arm [12]. However, the one-third power law was violated by the "unskilled" spiral tracing before voluntary training. The left-side graphs in Fig. 4 show the crude relationship between the tangential velocity and curvature radius of the hand's trajectory. The degree of scattered points may have influenced the score of the spiral test.

C. Muscle Synergies

The muscle synergies represent the balance among co-activations of A-A muscle pairs and are the basis vectors of the virtual trajectory represented in polar coordinates centered on the shoulder. As shown in Fig. 5, the muscle synergies indicated similar coordination patterns among different subjects and hardly changed before and after voluntary training for eight days. That is to say, the effect of the training was not observed with regard to muscle synergies. The inner product values of the synergy vectors in each direction for all subjects before and after training were $0.99\pm6.7\times10^{-4}$ for $\boldsymbol{u_R}$, $0.98\pm7.9\times10^{-3}$ for $\boldsymbol{u_\Phi}$ and $0.97\pm8.0\times10^{-3}$ for $\boldsymbol{u_{R\times\Phi}}$. Similar invariant values were extracted from the movements of all subjects before and after training, although the kinematics of the movements were quite different. This result implies that the muscle synergies may be invariant bases for movements. It is also interesting that the muscle synergies were composed of the A-A sum only, which is a meta-parameter associated with joint stiffness.

D. Virtual Trajectory

The virtual trajectory is the time sequence of equilibrium points representing the static balance positions of the limb endpoint in a musculoskeletal system. The CNS is likely to achieve the virtual trajectory distorted from the actual endpoint trajectory considering the dynamic effects (e.g., inertial force, Coriolis force and centrifugal force) in the course of movement. The important issue for motor control is how the CNS improves and achieves the virtual trajectory with multiple muscle activities. As shown in (6), the EP $\boldsymbol{p} = (R, \Phi)^{\mathrm{T}}$ can be represented as a projection of the A-A ratio vector onto the muscle synergy vectors, i.e., the weights for the muscle synergies. This means that the proposed method allows analysis of the virtual trajectory associated with muscle synergies. Figure 6 indicates the drastic improvement of the virtual trajectories for spiral tracing before and after training. The immature virtual trajectories before training were caused by the clumsiness of the hand trajectories, which resulted in lower scores of the spiral test, while the mature virtual trajectories after training formed beautiful but slightly distorted spiral curves that reflected the dynamic effects of movement. The direction of trajectory progress was inverted between the virtual and actual trajectories: the virtual trajectories progressed counterclockwise, but the actual trajectories progressed clockwise. This interesting phenomenon may originate from the difference between the radial and argumental impedances at the endpoint. The arm stiffness in the argument direction tended to be much smaller than that in the radius direction [15]. This suggests that the arm movement in the argument direction is seriously affected by the dynamic effects during the movement and that the CNS might be required to achieve a distorted trajectory for dynamic compensation. Figure 7 shows the virtual trajectories in the radius and argument directions. In both cases before and after training, the virtual trajectories in the radius direction showed oscillating movements that preceded the actual trajectories with similar sequences showing gradually decreasing amplitudes. On the other hand, the virtual trajectories in the argument direction before training showed poor cyclicity. The disordered trajectories reflect the immature virtual trajectories in Fig. 6. However, the virtual trajectories in the argument direction were greatly improved with the eight days of voluntary training, and the unsophisticated trajectories changed into beautiful cyclic movements that preceded the actual trajectories oscillating almost out of phase (Fig. 7). The polished virtual trajectories after training, plotted in time and space, also show the beautiful cyclicity (Fig. 8). We compared the results with the cortical representation shown in [2]. Figure 8 shows the direct representation of virtual trajectories by EMG activity in the muscle synergy space, while [2] shows the direct representation of hand trajectories by neuronal population activity in the motor cortex. Again, note that the virtual trajectory during fast spiral tracing progressed in the opposite direction of the kinematic trajectory. Thus, the motor learning for the virtual trajectory in the argument direction, which is realized with muscle activities based on the muscle synergy for argument movements, may be closely related to the improvement in motor skill during fast spiral tracing.

These results led us to hypothesize that (1) human arm movement on a horizontal plane may be planned based on three muscle synergies, which are invariant bases for the radial, argumental, and null movements of the endpoint in polar coordinates centered on the shoulder; and that (2) human arm movement can be enhanced by voluntary training to improve virtual trajectories in the muscle synergy space. A key issue in motor learning is acquiring the "appropriate" virtual trajectories that consider the dynamic effect in movements, especially in the argument direction. Future work will include analyzing the virtual trajectories for more subjects and developing synergy-based intervention techniques for motor enhancement.

REFERENCES

[1] M. L. Latash, *Synergy*, Oxford University Press, 2008.

[2] A. B. Schwartz, "Direct cortical representation of drawing." *Science*, vol. 265, no. 5171, pp. 540-542, 1994.

[3] A. d'Avella, A. Portone, L. Fernandez, and F. Lacquaniti, "Control of fast-reaching movements by muscle synergy combinations," *J. Neurosci*., vol. 26, no. 30, pp. 7791-7810, 2006.

[4] N. Dominici, Y. P. Ivanenko, G. Cappellini, A. d'Avella, V. Mondi, M. Cicchese, A. Fabiano, T. Silei, A. D. Paolo, C. Giannini, R. E. Poppele, F. Lacquaniti, "Locomotor primitives in newborn babies and their development," *Science*, vol. 334, no. 6058, pp. 997-999, 2011.

[5] N. Hogan, and D. Sternad, "Dynamic primitives of motor behavior," *Biol. Cybern*., vol. 106, no. 11-12, pp. 727-739, 2012.

[6] H. T. T. Pham, Y. Ariga, K. Tominaga, T. Oku, K. Nakayama, M. Uemura, H. Hirai, and F. Miyazaki, "Extraction and implementation of muscle synergies in neuro-mechanical control of upper limb movement," *Adv. Robo.,* vol. 28, no. 11, pp. 745-757, 2014.

[7] K. Uno, T. Oku, P. Phatiwuttipat, K. Koba, Y. Yamashita, K. Murakami, M. Uemura, H. Hirai, and F. Miyazaki, "A novel muscle synergy extraction method to explain the equilibrium-point trajectory and endpoint stiffness during human upper-limb movements on a horizontal plane," *Proc. 5th IEEE RAS & EMBS Int. Conf. Biomed. Robot. Biomechatron.(BioRob 2014)*(accepted)

[8] A. G. Feldman, S. V. Adamovich, D. J. Ostry, and J. R. Flanagan, "The origin of electromyograms - explanations based on the equilibrium point hypothesis," *Multiple Muscle Systems,* Chapter 12, pp. 195-213, 1990.

[9] F. J. Kottke, D. Halpern, J. K. M. Easton, A. T. Ozel, and C. A. Burrill, "The training of coordination," *Arch. Phys. Med. Rehabil.,* vol. 59, no. 12, pp. 567-572, 1978.

[10] P. H. Verkerk, J. P. Schouten, H. J. Oosterhuis, "Measurement of the hand coordination," *Clinical Neurol. Neurosurg.,* vol. 92, no. 2, pp. 105-109, 1990.

[11] F. Lacquaniti, C. Terzuolo, P. Viviani, "The law relating the kinematic and figural aspects of drawing movements," *Acta Psychol.,* vol. 54, pp. 115-130, 1983.

[12] S. Schaal, and D. Sternad, "Origins and violations of the 2/3 power law in rhythmic three-dimensional arm movements," *Exp. Brain Res.,* vol. 136, no. 1, pp. 60-72, 2001.

[13] N. Bernstein, *The co-ordination and regulation of movements*, Oxford, Pergamon Press, 1967.

[14] D. M. Wolpert and J. R. Flanagan, "Q&A: Robotics as a tool to understand the brain," *BMC Biol.*, vol. 8, no. 1, pp. 92-94, 2010.

[15] H. Gomi, M. Kawato, "Human arm stiffness and equilibrium point trajectory during multi-joint movement," *Biol. Cybern.,* vol. 76, no. 3, pp. 163-171, 1997.