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Study on the Establishment Process of Muscle Synergy Based on Cosine Similarity*

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Abstract— **Muscle synergy is an important method for motor intention recognition in rehabilitation exoskeleton control. The use of the non-negative matrix factorization (NMF) to extract muscle synergy patterns often results in long calculation time due to the amount of data, which makes the effectiveness of synergy extraction low. In this paper, synergy matrices of the complete single-cycle signal while stretching and its segmented ones were extracted respectively. By studying the cosine similarity variation of synergy matrices between each continuous segment and the complete single-cycle EMG signals, it is found that there is a "building-stability-weakening" process on muscle synergy establishment. It is proposed to extract synergy mode with partial data from the "stable" segment, rather than using the complete single-cycle one, as similar result to single-cycle data synergy extraction could be obtained. The calculation time of NMF could be optimized by reducing the amount of data and the real-time characteristics of the synergy mode extraction could be improved at the same time. It is of great significance to use synergy matrix of NMF for motion intention recognition and exoskeleton control.**

Clinical Relevance— **This paper studies the establishment process of the synergy mode, and proposes a method for quickly extracting the synergy mode, which can improve the effectiveness of the recognition of motion intention and is of great significance for the real-time control of the rehabilitation exoskeleton.**

I. Introduction

Rehabilitation robots have brought dawn to the daily training and life support of patients with hemiplegia. However, when using exoskeleton to assist patients in daily life, how to recognize motion intention is still an urgent problem to be solved [1]. At present, the intention of movement is mainly identified through kinematic signals, dynamic signals and bioelectric signals (mainly electromyographic signals). Surface Electromyography (sEMG) [2], as a non-invasive output form of the neuromuscular system, is a way of motor intention recognition that can be used for exoskeleton control.

Muscle synergy refers to a constant proportional relationship involved in co-activation of muscles, and is a coded form of the central nervous system activating these muscles according to a specific proportion and timing [3]. When completing a specific motion task, the central nervous system recruits several muscle synergy modes [4] with different functions through a linear combination to form a control signal that regulates skeletal muscle coordinated contraction in time and space. This signal is transmitted to the descending nerve to motor neurons, to activate the muscle fibers that could produce muscle activity, which drives joints in turn to produce movements [5].

Literatures have proved that human movement is based on muscle synergy [6]. The central nervous system controls the activation time and activation intensity of the corresponding muscle synergy mode through the activation coefficient C, and realizes the coordinated regulation of muscle contraction activity through the weight matrix (W) of different muscles. By solving this problem of "blind source separation", the activation weight relationship between different muscles (that is, the muscle synergy mode W) and the timing adjustment coefficient (activation coefficient C) of the synergy mode can be used to characterize the sEMG signal feature matrix. This is the theoretical basis of using the muscle synergy pattern (W) extracted from the sEMG signal to recognize motion intention.

Principal Component Analysis (PCA) [7], Independent Component Analysis (ICA) [8], and Factor Analysis (FA) [9] are common blind source separation methods. Because the decomposition results have negative values, they are often meaningless in practical problems. NMF proposed by Lee and Seung [10] is considered close to the natural representation of synergies and outperforms PCA and rivals ICA as it is more physiologically relevant for EMG signals reflecting well behavior of muscles. Currently, NMF decomposition has become the main and one of the most popular methods for muscle synergy extraction and applications in movement analysis. For example, the dependence of joint angles was used to control the manipulator through EMG signals, and decoded the upper limb movement by training a mathematical model [11].

While, for specified motion tasks, it is usually necessary to use complete single-cycle data to obtain the muscle synergy mode through NMF method. The amount of the single-cycle data would lead to longer calculation time, and limitation on the real-time properties of motion intention recognition and exoskeleton control. The purpose of this article is to explore the establishment process of the muscle synergy mode in a single movement, and explore a way to use partial data in the "stable" segment to obtain the synergy mode similar to the result of the complete single-cycle data, so as to reduce the amount of data needed for NMF, and finally reduce the

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calculation time. On the premise of ensuring effectiveness, the real-time property of synergy extraction is improved.

II. METHODS

A. Participants and Procedures

Eight college students (four males, four females; aged 25±4.6 years old) were recruited for this study. All subjects were right-handed, with no neurological diseases or motor impairment. Each participant signed an informed consent in compliance with experimental protocols approved by the Ethics Committee of Chongqing University Cancer Hospital.

Participants sat on the bench with their backs kept upright, and their arms were naturally drooping and relaxed as the initial state. A baseball is placed at a distance of 650 mm in front of the subject, 45 degrees to the left, and 1300 mm above the ground to indicate the target position. Participants first stretched to grasp the baseball at the target position by using their right arm; after reaching the target position, they moved the hand to the position of one punch away from the body at the height of the heart in the middle of the chest, and finally restored the arm to the original position of natural droop. The whole process lasted 2 s and was repeated 20 times.

B. EMG Acquisition

Biceps Brachii (BB), Triceps Brachii (TB), Medial Deltoid (MD), Musculus Brachioradialis (MB), Anterior Deltoid (AD), Posterior Deltoid (PD), Pectoralis Major (PM) and Trapezius (TP) were the eight muscles mainly used to perform stretching movement in space. These muscles were labeled sequentially from 1 to 8. A surface EMG system (ME6000, Mega Electronics Ltd, Finland) was used to record the sEMG signals of the eight muscles while they performing the motion. Before data collection, the skin was shaved and wiped with alcohol, and the surface electromyography patch electrodes were fixed to the skin surface using an elastic gauze. During recording, the system bandwidth was set to 15-500 Hz and the sampling rate was 1 kHz.

C. Muscle Synergy Extraction

Data were processed offline in MATLAB 2016b. Continuous EMG signals were first filtered by 20-500Hz band-pass filter and 50Hz notch filter to remove signal noise and power frequency interference, and then obtained the EMG envelope with a 3Hz low-pass filter. Twenty cycles of EMG envelopes were captured by setting thresholds. Each cycle of the envelopes were normalized to 1000 for further analysis.

Based on the hypothesis of the muscle synergy control model, this paper used NMF to extract the muscle synergy of stretching. The formula of NMF is as follows, where W is the weight matrix, which represents the ratio of the contribution of each muscle, and C is the coefficient matrix, which represents the modulation curve of the corresponding weight matrix over time.

$$V_{m\times n} \approx W_{m\times r} \times C_{r\times m} \tag{1}$$

The number of muscle synergy used for reconstruction is determined by VAF, and its formula is as follows. In general, the number of synergy depends on the change rate of VAF as the number of synergy increases, as well as the values of the overall VAF and the single muscle VAF (musVAF).

$$VAF = 1 - \frac{\sum_{i,j}(V-V_r)^2_{i,j}}{\sum_{i,j} V^2_{i,j}} \tag{2}$$

Where V is the original matrix and V_r is the reconstruction matrix. The larger the VAF, the closer the reconstruction matrix is to the original matrix.

D. Research on the establishment process of synergy

In this paper, we assumed that for a single action, there would be an establishment process of the synergy matrix. In order to explore the establishment process, we calculated the Cosine Similarity between the continuous segmented signals and its corresponding single-cycle signal to evaluate the synergy pattern establishment process. Common similarity calculation methods include Euclidean Metric, Pearson Correlation Coefficient, Cosine Similarity and so on. As the Cosine Similarity uses the cosine value of the angle between the two vectors in the vector space to measure the difference between the two individuals, we chose the Cosine Similarity to discuss the establishment process of synergy models. Specifically, the W matrices calculated according to NMF were regarded as vectors, and the similarity between two W matrices could be measured by using the Cosine Similarity. The formula for calculating is as follows:

$$Similarity = \frac{\sum_{i=1}^{n} A_i \times B_i}{\sqrt{\sum_{i=1}^{n}(A_i)^2} \times \sqrt{\sum_{i=1}^{n}(B_i)^2}} \tag{3}$$

Where A_i and B_i represent the components of the vectors A and B, respectively.

The repeatability of synergy matrix of the same movement is the basis for the recognition of motion intention by using the synergy matrix. We calculated the similarity of W between adjacent single-cycle actions to verify the repeatability of the same action by the same subject and ensure the effectiveness of the obtained synergy matrix for intention recognition.

In order to study the establishment process of synergy mode, we first calculated the NMF of the segmented signals and the corresponding single-period signal, and then calculated the Cosine Similarity between the matrices W of each segment and the single-period. After that, the synergy model establishment process was studied based on the degree of similarity between the segmented and single-period.

III. RESULTS AND DISCUSSION

A. Does the continuous single-cycle motion synergy matrices have similarities?

Figure 1 shows the synergy matrices of stretching movement when the number of synergy was 1 and 3. The horizontal axis represented eight measured muscles, and the vertical axis represented the contribution of the muscles shown in the horizontal axis in the stretching movement.

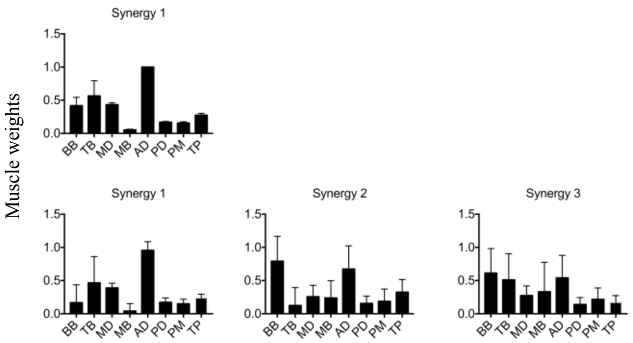

Figure 1. Synergy matrix of stretching movement.

Synergy 1 in the first row represented the synergy matrix when synergy number was chosen to be 1. Synergy 1 to synergy 3 in the second row showed the low-order to high-order synergy matrices extracted when the number of synergies was chosen to be 3.

According to the figure above, it can be seen that the synergy matrix when the number of synergy was 1 has smaller variance and better consistency than the case when number of synergy was 3. The results showed that BB, TB, MD AD played the major roles. BB and TB corresponded to elbow flexion, elbow hyperextension, respectively. AD corresponded to shoulder flexion and internal rotation, which was consistent with the muscle theory involved in the upper left extension discussed in this paper.

Then, we calculated the Cosine Similarity between adjacent single-cycle synergy matrices to verify whether the subjects have sufficient similarity to the motion synergy matrix W.

According to the NMF result of the single-cycle EMG signal envelope, it was known that when the change rate of overall VAF was less than 1%, the overall VAF was large than 98%, and the minimum musVAF was large than 91%, then the number of synergy was best to be 3. In addition, when the number of synergy was 1, the overall VAF was greater than 81.03%, and the minimum musVAF was greater than 74.15%.

Previous studies have indicated that low-order synergy represents the basic motion mode, and high-order synergy represents the fine motion mode [12]. As this paper mainly studied the establishment process of the synergy matrix for motion intent recognition, rather than evaluating the reconstruction results, we mainly discussed the establishment process of the synergy mode by calculating the Cosine Similarity between the low-order synergy matrices when the number of synergy was chosen to be 1 and 3.

Figure 2 and Figure 3 show the Cosine Similarity between adjacent single periods of eight subjects when the number of synergy was 1 and 3, respectively. Among which the lines of blue, red, and yellow represented the results of low-order synergy matrix to high-order synergy matrix, in the order of synergy 1, synergy 2 and synergy 3.

From the results below, it can be seen that with the increase of the number of synergy, the similarity during the adjacent single-cycles decreased. And with the synergy order increasing, lower-order synergy showed higher Cosine Similarities than the higher-order ones.

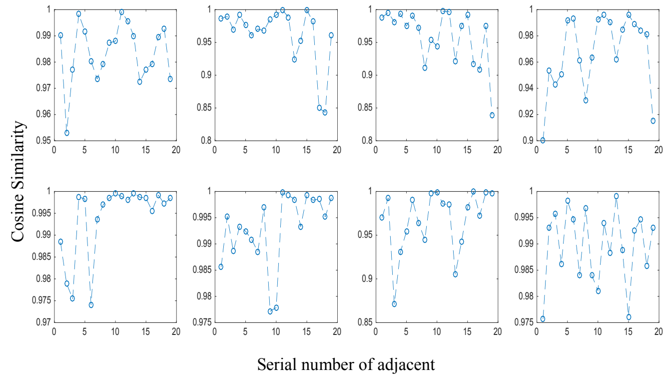

Figure 2. Single-cycle Cosine Similarity when the number of synergy was 1.

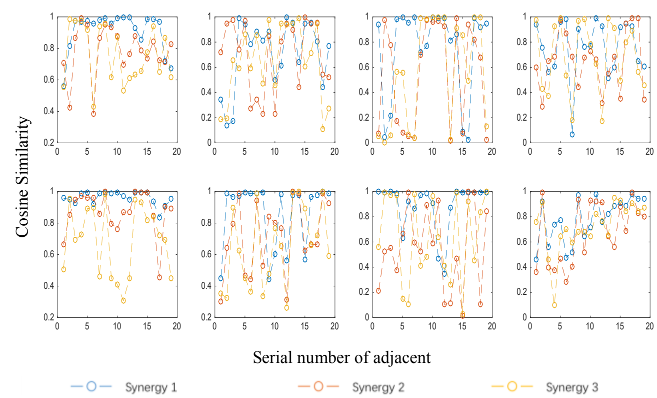

Figure 3. Single-cycle Cosine Similarity when the number of synergy was 3. Where blue, red, and yellow corresponded to synergy 1, synergy 2, synergy 3.

From the above results, it can be seen that with the increase of the number of synergy, the similarity during the adjacent single-cycles decreased. And with the synergy order increasing, lower-order synergy showed higher Cosine Similarities than the higher-order ones.

B. Discussion on similarity between each different segment and the corresponding single-cycle

The standardized single-cycle EMG envelope signal was divided into 10 segments, and the NMF was calculated for each single-cycle and segmented EMG envelopes respectively.

For the calculation results of the single-cycle signal NMF, when the overall VAF change rate was less than 1%, the number of synergy should be selected to be 3. For the calculation results of the single-cycle segmented signal NMF, when the overall VAF change rate was less than 1%, the number of synergy should be 1-2. It can be seen that under the same condition of VAF, the number of synergy required by a segmented signal is less than that of a single-cycle one.

Figure 4 and Figure 5 shows the Cosine Similarity between each segmented signal and the single-cycle one when the number of synergy was 1 and 3, respectively.

Here, rows 1 to 8 corresponded to subjects 1 to 8, the abscissa corresponded to each consecutive 20 cycles of each movement. As each cycle was divided into 10 segments, there was a total of 200 coordinate points in each row; the ordinate showed the Cosine Similarity value between segmented signals and the single-cycle one.

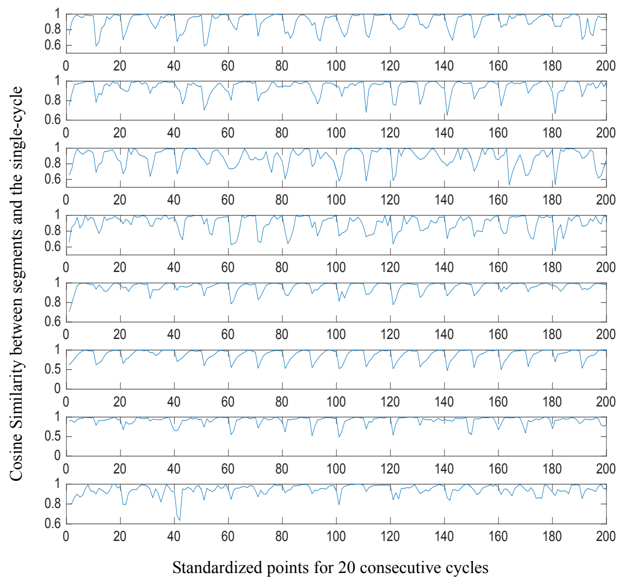

Figure 4. Cosine Similarity between segmented signals and the single-cycle signal when the number of synergy was 1.

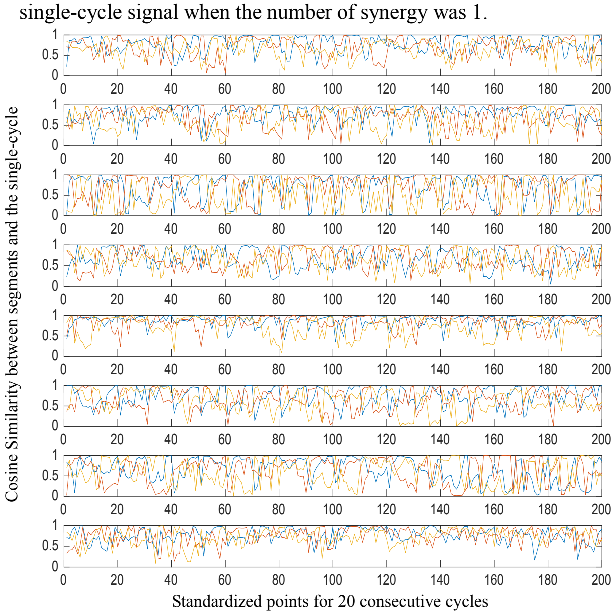

Figure 5. Cosine Similarity between segmented signals and the single-cycle signal when the number of synergy was 3. Where blue, red, and yellow corresponded to synergy 1, synergy 2, synergy 3.

From the above results, it can be seen that when the number of synergy was 1, the cosine similarity value of the continuous segment and the single-cycle synergy matrix W showed a change of "establishment-steady-weakness", and this change showed better periodicity with the repetition of single-cycle actions.

When the number of synergy was 3, the cosine similarity results of each segment and single-cycle data showed a certain periodicity in the low-order synergy, but showed no obvious periodicity with large fluctuations in the high-order synergy. It may be caused by the reason that the low-order synergy represents the basic movement mode and has better consistency, while the fine movement represented by the high-order synergy often brings in the difference caused by the movement.

All in all, the synergy of a single movement has a process of "establishing-steady-weakening". Using the partial signals of the "steady" section can approximately obtain the synergy information as the complete single-cycle data. This result is of great significance for compressing the time for synergy extraction by NMF. In addition, by comparing the Cosine Similarity of the low-order synergy when the number of synergy was 1 and the number of synergy was 3, it is found that the former has better periodic performance and more stable changes. This may reveal that the lower order of the synergy, the more obvious the establishment process of a synergy, and the better the accuracy of using partial segmented data to approximately replace the complete single-cycle data.

IV. Conclusion

This paper verified the hypothesis of the existence of the establishment process of muscle synergy. It is expected to extract muscle synergies by NMF from the initial part of the steady segment of the single-cycle to obtain results approximate with the that of the complete single-cycle. By reducing the amount of data calculated by NMF, the extraction time of synergy mode is reduced. It is expected that under the premise of ensuring effectiveness, improving the real-time performance of motion intent recognition using NMF is of great significance for real-time control of exoskeleton based on surface electromyography.

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