Effects of Contraction Path and Velocity on the Coordination of Hand Muscles During a Three-digit Force Production Task

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***Abstract*— Though many studies indicated that the behavior of single muscle was different between contraction and relaxation, the effect of contraction history profile on multiple muscles has not been investigated. In this study, we analyzed the influence of contraction history on the coordination patterns of hand muscles during a three-digit force production task. The effects of the contraction and relaxation paths with two contraction velocities (5% and 10% maximum voluntary contraction per second) were investigated. The results showed that the force-independent characteristic of muscle coordination patterns still held regardless of the contraction history profiles. In addition, the effect of contraction path was more significant than that of velocity. The study provides a potential way to overcome the impact of contraction disturbance for improving the robustness of the human-machine interface (HMI) based on electromyographic (EMG) pattern recognition.**

I. INTRODUCTION

The production of human hand movements relies on the coordination of multiple hand muscles [1]. Based on the complex biomechanical architeture of the hand, people can achieve a wide variety of postures with different forces during manipulative actions [2]. The neural mechanisms underlying the coordination of hand muscles for posture force production have been investigated by many researchers through recording the electromyographic (EMG) signals of the corresponding muscles [1], [3], [4], [5], [6].

Valero-Cuevas studied the single-digit force production task and revealed that the EMG activity scaled linearly with force across multiple hand muscles [3]. Poston *et al*. extended the work of Valero-Cuevas and found that the finding also applied to the multiple-digit situation, i.e., EMG amplitude of hand muscles scaled uniformly as a function of grasp force for a given motion [4]. Their work provided significant insight into how hand muscle patterns change during the modulation of the output force.

However, their studies were all based on the experiment where the digit force was increased from zero to the target level, i.e., the contraction history profile was not considered in the experiment. They did not compare the performance of muscles under different contraction profiles. Ridgway *et al*. investigated the magnitude of force when calcium concentration was decreasing and increasing and found the existence of hysteresis in the force-calcium relationship [7]. Kamavuako *et al*. further revealed that hysteresis was also present in the EMG feature-force relationship [8]. Orizio *et al*. studied the strategy of motor units activation and deactivation and indicated that the deviation existed between these two strategies and the threshold of motor unit recruitment and de-recruitment might be influenced by the up-going or down-going contraction speed [9].

These studies proved that the behavior of a single muscle was different between the contraction and relaxation. So the contraction profiles may have an effect on the coordination of multiple muscles through influencing the behavior of the single muscle. On this basis, the aim of this study was to investigate whether the contraction history had an influence on the muscle coordination patterns during the force production task. A three-digit grasp experiment was designed with four different contraction profiles to reach the target force level. The effects of contraction path and contraction rate had been investigated by comparing the similarity of the corresponding muscle activation pattern (MAP) vectors.

II. METHODS

A. Data acquisition

Four right-handed adults (all males, 21 - 28 years old) participated in the study. All subjects were healthy and reported no history of neurological disorders. They provided informed consent before the experiment and all the procedures were in accordance with the Declaration of Helsinki.

The subjects were asked to sit in an adjustable chair and perform a three-digit grip with their right hands. The experimental setup is presented in Fig 1. The commercial dynamometer (Biometrics Ltd., UK) was used to measure the magnitude of the grip force. The sampling frequency was set to 50 Hz. During the experiment, the participants needed to keep their wrists halfway between pronation and supination. The thumb tip was positioned on the convex part at the middle of one bar. The index and middle fingertips were positioned on the concave part at the two ends of another bar.

The sEMG signals were recorded by a commercial myoelectric system (Biometrics Ltd., UK, 10-450 Hz band pass filter) with 1000 Hz sampling frequency. The myoelectric electrodes were attached on five hand muscles, which were related to the movement of the thumb, index and middle fingers. The investigated muscles were the extensor digitorum communis, extensor pollicis brevis, flexor pollicis longus, flexor digitorum superficials and flexor digitorum profunds.

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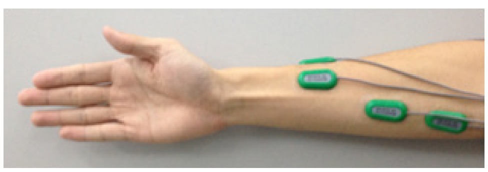
Fig. 1. Experimental Setup. The dynamometer is fixed on the table, and the cushion is placed under the wrist of the subject to make the subject comfortable. The digits are asked to put on the convex and concave part to constrain the movement.

The locations of electrodes are shown in Fig. 2. Before electrodes placement, the skin was cleaned with disposable alcohol pads to reduce impedance.



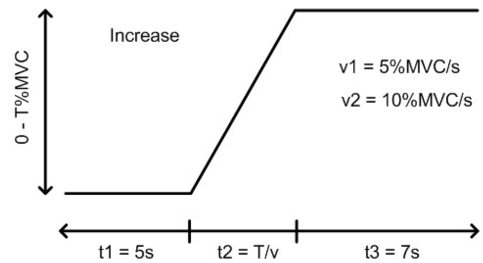
(a)

(b)

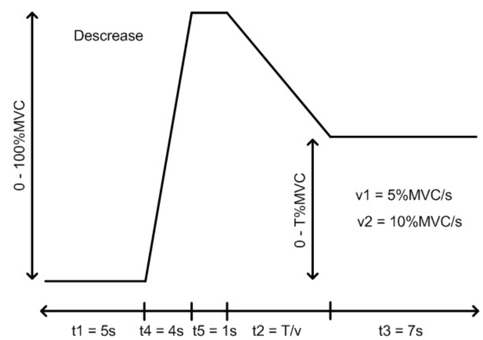
Fig. 2. Placement of EMG electrodes on the forearm: (a) anterior view, (b) posterior view. The five investigated muscles are extensor digitorum communis, extensor pollicis brevis, flexor pollicis longus, flexor digitorum superficials and flexor digitorum profunds.

The values of maximum voluntary contraction (MVC) needed to be obtained at the beginning of the experiment. The subjects were asked to increase their grasp force as much as possible and maintain the contraction for 3 seconds. The procedure was repeated three times and no visual feedback was provided to the subjects. The average value of the three trials was used as a reference to compute the fore values for the following submaximal contraction task. There was a period of 3 min for rest between trials to avoid fatigue.

The contraction profiles are shown in Fig. 3. There were a total of three target force levels, 30% MVC, 50% MVC, 70% MVC. For each level, the subjects were asked to perform four different profiles to reach the target, which were ascending and descending isometric contractions with 5% MVC/s and 10% MVC/s tension rate, respectively. For the ascending profile, the subjects kept rest for the first 5 s, then increased the contraction according to the requested rate. After reaching the target level, they maintained the contraction for 7 s. For the descending profile, the subjects needed to reach the MVC after the first 5 s, then maintain the effort for 1 s, decrease the contraction with the requested rate and sustain the contraction for 7 s. We denoted the increase contraction profile with 5% and 10% MVC/s as IV1 and IV2, respectively. The decrease contraction profile with 5% and 10% MVC/s was denoted as DV1 and DV2, respectively. During the experiment, the real contraction curve and the requested profile were provided on a monitor located in front of the subject to provide the necessary visual feedback. The subjects performed one block of three trials for each profile. Between each trial a period of 2 min rest was allowed.



(a)



(b)

Fig. 3. Contraction profiles with 5% and 10% MVC/s tension rate: (a) increase isometric contraction, (b) decrease isometric contraction. The increase contraction profiles with 5% and 10% MVC/s were denoted as IV1 and IV2, respectively. The decrease contraction profiles with 5% and 10% MVC/s were denoted as DV1 and DV2, respectively.

B. Data analysis

The sEMG signals were visually inspected to verify the absence of artifacts before processing. For each trial, the segment of the constant force period, i.e. the last 7 s, was selected and then rectified, averaged over the whole duration. Then the values were averaged across all three trials within each force profile. All the values for five muscles were used to create a 5-dimensional (5D) vector, representing the EMG pattern of all muscles for each condition. The vector was referred to as the muscle activation pattern vector.

To determine whether subjects used either the same or different hand muscle activation patterns across different tasks, we calculated the cosine of the angle between pairs of MAP vectors. The cosine value of the angle between two vectors was equivalent to the Pearson's correlation coefficient and used to quantify the degree of similarity in their orientation. Let $MAP_{s,f,p,v}$ denote the MAP vector for subject s with force level f, contraction path p, and velocity v.

The similarity between force level f_1 and f_2 for path p, velocity v is computed as

$$\frac{1}{4}\sum_{s=1}^{4} cos < MAP_{f_1,p,v,s}, MAP_{f_2,p,v,s} > \quad (1)$$

where $cos <,>$ denotes the dot product of two vectors normalized by the product of vector modules. There are a total of three pairs of force level (30% vs. 50%, 30% vs. 70%, and 50% vs 70%) to calculate.

The similarity between different contraction velocity v_1 and v_2 for path p, force level f is computed as

$$\frac{1}{4}\sum_{s=1}^{4} cos < MAP_{f,p,v_1,s}, MAP_{f,p,v_2,s} > \quad (2)$$

There is one pair of velocity level, 5% MVC/s and 10% MVC/s, to calculate.

The similarity between different contraction path p_1 and p_2 for velocity v, force level f is computed as

$$\frac{1}{4}\sum_{s=1}^{4} cos < MAP_{f,p_1,v,s}, MAP_{f,p_2,v,s} > \quad (3)$$

There is one pair of contraction path, increase and decrease, to calculate.

C. Statistical analysis

The value for the cosine of the angle (α) was limited within the range between 0 and 1. For the statistical purpose, its absolute value needed to be transformed by performing the Fisher's z-transformation:

$$z = 0.5 * \{log[1+cos(\alpha)]/[1-cos(\alpha)]\} \quad (4)$$

Analysis of Variance (ANOVA) was used to test the statistical significance. One-way ANOVA was performed on the cosine value to test the effect of path and velocity under different force levels. The force level was regarded as a fixed factor. Two-way ANOVA was performed on the cosine value to compare the effect of contraction path and velocity under different force levels. The force level and the corresponding contraction profiles were regarded as two fixed factors.

III. Results and Discussion

The main goal of the present study was to determine the effect of contraction path and velocity on the coordination of simultaneously active hand muscles with different force levels. We first described the results of force statistics to validate the experimental protocol.

The statistics of force values are shown in Fig 4. The standard deviation (SD) of level 30% was a little bigger than that of level 50% and 70%. It meant that it was hard for the subjects to produce the stable small force. However, all the values were within the acceptable range (± 10% MVC). The data was valid for the following analysis.

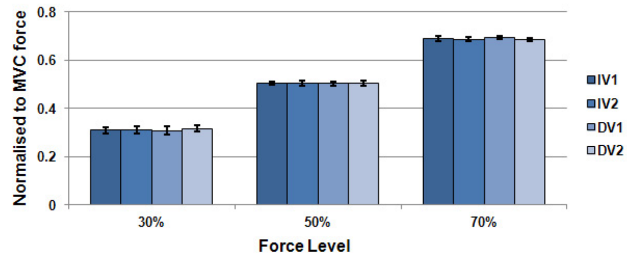


Fig. 4. Force statistics for four different contraction path. The SD of level 30% is a little bigger than that of lvel 50% and 70%. All the values are within the acceptable range (± 10%).

Fig. 5 shows the cosines of the angle between MAP vector pairs for three force comparisons with four different contraction histories. The high similarity in MAP vectors for neighboring force still existed for four different contraction profiles. For the increase contraction profile (IV1, IV2), the similarity between force pair of 50% and 70% was higher than that of 30% and 50%, which is contrary to the situation for the decrease profile (DV1, DV2). However, the cosines of MAP vectors were overall very high (above 0.96) throughout all target force comparisons for all the force profiles. It indicated that the force independent characteristic for the direction of MAP vectors still held, no matter how the contraction level was reached.

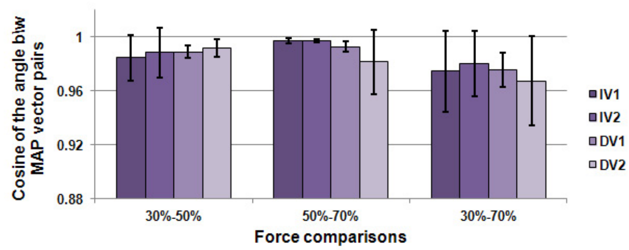


Fig. 5. The cosines of the angle between pairs of MAP vectors for each pairwise force comparison. All the comparisons keep the high value under four conditions (above 0.96).

Fig. 6 shows the cosines of the angle between MAP vector pairs for velocity comparison with different contraction path, and for contraction path comparison with different contraction velocity throughout all three effort levels. The cosine value for velocity comparison IV1-IV2 was higher than path comparison IV1-DV1 throughout all three force levels, and it was the same for DV1-DV2 and IV2-DV2. It indicated that the influence of contraction path on the coordination of muscle patterns was higher than that of contraction velocity. The significant test was also confirmed the result ($P < 0.05$). On the other hand, the similarity between MAP vectors of contraction path comparison IV1-DV1, IV2-DV2 with force level 30% was lower than that with force level 50% and 70%. The target force may have an effect on the influence of contraction path. But it was not significant ($P > 0.1$). As for the effect of velocity, the values of the comparisons IV1-IV2, DV1-DV2 were similar through all three force levels. The effect of velocity was not influenced by the force level ($P > 0.1$).

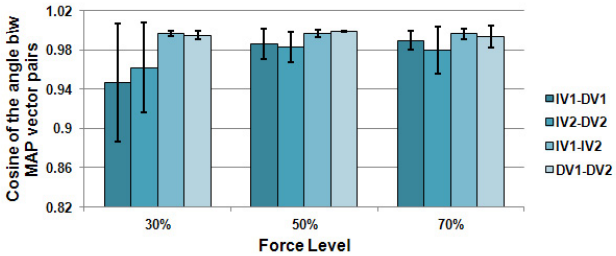


Fig. 6. The cosines of the angle between pairs of MAP vectors for velocity comparison and contraction path comparison through different force levels. IV1-DV1 and IV2-DV2 denote the similarity between MAP vectors of different contraction path with velocity 5% and 10% MVC/s, separately. IV1-IV2 and DV1-DV2 denote the similarity between MAP vectors of different contraction velocity with increase and decrease path, separately.

This study focused on the effect of the contraction history on the direction of MAP vector pairs. The differences in the amplitude of MAP vectors will be investigated in the future study. On the other hand, the results presented in this study was obtained in a three-digit grip. Whether they are applied to other tasks is also the subject of the future investigations.

The results of this study provided a potential method to improve the robustness of EMG pattern recognition-based human-machine interface (HMI) to the contraction variation. Variations in muscle contraction have a substantial impact on the performance of HMI [10]. The common solution is to incorporate changes into training phase[11]. However, it will prolong the training time and limit the clinical viability of the system[12]. On the basis of this study, for a given motion, the direction of MAP vector was invariant across a wide range of contraction levels, no matter by which way the level was reached. So it can be extracted as the feature set for pattern recognition and the performance of HMI with the disturbance of contraction variations may not be decreased without extra training.

IV. Conclusion

This paper investigated the effect of contraction history profiles on the coordination of multiple hand muscles, which included contraction and relaxation paths with two kinds of velocity, 5% MVC/s and 10% MVC/s. We found that the property that the coordination of multiple hand muscles was invariant across different grasp forces still existed for different contraction history profiles. The effect of contraction path was more significant than that of velocity. Our future work will focus on whether the finding is applicable to other tasks and on its application in improving the robustness of pattern recognition-based myoelectric prosthesis control.

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