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Muscle Synergy Analysis Based on NMF for Lower Limb Motor Function Assessment

Kexin Xiang, Weiqun Wang*,Zeng-Guang Hou, Chutian Zhang, Jiaxing Wang, Weiguo Shi, Yuze Jiao, Tianyu Lin

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***Abstract*— Accurate rehabilitation assessments are essential for designing effective rehabilitation methods and helping patients recover better. It's well known that commonly used scale assessment methods for neurorehabilitation suffer from the issue of subjectivity, thus investigation of objective assessment methods is very necessary. Muscle synergy analysis can be uesd to assess limb motor functions from the perspective of neuromuscular control. In this paper, a method for evaluation of human lower limb motor functions based on muscle synergy analysis is presented. Muscle synergy modules are designed using surface electromyography (sEMG) signals of the subjects' lower limbs by non-negative matrix factorizations (NMF). By comparing the cosine similarities of these synergy modules, it can be seen that muscle synergies of healthy subjects and patients are significantly different, while they are similar among healthy subjects. Therefore, a reference synergy module (RSM) is designed by averaging the muscle synergy modules for healthy subjects, and the similarities can be calculated by comparing the synergy modules for healthy subjects or patients with the RSM. In the experiment carried out in this study, average similarities of the three synergy modules for healthy subjects are respectively 0.97166, 0.87368 and 0.84932, and on the other hand, the average similarities for the three synergy modules for patients are respectively 0.59979, 0.56426 and 0.69042. Therefore, the similarities for healthy subjects are much higher than those for SCI patients, which denotes that the similarity between an individual synergy module and the RSM can be used as an objective assessing index for evaluating patients' motor function.**

***Index Terms*—muscle synergy, cycling, non-negative matrix factorization, rehabilitation assessments**

I. INTRODUCTION

Spinal cord injury (SCI) is a disease that can cause motor impairments. In China, there were approximately 39.0 new SCI cases per one million people in 2014, which increased to 43.2 new cases per one million people in 2018 [1]. SCI can negatively affect lower-limb voluntary muscle activities and requires effective rehabilitation treatments [2]. Therefore, the demand for lower limb rehabilitation has been increasing in recent years. In order to better evaluate the rehabilitation effects and provide patients with appropriate rehabilitation treatments, accurate rehabilitation assessments are very necessary.

Currently, the commonly used clinical assessment method is scale assessment, such as the Fugl-Meyer assessment [3], the Brunnstrom assessment [4], etc. These methods are subjective since they rely heavily on the experience of rehabilitation therapists. In order to obtain an objective assessment, some devices that can measure kinematic or physiological data have been widely used. Surface electromyography (sEMG) signals are electrical signals before muscle contractions collected by non-invasive electrodes placed on human skin's surface. The sEMG features used in current studies on rehabilitation assessment include root mean square (RMS), mean absolute value (MAV), and waveform length (WL) [5], etc.

From the theory of muscle synergy, it can be concluded that the central nervous system controls not just one muscle but a group of muscles to achieve limb movement [6]. Based on muscle synergy, sEMG can be divided into muscle synergy modules and muscle activation coefficient matrices. The muscle activation coefficient matrix represents the activation of the corresponding muscle groups, and muscle synergy modules represent the activation weights of different muscles in the muscle groups. A variety of algorithms can be used to achieve this separation, such as principal component analysis (PCA) [7], independent component analysis (ICA) [8], and non-negative matrix factorization (NMF) [9]. According to the meaning of muscle synergy, the separation components are all non-negative. Since that non-negative decomposition can be guaranteed by NMF, it can be inferred that NMF is more suitable than PCA and ICA for muscle synergy analysis.

There are many applications of muscle synergy analysis in the studies of limb movement. In the fields of motor intention recognition, locomotion transition mode recognition and human gait tracking , satisfied results have been achieved based on muscle synergy [10]-[12]. For movement analysis, the relationship between limb movement and muscle activation during activities, such as balance responses when perturbed

* Corresponding author
Kexin Xiang, Weiqun Wang, Jiaxing Wang, Weiguo Shi, Yuze Jiao and Tianyu Lin are with the State Key Laboratory of Management and Control for Complex Systems, Institute of Automation, Chinese Academy of Sciences, Beijing 100190, China, and also with the School of Artificial Intelligence, University of Chinese Academy of Sciences, Beijing 100049, China. {xiangkexin2020,weiqun.wang, jiaxing.wang, shiweiguo2017, jiaoyuze2019, lintianyu2020} @ia.ac.cn
Zeng-Guang Hou is with the State Key Laboratory of Management and Control for Complex Systems, Institute of Automation, Chinese Academy of Sciences, Beijing 100190, China, also with the School of Artifificial Intelligence, University of Chinese Academy of Sciences, Beijing 100049, China, and also with CASIA-MUST Joint Laboratory of Intelligence Science and Technology, Institute of Systems Engineering, Macau University of Science and Technology, Macao 999078. zengguang.hou@ia.ac.cn
Chutian Zhang is with Macau Institute of Systems Engineering, Macau University of Science and Technology, Macau, China, also with the CASIA-MUST Joint Laboratory of Intelligence Science and Technology, Institute of Systems Engineering, Macau University of Science and Technology, China. 2109853pmi30005@student.must.edu.mo

TABLE I
PATIENTS' INFORMATION[15]

Number of Patient	Gender	Age	Damage Level
1	male	40	Incomplete SCI of the fourth vertebra of the neck (both sides of the lower limbs were damaged)
2	female	46	Incomplete SCI of level C1 (one side were damaged)
3	male	43	Incomplete SCI of the 10th vertebra of the chest (one side muscle atrophy)
4	male	40	Cauda equina injury (both sides of the lower limbs were damaged)

at different walking speeds [13] and changes in muscle activation during rectilinear and curvilinear walkings, have been widely studied [14].

Muscle synergy can be used to analyze motor function from the perspective of neural control of muscles, which has stronger physiological significance. In this paper, the muscle synergy of healthy subjects and SCI patients during cycling is explored to find the differences in muscle activation when they perform the same exercise. The least number of synergy modules required for muscle synergy is given, and the stability is analyzed. Then, the reference synergy modules (RSM) is designed by using healthy subjects' sEMG signals. The level of motor function can be represented by the similarity to the RSM.

The remainder of this paper is organized as follows: the data processing and calculation method are given in Section II; the results and discussion are given in Section III; the conclusion is given in Section IV.

II. METHODS

A. Participants and Experimental Protocol

This paper's data included healthy subjects and patients' sEMG signals obtained from [15]. In this experiment, the subjects were required to complete the continuous cycling exercises at a slow speed for about 22s. Ten healthy subjects and four SCI patients participated in the experiment. Seven muscles, including rectus femoris (VR), vastus lateralis (VL), semitendinosus muscle (SM), biceps femoris (BF), tibialis anterior (TA), extensor pollicis longus (EP), and gastrocnemius muscle (GM), were recorded during the cycling. The knee joint angles were recorded at the same time. The sEMG signal acquisition equipment was FlexComp (Thought Technology Ltd, Canada), and the joint angle measurement equipment was InclinoTrac (Thought Technology Ltd, Canada). The sampling rates were both 1024 Hz.

The information about the patients in the experiment is given in TABLE I. Data from all patients were collected from the left legs, which were the affected sides.

B. Data Processing

The data need to be preprocessed at first. Raw sEMG signals were first high-pass filtered (80 Hz) with a fourth-order Butterworth filter to remove signal noise, then they were full-wave rectified. After that they were low-pass filtered (2 Hz) with a fourth-order Butterworth filter to get the envelope of the signals[16].

After filtering, the data were divided into single-cycle segments. The data were segmented according to the joint angles since the signals were collected continuously and included multiple cycling cycles. After segmentation, 39 data segments for healthy subjects and 22 data segments for patients were obtained.

C. Muscle Synergy

Muscle synergy is a method to explore the generation and execution of body movement from the perspective of motor control. According to this method, the nervous system transmits motor control information through nerve oscillations, dividing the muscles into synergistic muscle groups and realizing motor control by synergistic activation. NMF is a commonly used method for muscle synergy analysis. This method is used for the analysis of lower limb cycling exercises. By NMF, multi-channel signals can be decomposed into two non-negative matrices as follows:

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

where $V_{m\times n}$ denotes the raw sEMG data, which includes m channels, and n sample points are contained in each channel. $W_{m\times r}$ denotes the synergistic muscle groups, representing the level of muscle activation in each synergy module. $H_{r\times n}$ is the activation coefficient matrix, which represents the activation change of a muscle synergy module over time. Moreover, r represents the number of synergy modules that are involved.

NMF can be regarded as compressing an m channels signal into r channels. Some information about the signal will be lost in the process. When the number of synergy modules r is too small, the loss of information will be significant. The number of synergy modules is determined by the method of variance account for (VAF). The sEMG signals can be reconstructed by W and H. The total VAF represents the ratio of reconstructed sEMG signals to original signals, which can be given by:

$$tVAF = 1 - \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}(V_{i,j} - V_{i,j}^{R})^2}{\sum_{i=1}^{m}\sum_{j=1}^{n}(V_{i,j})^2} \tag{2}$$

where V represents the original sEMG envelope, and V^R represents the constructed signal by W and H. This calculation is also made for single channels, representing the remaining information of a sEMG channel after the reconstruction.

The number of synergy modules were determined when the tVAF$\geq$0.9 and VAF$\geq$0.75[17].

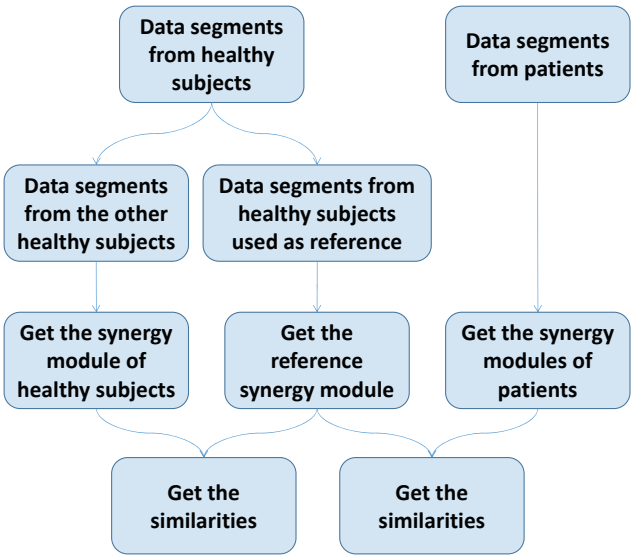

Fig. 1. The flowchart for RSM and test process.

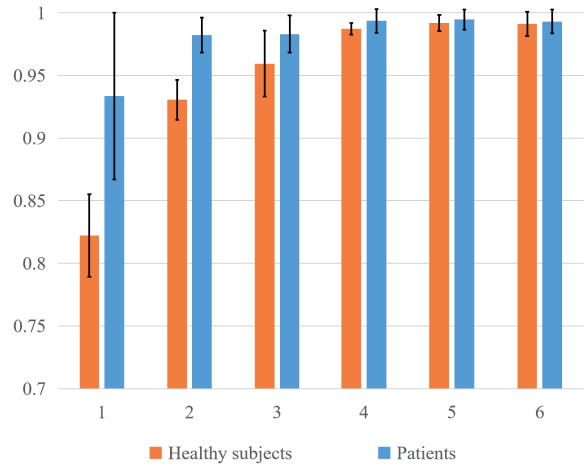

Fig. 2. The VAF comparisons of different number of synergy modules for healthy subjects and patients.

TABLE II
THE NUMBER OF SYNERGY MODULES

The number of muscle synergy	Healthy subjects (percentage)	Patients (percentage)
2	5%	23%
3	95%	77%

D. Similarity Analysis and Reference Synergy Module

The difference in lower limb muscle synergy during cycling exercise between healthy subjects and patients needs to be analyzed. Therefore, the similarities of muscle synergy modules need to be obtained. Cosine similarity is used to get the similarity of two vectors corresponding to two muscle synergy modules in this study. As each column in the muscle synergy matrix can be regarded as a vector, the similarity of muscle synergy modules can be calculated by:

$$Similarity = \frac{v_1 \cdot v_2}{|v_1||v_2|} \tag{3}$$

where v_1 and v_2 represent muscle synergy modules that are needed to be compared.

Through calculating the intra-subject similarities, similarity analysis for stability (SAS) can be carried out. The analysis is about the stability of the muscle activation when the subjects perform the same exercises. The similarity analysis for consistency (SAC) can be carried out through calculating the inter-subject similarities. The analysis is about whether there is a consistent muscle synergy module among different subjects.

Through experiments, it was found that the synergy modules for healthy subjects were similar, while the SCI patients were quite different. So an RSM can be used to distinguish between healthy subjects and patients. Fig. 1 is the processing flowchart. Firstly, the data of the first five out of ten healthy subjects are selected as the reference. The RSM is obtained through the reference subject data. Then the similarities are calculated between the RSM and the data of other subjects, including the other five healthy subjects and patients. The similarity between RSM is used to assess the motor function.

III. RESULT AND DISCUSSION

A. Number of Muscle Synergy Modules

The tVAF needs to be calculated according to (2) to determine the least number of synergy modules. The results are shown in Fig. 2. The results show that tVAF is significantly higher in the patient group ($P \leq 0.01$) compared with healthy subjects when the number of synergy modules was 1 to 4. Meanwhile, the VAF corresponding to each channel was also calculated. The number of synergy modules for all data segments were obtained according to the $tVAF \geq 0.9$ and $VAF \geq 0.75$ criterion. The results of healthy subjects and patients are given in Table II. From the results in the table, it can be seen that compared with healthy subjects, more patients' data segments are divided into two synergy modules. The results indicate that the sEMG data of patients can be represented by fewer synergy modules and SCI patients have simpler muscle activation patterns of lower limb movements than healthy subjects.

B. Muscle Synergy Comparison

According to the calculation given in subsection A, it can be seen that when the number of synergy modules is 3, all the data segments satisfy the criterion. The comparison of muscle synergy modules between healthy subjects and patients when the number of synergy modules is 3 is given in Fig. 3.

Muscle activation's temporal and spatial components during cycling can be obtained from Fig. 3. For healthy subjects, the synergy 1 is activated around the middle of the cycling

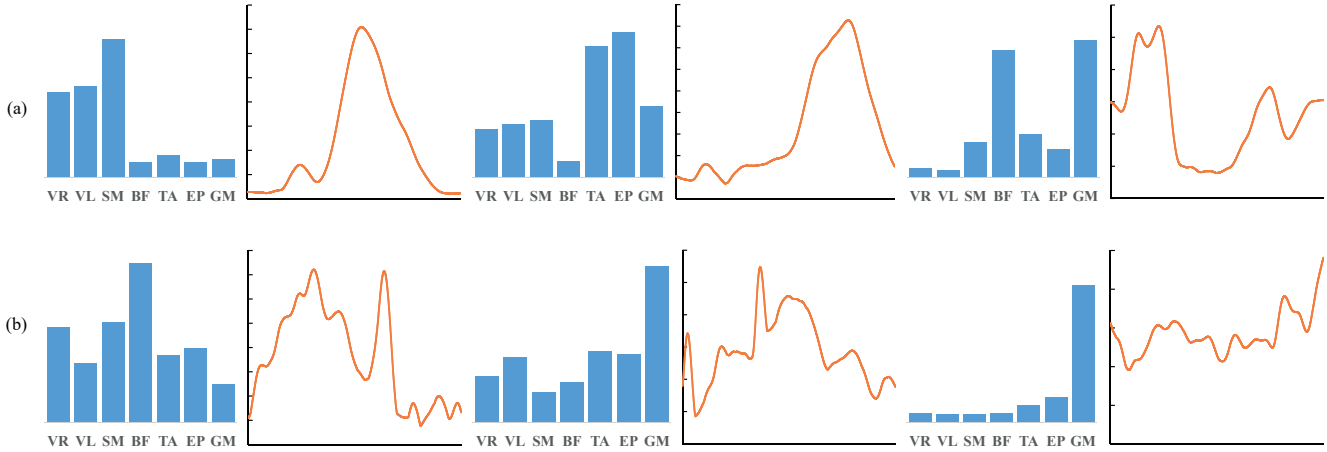

Fig. 3. The muscle synergy modules and activation coefficient matrices of (a) healthy subjects and (b) patients when the number of muscle synergy modules is 3. The blue columns are the mean synergy vectors of all the data. The red lines are the mean activation coefficients of all data. The subfigures from left to right represent respectively synergy 1 to 3.

cycle ($45\% \sim 65\%$ cycle). The synergy 2 is activated around the end of the cycling cycle ($60\% \sim 85\%$ cycle). The synergy 3 is activated around the beginning of the cycling cycle ($10\% \sim 25\%$ cycle). For patients, the synergy 1 is activated around the beginning of the cycling cycle ($15\% \sim 45\%$ cycle). The synergy 2 is activated around the middle of the cycling cycle ($35\% \sim 60\%$ cycle). While, the activation of synergy 3 fluctuates.

To further analyze the differences in muscle synergy, the active muscles in each muscle synergy module is discussed. The thigh muscle groups (VR, VL, SM) in the healthy subjects are activated in the synergy 1. The anterior and posterior calf muscle groups (TA and EP) are activated in the synergy 2. Furthermore, the BF and GM are activated in the synergy 3. In the patients, the thigh muscle groups (VR, SM, SF) are activated in the synergy 1. The GM is activated in the synergy 2 and the GM is activated in the synergy 3.

According to the above analysis, healthy subjects can make full use of each muscle to complete the exercise. However, it may be difficult for patients to control some muscles, so muscle compensation occurs. It can be seen that during the cycling, the gastrocnemius muscle often compensates for force in patients.

C. Similarity Analysis for Motor Function Assessment

The exercise for each subject includes multiple continuous cycling cycles. SAS can be carried out by calculating the similarities of these cycles. The muscle synergy modules for all data segments were calculated firstly. Then the similarities of all muscle synergy modules were calculated in pairs for each subject and these values were averaged. For example, four data segments were collected from subject 1. Four groups of muscle synergy modules could be get from them. The similarities were calculated in pairs for the four groups of muscle synergy modules, and six similaries were get. Then, the six similarities were averaged. The same calculation to subject 1 was performed also for other subjects. The results of intra-subjects are given in Table III.

TABLE III
INTRA-SUBJECT SIMILARITIES

Subject	Synergy1	Synergy2	Synergy3
Healthy subject 1	0.99352	0.89002	0.89798
Healthy subject 2	0.93660	0.87022	0.93007
Healthy subject 3	0.92488	0.82341	0.88219
Healthy subject 4	0.92829	0.89315	0.88931
Healthy subject 5	0.98913	0.94108	0.95325
Healthy subject 6	0.94290	0.76525	0.76803
Healthy subject 7	0.95454	0.77143	0.68175
Healthy subject 8	0.98727	0.83968	0.80419
Healthy subject 9	0.99176	0.88754	0.83475
Healthy subject 10	0.90397	0.76124	0.79378
Patient 1	0.98993	0.75570	0.54629
Patient 2	0.98388	0.90695	0.49233
Patient 3	0.86661	0.92364	0.62676
Patient 4	0.96695	0.97332	0.87670

According to the Table III, it can be seen that the similarities of synergy 3 for patient 1, 2, and 3 are lower than that for healthy subjects ($P \leq 0.01$).

In order to further analyze the movement characteristics of healthy subjects and SCI patients, the SAC were carried out by calculating the inter-subjects similarities. 39 data segments were collected from healthy subjects and 39 groups of muscle synergy modules were get from them. The similarities were calculated in pairs for these muscle synergy modules, and 741 similaries were get. Then, these similarities were

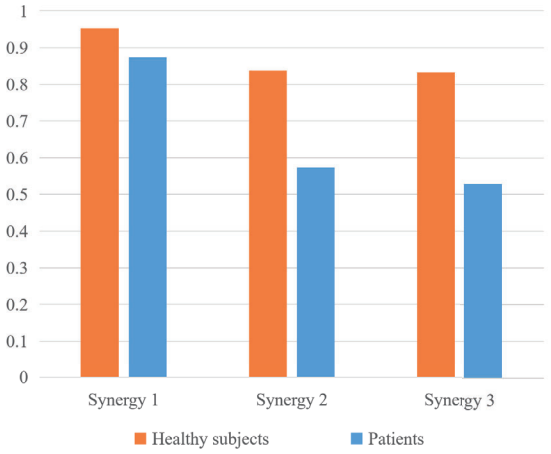

Fig. 4. The inter-subject similarities. From left to right are the results for three synergy modules.

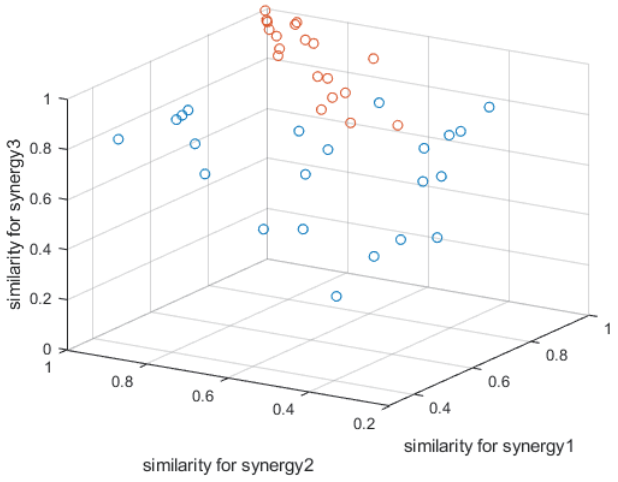

Fig. 5. The points used similarities from three synergy modules as coordinates, where the red points represent the healthy subjects and the blue points represent the patients.

averaged. Data segments from patients were also performed by the same calculation method. The results are shown in Fig. 4.

According to Fig. 4, it can be seen that the similarities of healthy subjects for all three synergy modules are higher than 0.8. This results indicates that for healthy subjects, the muscle synergies of the leg during cycling are similar. In other words, different healthy subjects have similar leg muscle activation patterns when they are doing the same cycling. By contrast, the similarities of patients are relatively lower. It shows that different patients accomplish the same cycling exercise with different muscle synergy patterns.

By the above analysis, it can be concluded that muscle synergy modules among healthy people are similar, while those for patients are different. So the RSM can be used to distinguish them. The RSM is obtained by healthy subject 1 to healthy subject 5. Then the similarities are calculated between it and other subjects. The results are plotted on

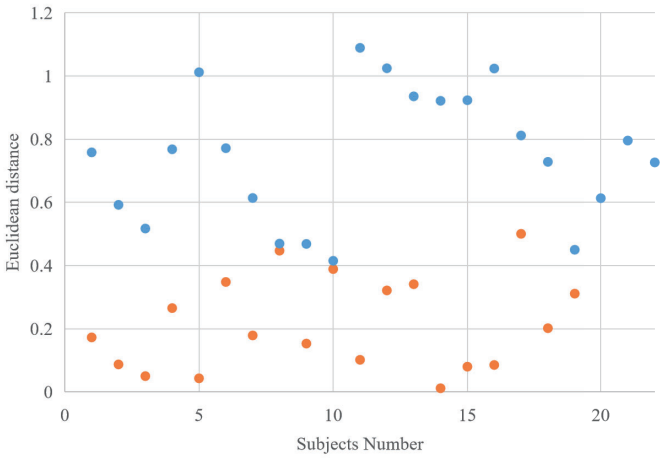

Fig. 6. The Euclidean distances from (1, 1, 1). The x-axis is the subject number and the y-axis is the Euclidean distance. The red points represent the healthy subjects and the blue points represent the patients.

the Fig. 5, using the values from three synergy modules as coordinates.

From Fig. 5, it can be seen that the points for healthy subjects are mostly clustered around (1, 1, 1), and all the points for patients are far away from (1, 1, 1). The mean result for all patients is (0.59979, 0.56426, 0.69042), while the mean result for all healthy subjects is (0.97166, 0.87368, 0.84932).

The Euclidean distances were calculated between these points and (1, 1, 1). The results are shown in Fig. 6. It can be seen that points for healthy subjects have smaller distance values overall. The mean distance for healthy subjects is 0.2151, while that for SCI patients is 0.7468. Therefore, the conclusion can be obtained that using the RSM can be used to distinguish healthy people and SCI patients. The similarity based on RSM can be used to assess the level of motor function.

IV. Conclusion

In this paper, the muscle synergy differences between healthy subjects and SCI patients are discussed. It is found in this study that compared with healthy subjects, the stability of patients' muscle activation in the same motion is lower, and meanwhile, the healthy subjects have similar muscle synergy modules, which are different from the patients. On the other hand, the RSM is proposed using healthy subjects' data. The similarities between the RSM and the muscle synergy modules for healthy subjects were higher than those for SCI patients. It can be concluded that the similarity based on RSM can be used as an objective assessment index for evaluating lower limb motor function.

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