Muscle Synergy Analysis for Similar Upper Limb Motion Tasks

Lu Tang, Fei Li, Shuai Cao, Xu Zhang, Xiang Chen

Abstract—**Muscle synergy is considered as a vector specifying a pattern of relative muscle activation. The goal of this paper is to explore whether there exists similarities between muscle synergies in similar upper limb motion tasks. One center-out-center reaching task and two path movement tasks with regard to the elbow and shoulder joints were designed, and seven healthy adults were recruited in this study. Surface electromyographic (sEMG) signals were recorded from 10 upper arm and shoulder muscles, and muscle synergies were extracted using nonnegative matrix factorization algorithm. Although there existed individual differences among subjects, experimental results showed that the structures of muscle synergies extracted from these three similar tasks were similar on the ground of the values of Pearson's correlation coefficient was greater than 0.85. Through this finding, the neuromuscular control strategies of upper limb in similar tasks could be explained clearly, which also provided significant evidence to support the hypothesis of muscle synergies.**

I. Introduction

Human activities are extremely complicated in terms of both neural activation and biomechanical output [1, 2]. Most studies in neuroscience focus on how the Central Nervous System (CNS) overcomes the complexity of human dynamics and coordinates the large number of muscles to achieve different kinds of behavioral goals [3]. Describing the control mechanism of CNS precisely is still an unsolved problem in this field, and some researchers put forward the hypothesis that diverse motor behaviors are generated by a relatively low-dimensional organizational structure. According to this hypothesis, the CNS controls co-activated muscles to reduce the complexity of the motor control. In recent years, plenty of evidences in support of the view that the CNS may generate motor commands through a linear combination of a set muscle synergies have been presented [4-7].

Muscle synergy is considered as a vector specifying a pattern of relative muscle activation. Under this assumption, the absolute activation of each synergy is presumed to be modulated by a single neural command signal, and the pattern of the activation across multiple muscles may be unique to each individual [8]. A single muscle can simultaneously belong to multiple synergies, and the degrees of activation of muscles that belong to one muscle synergy are fixed. To simplify the large number of Degrees of Freedom (DOFs) in the musculoskeletal system during movements, muscle synergies must be limited in quantity and robust across tasks [9]. Previous studies have indicated that EMG data recorded form a series of motor tasks, for example postural responses in animals, walking and upper limb reaching in humans, can be decomposed into limited muscle synergies [4, 5, 10-14]. D'Avella and Bizzi observed that five functional muscle synergies extracted from walking, jumping, and swimming of frogs were similar, and three synergies of the five were shared across behaviors whereas others are behavior-specific [12]. Ivanenko found that five basic temporal activation components were likely to be controlled and shared by cooperating with voluntary motor tasks across walking, during which subjects kicked a ball, stepped over an obstacle, or reached down and grasped an object on the floor [14]. Although these achievements have proved the hypothesis of muscle synergies in their respective ways, related studies still have their limitations and more evidences to support the hypothesis are needed.

In order to verify the hypothesis further and get more understanding of the neuromuscular control strategies of similar tasks, this study aims to conduct muscle synergy analysis of upper limb motions. The related research, such as D'Avella et al. found that the muscle activity of upper limb during diverse movements can be characterized by a definite set of muscle synergies [13]. Moreover, P. Tropea1 et al. compared the muscle synergies of upper limbs in stroke patients and healthy subjects, and observed that the difference can reflect the functional deficit induced by the pathology [10]. Different from their works, an experimental scheme with more complex and macroscopic tasks including three similar tasks related to the movement of the upper limb is put forward in this study. More specifically, we try to explore whether similar upper limb motion tasks share fully or partly the same muscle synergies. This study can also provide the basis to explore the control strategies of upper limb movements in patients with neuromuscular disease.

II. Method

A. Subjects

Seven healthy adults (4 males and 3 females, and with average ages of 23±4.1) were involved in this study, who are all right-hand dominant, with no known neurological diseases, no muscular or skeletal impairments history of the upper limbs and the trunks, and no functional abnormalities. Before starting the experimentations, each subject had signed an informed consent.

B. Three similar motion tasks

Subjects were seated upright in front of an adjustable table and carried out all the tasks in the horizontal plane. In order to restrain wrist and trunk movements, they were fastened with the bandage. Subjects were instructed to carry out a series of trails (15-20 times per task) including the following tasks:

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1) One center-out-center reaching task (Exp1): Subjects were asked to perform this task clockwise from the center point to eight equidistant points arranged along the circumference of a horizontal panel by holding a cylinder (Fig. 1A, high: 8cm; radius: 1.5cm, starting from the top point).

2) Two path-movement tasks (Exp2 and Exp3): Subjects performed path-movement task staring from the center and moving cylinder along the direction of the arrow as shown in Fig. 1B and Fig. 1C.

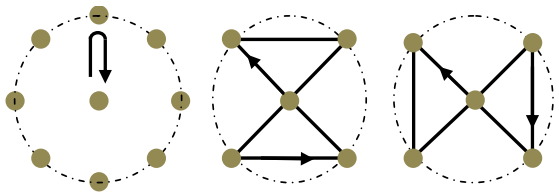

Figure 1. A: Center-out-center reaching task (clockwise from the top point); B and C: Path-movement tasks. Dashed circle radius is 20cm. All the tasks were started from the center point. In the Exp2 and Exp3, subjects were asked to move cylinder along the black line.

The route and direction of center-out-center reaching task and path-movement tasks were partly the same. During the experiment, subjects tried to keep the speed at 16 (cm/s) and the wrist and forearm should always touch the table to overcome the gravity of the forearm. Before starting the experiment, subjects performed a simple learning under the guidance of professionals in order to complete the tasks smoothly.

C. Data Acquisition

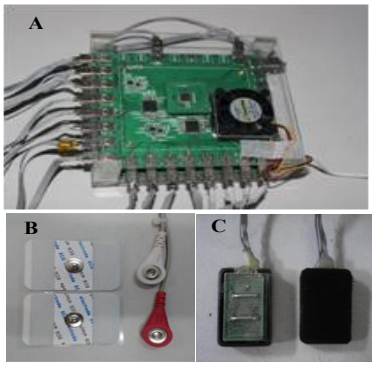

Figure 2. A: Home-made 16-channel sEMG system; B: disposable self adhesive electrodes; C: bipolar Ag-AgCl surface electrodes.

As the subjects performed the tasks, sEMG signals were recorded from 10 upper arm and shoulder muscles including: brachioradialis (BRAD), brachial (BRAC), biceps brachii(BIC), triceps brachii (TRI), anterior deltoid (DELA), medial deltoid (DELM), posterior deltoid(DELP), latissimus dorsi (LAT), upper trapezius (TRAP), and pectoralis major (PECM). In order to get higher quality of sEMG signals, three bipolar Ag-AgCl surface electrodes were placed on BRAD、BIC and TRI and seven disposable self adhesive electrodes were placed on the other muscles. Electrodes were placed in accordance with the guidelines of surface EMG for noninvasive assessment of muscles (SENIAM) [15]. The reference electrode was placed over the left electrically neutral lateral epicondyle [10]. Each recorded site was cleaned with alcohol before placing the electrodes. All the data were collected by a home-made 16-channel sEMG system (Fig.2) and the sampling rate was set to 1000Hz. All data were saved and then analyzed with Matlab 7.1.4 (The Mathworks, Natick, MA).

D. Extraction of muscle synergies

Before extracting muscle synergies, the collected sEMG signals were pre-processed according to the following steps: high-pass-filtering (window-based finite impulse response filter, 50th order, cutoff at 40 Hz), rectification, and low-pass-filtering (window-based finite impulse response filter, 50th order, cutoff at 20 Hz). Each row of the pre-processed sEMG matrix ($\boldsymbol{V_{m\times t}}$, $\boldsymbol{m}$ is the number of muscles and $\boldsymbol{t}$ is recorded time) [16] was normalized with respect to its' sub-maximal [17] and sampled into 1000 points. After decomposing $\boldsymbol{V_{m\times t}}$ data matrix with nonnegative matrix factorization algorithm, two matrices ($\boldsymbol{C_{n\times t}}$ and $\boldsymbol{W_{m\times n}}$, $\boldsymbol{n}$ is the number of synergies) would be identified, where $\boldsymbol{W_{m\times n}}$ is muscle synergy matrix and $\boldsymbol{C_{n\times t}}$ is synergy activation coefficient matrix. A vector of $\boldsymbol{W_{m\times n}}$ represents the relative weighting of muscles in each module and the coefficient $\boldsymbol{C_{n\times t}}$ represents the neural command that specifies how much each synergy will contribute to a muscle's total activity pattern [18]. Therefore, the muscle activation pattern $\boldsymbol{V_{m\times t}}$ can be reconstructed as the equation $\boldsymbol{V_{m\times t}' = W_{m\times n} \times C_{n\times t}}$.

The minimum number of muscle synergies were calculated according to the variability accounted for ($\boldsymbol{VAF}$) shown in formula (1) [19], which was used as squared error values.

$$\boldsymbol{VAF = 1 - (V_{m\times t} - V_{m\times t}')^2 / V_{m\times t}} \qquad (1)$$

To ensure the extracted muscle synergies can adequately compose the sEMG signals, the $\boldsymbol{VAF}$ were estimated by increasing gradually the number of the synergy (starting from 1). The minimum number of muscle synergy was not determined until the minimum $\boldsymbol{VAF}$ was greater than 95%. The averaged muscle synergy matrix of all the trials of a task was used to represent the muscle synergy matrix for each subject. After grouping, the average of muscle synergy matrix of all the subjects was used to represent the muscle synergy matrix of each task.

E. Similarity analysis between synergies

Similarities between muscle synergies extracted from three tasks were analyzed. Firstly, muscle synergy from each subject was extracted respectively. For each task, similar muscle synergy patterns across subjects were grouped based on the best-matching of vectors in $\boldsymbol{W_{m\times n}}$ matrix. Similarity between muscle synergies was determined by the Pearson's correlation coefficient ($\boldsymbol{r}$). The greater $\boldsymbol{r}$ value means the higher matching degree. Two muscle synergies were considered to be "similar" when r is larger than 0.85 [17].

III. Result and Analysis

The extracted muscle synergy modules of center-out-center reaching task and the two path-movement tasks are shown in Fig. 3, Fig. 4 and Fig. 5 respectively. Group means and standard deviations of seven subjects' muscle synergies are represented by black bar profiles and red bar in the figures. For all the seven subjects, four muscle synergies were extracted from sEMG signals during the three similar tasks. For each task, the similar structures of muscle synergies were grouped. After grouping, the macroscopic scale signified certain regularity.

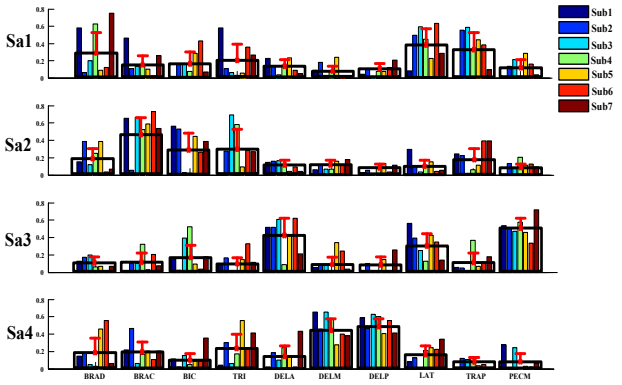

Figure 3. Four muscle synergies extracted from Exp1. Colourized bars show the relative weighting of a muscle and black bar with red represent group means and standard deviations. One subject corresponds to a fixed colour. Labels on the horizontal axis are ten muscles and labels on the vertical axis are four muscle synergy (Sa1, Sa2, Sa3, Sa4).

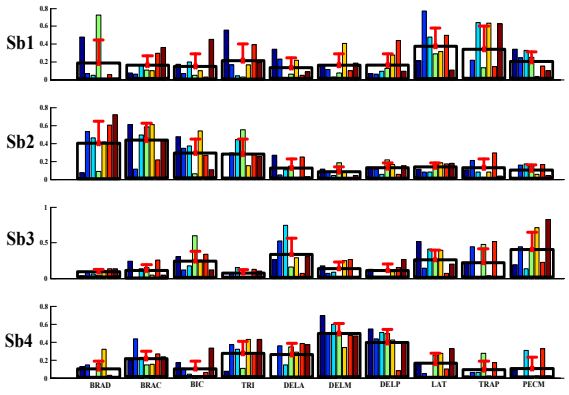

Figure 4. Four muscle synergies (Sb1, Sb2, Sb3, Sb4) extracted from Exp2.

From the hypothesis of muscle synergy, each muscle synergy represents a characteristic pattern of muscle activation. From Fig. 3, we can observe that the first synergy (Sa1) reflects mainly the activity of BRAD, LAT and TRAP; the second synergy (Sa2) consists of BRAD, BRAC, BIC and TRI; the third synergy (Sa3) is mainly characterized by BIC, DELA, LAT and PECM whereas the fourth synergy (Sa4) is loaded by BRAC, TRI, DELA, DELM and DELP.

Fig. 4 and Fig. 5 are similar to Fig.3 in the number and structure of the extracted muscle synergies. Specially, the structures of the third synergy (Sb3 and Sc3) and the fourth synergy (Sb4 and Sc4) are respectively similar to Sa3, Sa4. However, the contribution of BRAD in Sb1 is lower than Sa1 and the contribution of BRAD in Sb2 is higher than Sa2. For the Exp3, the activity of LAT in Sc1 is lower than Sa1 and the contribution of BRAC in Sc2 is lower than Sa2.

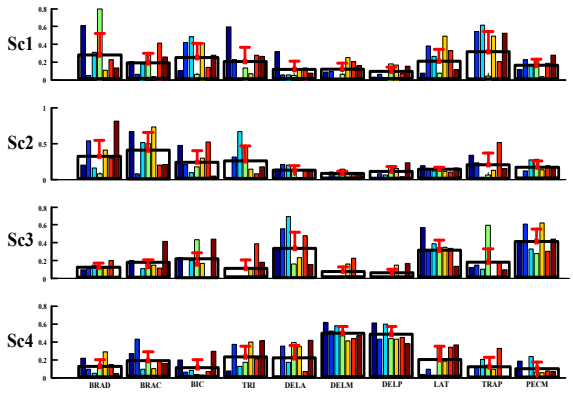

Figure 5. Four muscle synergies (Sc1, Sc2, Sc3, Sc4) extracted from Exp3.

TABLE I. Individual Differences Analysis For Muscle Synergy Sa1

	Sub1	Sub2	Sub3	Sub4	Sub5	Sub6	Sub7
BRAD	+	-	+	-	+	+	-
BRAC	-	+	+	+	+	-	+
BIC	-	+	+	+	+	-	+
TRI	-	+	+	+	+	+	+
DELA	+	+	-	+	+	+	-
DELM	+	-	+	+	+	+	+
DELP	+	+	+	+	+	+	-
LAT	-	+	+	+	+	-	+
TRAP	-	+	-	+	+	+	-
PECM	-	+	+	+	-	+	+

a. The significant difference level of each muscle between individual and the others in Sa1. (Student's t test: The symbol of '+': P>0.05 and '-': P<0.05)

To explore further the similarities of the muscle synergies extracted from Exp1, Exp2 and Exp3, r values between synergies of the three similar tasks were calculated and given in Fig. 6. The regions with the more deep red represent the bigger similarities between two synergies. In Fig. 6, the red regions almost appear in the direction of oblique 45 degree, except the ones corresponding to Sb1-Sc1. This result demonstrates that the corresponding muscle synergies are very similar in the three similar tasks. Further, the average of muscle synergies between subjects was used as representative for each task, and then the r values were computed between tasks. Finally, r values of 0.86, 0.90 and 0.91 were obtained between Exp1 and Exp2, Exp2 and Exp3, and Exp1 and Exp3 respectively. Due to all the r values are larger than 0.85, the muscle synergies extracted from these three tasks can be considered as "similar".

However, although macroscopic scale signifies certain rules, there exist differences among subjects and muscles. Based on the comparatively analysis of the three tasks shown in Fig. 3 to Fig. 5, we find that subject 4 show big individual differences in most of the extracted muscle synergies, and the activation degrees of BRAD and TRI in Sa1, Sb1 and Sc1 of subject 1 are much higher than those of the others. From the further analysis (as an example, analysis result of Sa1 with student's t-test is given in Table I.), subjects are found to show different individual differences. As shown in Table I, six muscles have significant differences between subject 1

and the others, so subject 1 has the greatest individual differences in Sal. We suppose that different habits of upper limb movement between subjects lead to these individual differences. Also, differences between muscles are found. BRAD and TRAP have significant individual differences in three subjects respectively, but TEI, DELM, and DELP show significant differences in only one subject. The location errors caused by the small size of BRAD and the noise related to voluntary neck movements during experiments are considered to be the major factors resulting in individual differences between muscles.

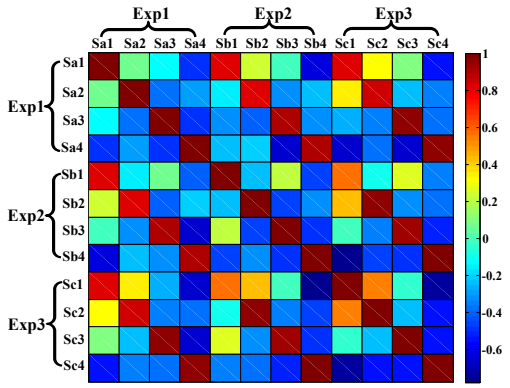

Figure 6. The relationship between muscle synergies in three similar tasks.

IV. CONCLUSION

Focusing on the hypothesis that the CNS may generate motor commands through a linear combination of fixed muscle synergies, this paper explored preliminarily the similarities of muscle synergies between three similar tasks with regard to the movements of elbow and shoulder joints. Muscle synergies were extracted based on sEMG signals from 10 upper limb and trunk muscles with NMF algorithm. As a result, four similar muscle synergies were extracted in three tasks respectively, which indicated that the CNS could control the three movement tasks by recruiting four similar muscle synergies. Thus we supposed that the four similar modules were the basic muscle synergies related to the flexing/extending movements of elbow and shoulder joints. When people carried out upper limb motions, CNS might recruit these four similar muscle synergies to complete the corresponding movement. However，there existed individual differences caused by subject's habits of upper limb movement, the location errors of electrode and noise related to voluntary movements. The finding of this study is beneficial to support the hypothesis of muscle synergies, and also provides the basis for us to further explore the control strategies of upper limb movements in patients with neuromuscular disease.

Although this study has provided significant evidence to support the hypothesis that diverse motor behaviors are generated by recruiting the limited muscle synergies, the limited tasks and subjects, however, may influence the reliability of this research. In future work, we will design more representative tasks, and recruit more subjects to further verify the conclusion.

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REFERENCES

[1] G. L. Gottlieb, "Muscle activation patterns during two types of voluntary single-joint movement," J Neurophysiol, vol. 80, 1998, pp. 1860–1867.

[2] D. A. Winter and H. J. Yack, "EMG profiles during normal human walking: strideto- stride and inter-subject variability," Electroencephalogr Clin Neurophysiol, vol.67, 1987, pp. 402–411.

[3] N. A. Bernstein, The Coordination and Regulation of Movements. Oxford, UK: Pergamon Press, 1967.

[4] E. Bizzi, V. C. K. Cheung, d'Avella A, Saltiel P, "Combining modules for movement," *Brain Res Rev*, 2008, vol. 57, pp. 125–133.

[5] A. d'Avella et al., "Combinations of muscle synergies in the construction of a natural motor behavior," *Nature neuroscience*, vol. 6, Mar-2003, pp. 300–8.

[6] P. Saltiel, K. Wyler-Duda, A. d'Avella, M. C, "Muscle synergies encoded within the spinal cord: Evidence from focal intra spinal NMDAiontophoresis in the frog," *J Neurophysiol*, vol. 85, 2001, pp. 605–619.

[7] P.Saltiel, K. Wyler-Duda, A. d'Avella, R. J. Ajemian, "Localization and connectivity in spinal interneuronal networks: The adduction–caudal extension flexion rhythm in the frog," *J Neurophysiol*, vol. 94, 2005, pp. 2120–2138.

[8] L. H. Ting and J. McKay, "Neuromechanics of muscle synergies for posture and movement," *Current opinion in neurobiology*, vol. 17, Dec-2007, pp. 622–8.

[9] L. H. Ting and J. Macpherson, "A limited set of muscle synergies for force control during a postural task," *Journal of neurophysiology*, vol. 93, pp. 609–13, Jan-2005.

[10] P. Tropea1, V. Monaco1, "Effects of early and intensive neuro-rehabilitative treatment on muscle synergies in acute post-stroke patients: a pilot study," *Journal of NeuroEngineering and Rehabilitation,* 2013, vol. 10, pp.103-117.

[11] O.G. Torres, J. M. Macpherson, L. H. Ting, "Muscle synergy organization is robust across a variety of postural perturbations," *J Neurophysiol*, vol. 96, 2006, pp. 1530-1546.

[12] A. d'Avella and E. Bizzi, "Shared and specific muscle synergies in natural motor behaviors," Proc Natl Acad Sci USA, vol. 102, 2005, pp. 3076–3081.

[13] A. d'Avella, A. Portone and L. Fernandez, "Control of Fast-Reaching Movements by Muscle Synergy Combinations," *The Journal of Neuroscience*, vol. 26, 2006, pp. 7791–7810.

[14] Y. P. Ivanenko et al., "Coordination of locomotion with voluntary movements in humans," *J Neurosci*, vol. 25, 2005, pp. 7238–7253.

[15] H. J. Hermen, B. Freriks, C. K. Disselhorst, G. Rau, "Development of recommendations for SEMG sensors and sensor placement procedures," *J Electromyogr Kinesiol*, vol. 10, 2000, pp. 361–374.

[16] D. Lee and H. Seung, "Learning the parts of objects by non-negative matrix factorization," *Nature*, vol. 401, 1999, pp. 788–91.

[17] J Yang and D. Winter, "Electromyographic amplitude normalization methods: improving their sensitivity as diagnostic tools in gait analysis," *Archives of physical medicine and rehabilitation*, vol. 65, 1984, pp. 517–21.

[18] F. Li, "Lower-limb muscle synergies in children with cerebral palsy" *2013 IEEE Int. Conf. Conference on Neural Engineering,* pp. 1226–1229.

[19] D. Clark, et al, "Merging of healthy motor modules predicts reduced locomotor performance and muscle coordination complexity," *J Neurophysiol*, vol. 103, 2010, pp. 844-857.