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Gait Motor Function Evaluation Based on Muscle Synergy Method*

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***Abstract* - Considering the complexity and functionality of multi-muscle synergies, involved in the human lower limb gait movement, a gait function evaluation method, based on synergy structure, is proposed. Firstly, the surface electromyography (sEMG) from selected muscles are collected and pretreated, to extract its envelope. Next, it is decoupled by the algorithm of non-negative matrix decomposition, so that the synergy elements of the gait action can be extracted and the corresponding activation coefficients calculated, while subsequently these data are converted into normalized form. Then, the energy distribution and complexity of the synergy motion are analyzed. Finally, the function of gait motion is mapped, according to synergy structure, to determine whether the gait phases are normal or not. This study is helpful for quantitative analysis of lower limb gait and evaluation of motor function, in the framework of rehabilitation therapy.**

***Index Terms* - sEMG; gait; muscle synergy; functional mapping; motion evaluation**

I. INTRODUCTION

In recent years, muscle synergy analysis has been applied in the neuro-rehabilitation engineering, clinical medicine, sport science, especially in the field of human-computer interaction [1]. However, it is difficult to understand the mechanism of motor control, from the perspective of neural control, while improving the recognition rate of synergy. Therefore, the evaluation of motor function, using synergistic structure, remains an issue to be further studied [2]. Gait synergy is a method of skeletal muscles control, to accomplish various tasks, by self-adaptively executing a series of muscle synergistic activation commands. The gait function evaluation method of synergistic structure has great potential in revealing the control strategies of the nervous system motion [3].

During gait motion, surface electromyography (sEMG) signals of each muscle formed by the superposition of action potentials on the skin surface, is related to the movement of limbs [4]. Muscle synergy has been used to analyze motor characteristics and perceptual behavior patterns, via sEMG signals, during limb movements, while also revealing the motion control strategies of the Central Nervous System (CNS) and evaluating human motor function and rehabilitation effects. Synergy control of limb movements is shown by a large number of rhythmic or discrete motion modes, reflecting the relative contribution of a single muscle, within the muscle group [5]. Cooperative action, in the case of healthy individuals, is exhibited by the synergy of multiple muscles, whereas in the case of patients with nervous system injury, the action/gait will be unable to be performed well, because of certain muscle defect [3], showing motor dysfunction.

The mechanism of muscle synergy is studied, in the published literature [6], by crawling at different speeds on a treadmill, while the synergy effect of each limb is extracted, using non-negative matrix decomposition. Results show that limb coordination is relatively stable in human crawling, while the synergy structure, under different speeds, maintains good consistency. The question of whether straight and curve walking shared the same neuro-motor tissue, is studied in the prior art literature [7], concluding that straight and curve walking shared control instructions.

In this paper, a gait function evaluation method, based on muscle synergy, is studied. The outline of the paper is as follows. The research background is introduced in Section 1. The algorithm principle of the synergy analysis and the method of functional mapping of synergy structure are described in Section 2. The signal acquisition and envelope extraction are addressed in Section 3. Some problems, such as the extraction of synergistic element and activation coefficient, gait motion evaluation via synergistic function mapping, are discussed in Section 4. Finally, conclusions are presented in Section 5.

II. GAIT SYNERGY ANALYSIS

A. Muscle Synergy

In the process of gait motion, several muscles and bones work together to form low-dimensional control units, based on coupling through the central nervous system. These control units are called Synergy [3]. Synergistic elements, in the role of nerve activation instructions, produce the corresponding basic joint movements, while sets of basic movements form a variety of limb motion. Based on the muscle synergy theory, an effective approach is provided, for human motion modeling and analysis, through the quantitative analysis of synergistic elements and activation instructions. Assuming that the synergistic element, corresponding to an independent action, is activated, the other remaining elements activation values of

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actions are considered zero. The relation with the matrix expression is as follows:

$$M_{N\times T} = W_{N\times K} \times H_{K\times T} + E_{N\times T} \tag{1}$$

The quantitative equation is,

$$M_{N\times T} \approx W_{N\times K} \times H_{K\times T} = [w_1 \quad w_2 \quad \cdots \quad w_K] \times \begin{bmatrix} h_1 \\ h_2 \\ \cdots \\ h_K \end{bmatrix} = \sum_{i=1}^{K} w_i h_i \tag{2}$$

where, $M_{N\times T}$ represents the envelope of the sEMG signal (N is the number of muscles and T is the time series length). $\boldsymbol{W}_{N\times K} = [\boldsymbol{w}_{i1}, \boldsymbol{w}_{i2}, \cdots, \boldsymbol{w}_{in}](i=n)$ represents the synergistic structure matrix and $\boldsymbol{w}_{in}$ is the magnitude of the muscle contribution in the combined pattern. K represents the number of muscle synergistic elements and $\boldsymbol{H}_{K\times T} = [\boldsymbol{h}_{1j}, \boldsymbol{h}_{2j}, \cdots, \boldsymbol{h}_{kj}](j=t)$ represents the activation coefficient matrix, which is the contribution of each muscle synergy to the overall excitation; $E_{N\times T}$ represents the noise signals. Usually, in the algorithm of the Non-negative Matrix Factorization (NMF), the base matrix dimension, i.e., the number of synergy $\boldsymbol{K}$, is initially unknown, while it can be determined by the following two methods.

1) The numbers are determined by the matrix, as reconstructed by the factor matrix, while the precision of the original matrix is generally measured by the magnitude of the interpretation coefficient VAF, as follows [8]:

$$VAF = 1 - \frac{\sum_{i,j}(M - M_r)_{ij}^2}{\sum_{i,j} M_{ij}^2} \tag{3}$$

where, M and M_r are the original and reconstructed matrix, respectively. The range of parameter VAF lies between 0 and 1. A higher value of VAF indicates smaller reconstruction error and higher accuracy, whereas, when the value of the VAF parameter is equal to a certain threshold, muscle synergy of the current numbers can be used to reconstruct the original myoelectric signals.

2) According to the Reference [9], in general, it can be considered that there are several independent actions that compose the same synergistic elements, but this method cannot be used with large numbers of independent actions.

The extraction phase of the activation coefficient [10] is divided into two stages: training and extraction. The algorithm flow chart is shown in Fig. 1.

In the training phase, first, the acquired EMG signal is processed, that is, the mean value of the EMG signal, in the relaxed state of the muscle, is subtracted. Next, the time domain feature of the EMG signal, after de-reference, is calculated, to obtain $M(\boldsymbol{E})_{test}$. Then, the synergistic element W_i is obtained, by using the NMF algorithm for each independent action, while the synergistic element W_i of each individual action is respectively used, normalized according to its maximum values.

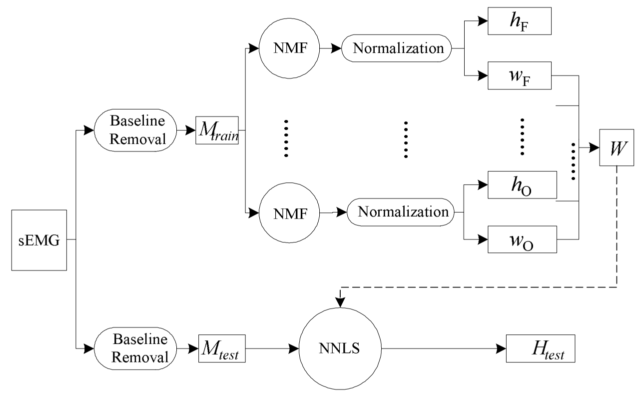

Fig. 1 Flow chart of the activation coefficient extraction process

In the extraction phase, it is necessary to use the synergistic element matrix $\boldsymbol{W}$, as calculated by the training phase, while the characteristic signal $M(\boldsymbol{E})_{test}$ is to be analysed, in turn, to find the activation coefficient matrix $\boldsymbol{H}$ with the generalized inverse, which is easy to cause the negative value [11]. But the value of $\boldsymbol{H}$ should be non-negative in accordance with the model of NMF quantified muscle synergy. In this paper, the non-negative least squares algorithm, proposed in Reference [12], was used to extract the activation coefficients, thus avoiding the error caused by the lack of useful information. The complete solution process is shown in Fig. 1.

B. Non-negative Matrix Factorization

The algorithm of Non-negative Matrix Factorization (NMF) can make sure that the synergistic elements and activation coefficients are both non-negative [13]. The synergy element $\boldsymbol{W}_i$ reflects the participation proportion of each muscle, while the activation coefficient element $\boldsymbol{H}_i$ represents the degree of activation. The solution of NMF can be regarded as an optimization problem, described as:

$$\min_{W,H} \frac{1}{2}\left\| M - WH \right\|_F^2 \tag{4}$$
$$\text{s.t. } \mathrm{M} \geq 0, W \geq 0, H \geq 0$$

where, $\left\| \bullet \right\|_F^2$ represents the Frobenius norm, $\boldsymbol{W}$ and $\boldsymbol{H}$ are non-convex in the objective function. According to the theory of Lee and Seung [14], the optimal solution of the NMF algorithm can be obtained by the following iterative rules:

$$W_{ik} \leftarrow W_{ik} * \frac{(M \times H^T)_{ik}}{(W \times H \times H^T)_{ik}} \tag{5}$$

$$H_{kj} \leftarrow H_{kj} * \frac{(W^T \times M)_{kj}}{(W^T \times W \times H)_{kj}} \tag{6}$$

C. Functional Mapping of Synergy Structure

According to the theory of muscle synergy, specific motor functions are the result of synergistic effects of each muscle. In order to obtain the motion function, corresponding to the synergy structure, the functional structure matrix $\boldsymbol{F}_{n\times m}$ and the synergy structure matrix $W=[w_1,w_2,\cdots,w_n]$ are considered, where n notes the number of muscle synergy and the i-th synergy w_i consists of m-block muscles. This conversion process is called the functional mapping. The role of functional mapping is to detect the existence of specific inter-muscular combination mode and to focus on the combination mode of muscles, between each synergistic structure. This method can provide the motor function, corresponding to the combination of muscles, while the difference can be quite obvious.

The specific steps for obtaining the synergy structure are as follows:

(1) Perform a maximum normalization process on the synergy structure matrix W;

(2) The element of matrix $F_{n\times m}$ can be determined as follows:

When the amplitude $w_{ij}(1 \le i \le m)$ is greater than 0.5, it is considered that the i-th muscle, in the j-th synergistic structure, is in an active state, so the respective element is marked as 1. Otherwise, the muscle is considered inactive, so the respective element is marked as 0;

(3) The functional structure matrix $F_{n\times m}=[f_1, f_2 \dots f_n]$ is obtained by the transposition of the matrix $F_{n\times m}$;

(4) For any synergy structure matrix W, a matrix of conversion F_w can be obtained by functional mapping, as:

When the amplitude of the synergy structure matrix $w_{in}(1 \le i \le 8)$ is greater than the set threshold, it is considered that, the i-th muscle is in an active state and is recorded as 1, whereas when the value is less than the threshold, it is not activated and so it is set to 0. Thus, a matrix $F_{m\times n}$ is obtained.

In this paper, the matrix is $F_{8\times 4}$, while the functional structure matrix is $F_{4\times 8}=[f_1, f_2, f_3, f_4]$. Next, for the synergistic structure matrix $W_{8\times 4}$ and the extracted synergy elements, the $F_{w_{4\times 4}}$ matrix is solved through functional mapping. Regarding matrix F_w, when the value of the diagonal element is the maximum in the corresponding row and column, the synergy structure matrix W is considered to have a complete functional synergistic structure, similar to that of a healthy person. Otherwise, it is considered that the functional synergy structure is missing.

III. Experimental Data Acquisition And Extraction

A. sEMG Data Acquisition

In the gait experiment, the muscle group was selected according to its contribution to the action of the movement and the correlation as well as classification performance of the respective sEMG signal. Considering the effects of the movement and measurement in lower limb motion, in this study, eight representative muscles were selected: Tibialis Anterior (TA), Soleus muscle (SO), Lateral Gastrocnemius (LG), Vastus Medialis (VM), Rectus Femoris (RF), Semitendinosus (SE), Adductor Longus (AL), and Tensor Fasciae Latae (TFL). The functions of the muscle are shown in TABLE I.

Ten healthy volunteers participated in the experiment (age 24±1.5years, height 1.72±0.11m, weight 65±6.2kg). They walked on the treadmill at a speed of 1.37m/s, while the sEMG data were acquired via Biometrics Ltd REF SX230-1000 with the sampling frequency of 1000Hz.

B. Envelope Extraction

Since the envelope signal of sEMG describes the muscle activity, the signal process is shown in Fig. 2.

TABLE I

FUNCTIONS OF SELECTED MUSCLES FOR LOWER LIMBS

Number	Muscles	Functions
1	Vastus medialis (VM)	Extensor of knee joint, hip joint flexion
2	Semitendinosus (SE)	Knee joint flexion, calf steering, hip joint extension
3	Adductor longus(AL)	Knee joint flexion, calf steering, hip joint extension
4	Tensor fasciae latae (TFL)	Hip joint flexion, medial rotation and abduction, stabilizing the knee joint
5	Rectus femoris (RF)	Knee joint extensor, stretching leg ,hip joint flexor
6	Tibialis anterior (TA)	Ankle joint flexor, dorsiflexion of foot
7	Lateral gastrocnemius (LG)	Extensor of ankle joint, plantar flexor, flexor lower leg Ankle flexor, standing, fixed ankle
8	Soleus (SO)	Ankle joint extensor, plantar flexion, standing

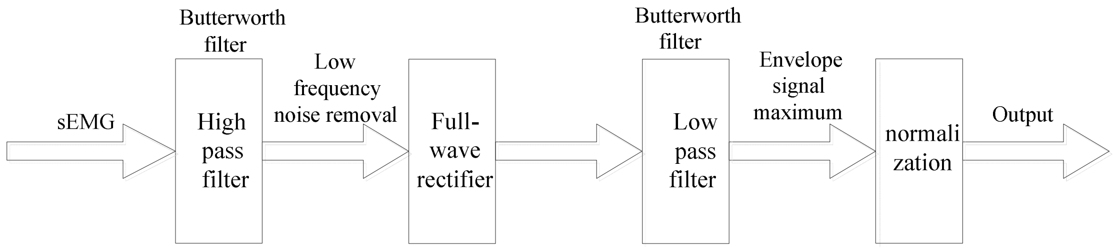

Fig. 2 Flow chart of signal processing

First, the original signal of each channel is processed via a high pass filter, to remove the motion artifact noise. Following, the full-wave rectification process is used to remove the mean value. Next, the low pass filter is used to remove the low-frequency signal.

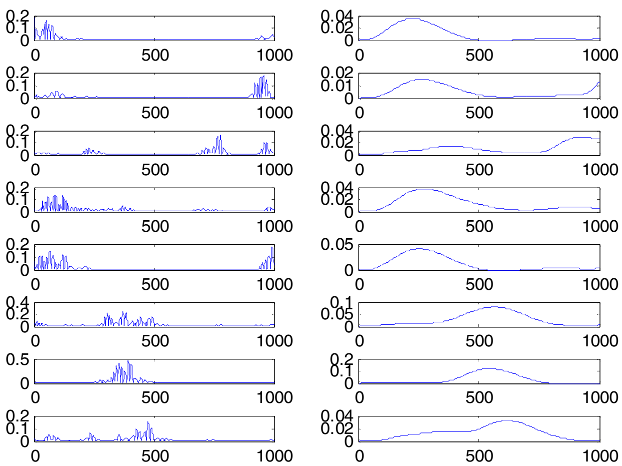

Fig. 3 Envelope extraction.

Finally, the envelope information of the signal, with the corresponding maximum value, is normalized to obtain the envelope signal. In this paper, the acceleration signal is used to detect the gait cycle, while the starting point of the motion is mapped to the sEMG signal, to achieve gait segmentation [15].The pre-treatment of the eight muscles in a gait cycle and the envelope signal extraction are shown in Fig 3, where the horizontal axis represents the time series of the signal, and the vertical axis represents the amplitude of the signal. On the left part of Fig. 3, there is the image after the mean, while on the right side, there is the maximum normalized envelope information.

IV. Results And Discussion

A. Synergetic Element and Activation Coefficient

According to the muscle synergy theory, the combined mode between muscles is a synergistic structure, while the down-going neural signal, modulating the synergistic structure, is the activation coefficient [16]. A healthy adult walking can recruit four basic functional synergistic structures, each corresponding to the basic motor function of a specific time period of the gait cycle. In this paper, the gait synergy elements and activation coefficients are extracted, as shown in Fig. 4.

The extracted envelope signals are decomposed by non-negative matrix factorization algorithm, thus obtaining the synergistic structure and activation coefficient. In Fig. 4, the horizontal axis of the synergistic element represents 8 muscles and is discharged in the order of the channels. The activation coefficient reflects the energy level or activation level of the synergistic element. Four synergistic elements, i.e., $\boldsymbol{w}_1, \boldsymbol{w}_2.\boldsymbol{w}_3, \boldsymbol{w}_4$, are obtained. In $\boldsymbol{w}_1$ module, the vastus medialis muscle, the tensor fasciae latae muscle and the rectus femoris muscle are active, while in $\boldsymbol{w}_2$ module, the tibialis anterior and soleus muscles are active. In $\boldsymbol{w}_3$ module, the tibialis anterior and the lateral gastrocnemius muscles are active. In $\boldsymbol{w}_4$ module, the semitendinosus and adductor longus are also active.

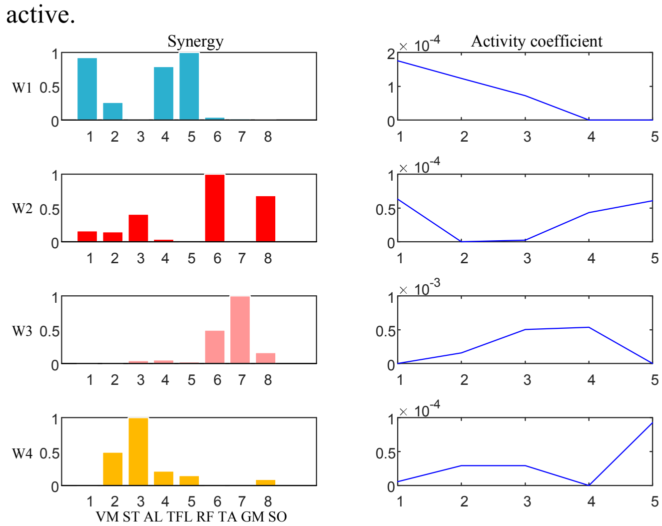

Fig. 4 Coefficients of muscle synergy and activity

A gait cycle can be divided into the support stage and the swing stage [17]. More specifically, the stages can be described as: early support stage, medium support term, late support stage, early swing stage, late swing stage. The movement of the lower limbs and multiple muscles is more precisely and accurately described into stages, according to the activation model of gait coordinated movement, in combination with the actual human movement. In this paper, the activation coefficient division of the corresponding action phase is obtained by the gait synergy element $\boldsymbol{w}_1, \boldsymbol{w}_2.\boldsymbol{w}_3, \boldsymbol{w}_4$, as shown in Fig. 5.

The stages of a gait cycle are defined as shown in Fig. 5. The symbol **A** represents the same side double support, **B** the opposite side initial swing, **C** the opposite side final swing, **D** the opposite side double support, **E** the ipsilateral initial swing and **F** the same side finally swing. Each synergistic structure is combined with a specific muscle and activated separately, for a specific period of time, in the gait cycle.

In $\boldsymbol{w}_1$ module, the combined mode of muscles is activated at the early stage of the support. In $\boldsymbol{w}_2$ module, the combined pattern of muscles is activated early, in the early stage of the support and in the early stage of the swing. In $\boldsymbol{w}_3$ module, the combined pattern of muscles is activated in the late phase of the support late and in the early stage of the swing. In $\boldsymbol{w}_4$ module, the combined mode of muscles is activated in the swing in late. Synergy 1 (involving hip and knee extensor activity) provides gravity support, in the early stage of the support. Synergy 2 (involving the ankle flexor activity), in the early stage of the swing, assisting knee flexion, provides forward driving force, while maintaining the body's upright posture and preventing the body from leaning forward. Synergy 3 (involving the ankle ridge flexor and hip flexor activity) is responsible for the foot lift, in the early stage of the swing and middle stages of the swing phase, while it is responsible for the swing in the late. Synergy 4 (involving the posterior femoral muscle group) slows down the lower limbs to the heel, in the Swing in late, while it is responsible for pelvic stabilization, when the heel strikes the ground.

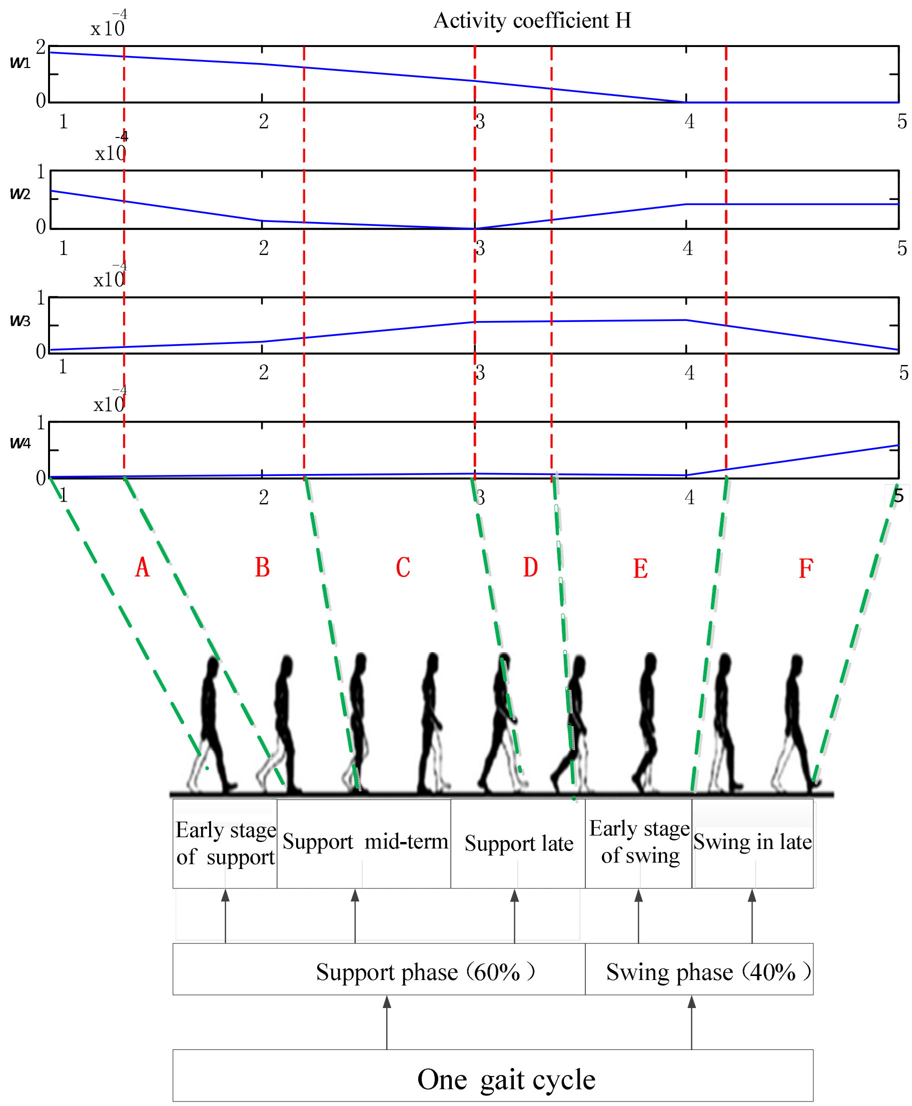

Fig. 5 Schematic diagram of gait movement stage division of synergy movement

B. *Contribution of Synergistic metafunction*

According to the motion function of one cycle gait, the participation of the collaborative module is analyzed and the contribution of the functions of the four synergistic elements is described, as shown in Fig. 6.

It is evident that the four synergistic elements correspond to the contribution degree in the gait motion. For a healthy adult, the collaborative structure template $\boldsymbol{W}=[\boldsymbol{w}_1,\boldsymbol{w}_2.\boldsymbol{w}_3,\boldsymbol{w}_4]^{\mathrm{T}}$, $\boldsymbol{F}_{4\times8}=[\boldsymbol{f}_1,\boldsymbol{f}_2...\boldsymbol{f}_n]=[10011000;00000110;00000101;01100000]$ is obtained from the acquisition step of the functional mapping described

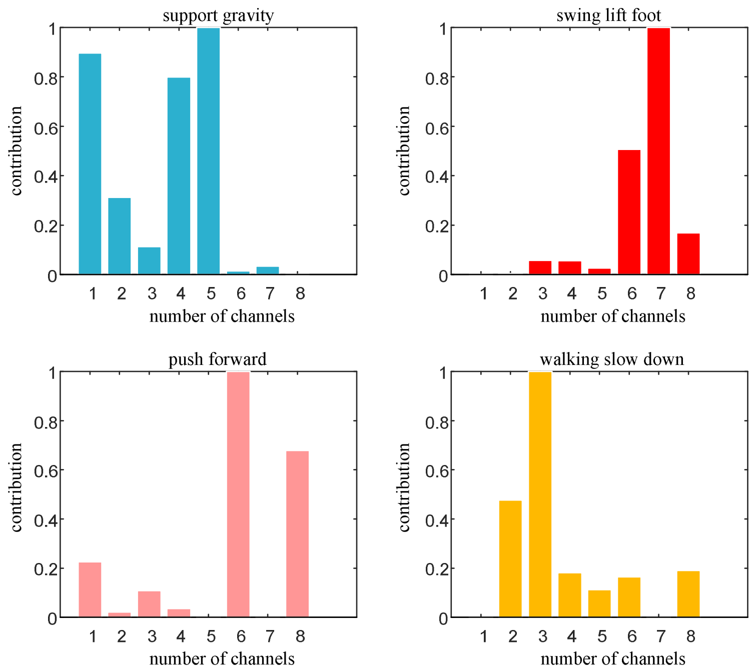

Fig. 6 Synergistic contributions in gait cycle

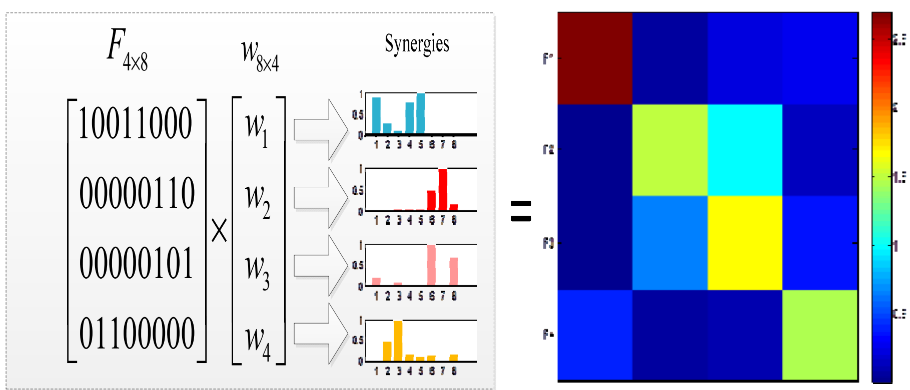

Fig. 7 Functional mapping of gait synergy mechanism

above. Wherein $\boldsymbol{f}_1$ represents the main muscles, participating in the support of gravity: the vastus medialis muscle, the tensor fasciae latae muscle and the rectus femoris muscle. $\boldsymbol{f}_2$ denotes the main muscles, involved in swinging the foot: the tibialis anterior and the lateral gastrocnemius muscles. $\boldsymbol{f}_3$ indicates that the main muscles, involved in pushing the step, are the tibialis anterior and the soleus muscles. $\boldsymbol{f}_4$ stands for the main muscles, involved in the deceleration of the foot: the semitendinosus and the adductor longus muscles.

C. Motor Function Assessment

A method for evaluating gait movement function is proposed, based on synergy structure. In this paper, the integrity of the synergy structure of normal human gait is used. In order to verify whether the four synergy structures, employed by healthy adults, correspond to the four sub-functions of gait movement, the synergy structures, extracted from ten healthy adults, are functionally mapped.

The amplitude of the diagonal element of the matrix is the maximum value, in the corresponding row and column. Where, the $\boldsymbol{W}_{8\times4}$ matrix is the extracted synergistic structure matrix, corresponding to the quantization formula $\boldsymbol{W}_{N\times K}$, that is, 8 muscle channels and 4 synergy elements: $\boldsymbol{w}_1, \boldsymbol{w}_2 . \boldsymbol{w}_3, \boldsymbol{w}_4$. Similarly, the $\boldsymbol{F}_{4\times8} = [\boldsymbol{f}_1, \boldsymbol{f}_2, \boldsymbol{f}_3, \boldsymbol{f}_4]$ is mentioned with its functions.

As seen in Fig. 7, the diagonal element amplitude of the matrix is the maximum within its corresponding row and column. This result indicates that the synergy structure is able to map the gait motion function. The fact that, the diagonal element amplitude is the largest in its corresponding row and column, indicates that the synergy structure can map the gait motion function, despite the apparent differences of different individuals. For patients with neurological damage, the corresponding co-maps deviate from the diagonal, i.e., the maximum amplitude in the row is not so on the diagonal.

V. Conclusions

In this paper, muscle synergy method is proposed, to evaluate the healthy individual's gait, by extracting synergistic elements and activation coefficients. The gait events are subdivided, according to activation coefficients, while the stages are divided according to the proportion of activation, in each gait stage, and the degree of muscle participation. In addition, through functional mapping of synergy structure, the quality of the respective synergy structure, as well as whether the gait is normal or not, are both evaluated. These works can provide valuable input to rehabilitation medical engineering field applications, such as lower limb motor evaluation, intelligent prosthesis and human-computer interaction.

References

[1] D. S. Pargman, E. Eriksson, O. Bates, B. Kirman, R. Comber, A. Hedman*, et al.*, "The future of computing and wisdom: insights from human–computer interaction," *Futures,* vol. 113, pp. 1-10, 2019.

[2] S. Wang, C. Guo, C. Gong, W. Chen, Y. Wang, and Z. Gu, "The effects of correcting tape on extensor synergy gait in hemiplegic patients," *China J Phys Med Rehabil,* vol. 40, pp. 740-744, 2018.

[3] F. Li, "Muscle synergy analysis for children with cerebral palsy based on surface electromyography," University of Science and Technology of China, University of Science and Technology of China, Hefei, China, 2014.

[4] N. U. Ahamed, Z. Taha, M. Alqahtani, O. Altwijri, M. Rahman, and A. Deboucha, "Age related differences in the surface EMG signals on adolescent's muscle during contraction," *IOP Conference Series: Materials Science and Engineering,* vol. 114, pp. 1-6, 2016.

[5] P. Binding, A. Jinha, and W. Herzog, "Analytic analysis of the force sharing among synergistic muscles in one- and two-degree-of-freedom models," *Journal of Biomechanics,* vol. 33, pp. 1423-1432, 2000.

[6] S. Ma, X. Chen, S. Cao, Y. Yu, and X. Zhang, "Investigation of the intra- and inter-limb muscle coordination of hands-and-knees crawling in human adults by means of muscle synergy analysis," *Entropy,* vol. 19, pp. 229-239, 2017.

[7] N. C. Bejarano, A. Pedrocchi, A. Nardone, M. Schieppati, W. Baccinelli, M. Monticone*, et al.*, "Tuning of muscle synergies during walking along rectilinear and curvilinear trajectories in humans," *Annals of Biomedical Engineering,* vol. 45, pp. 1-15, 2017.

[8] J. Chen, X. Zhang, and G. Yin, "Human gait events fast recognition method via surface electromyography," *China Mechanical Engineering,* vol. 27, pp. 911-916, 2016.

[9] N. Jiang, K. B. Englehart, and P. A. Parker, "Extracting simultaneous and proportional neural control information for multiple-DOF prostheses from the surface electromyographic signal," *IEEE Transactions on Biomedical Engineering,* vol. 56, pp. 1070-1080, 2009.

[10] J. Ma, N. V. Thakor, and F. Matsuno, "Hand and wrist movement control of myoelectric prosthesis based on synergy," *IEEE Transactions on Human-Machine Systems,* vol. 45, pp. 74-83, 2015.

[11] R. H. Jiang N, Vujaklija I, et al., "Intuitive, online, simultaneous, and proportional myoelectric control over two degrees-of-freedom in upper limb amputees," *IEEE Transactions on Neural Systems & Rehabilitation Engineering,* vol. 22, pp. 501-510, 2014.

[12] C. L. Lawson and R. J. Hanson, "Solving least squares problems," 1974.

[13] W. Huang, Y. Gao, Y. Zhang, Q. She, and Y. Ma, "Intermuscular coupling analysis based on non-negative matrix factorization and complex net-works," *Space Medicine & Medical Engineering,* vol. 32, pp. 159-166, 2019.

[14] M. Y. Yang S, "Global minima analysis of Lee and Seung's NMF algorithms," *Neural Processing Letters,* vol. 38, pp. 29-51, 2013.

[15] L. Zhou, Y. Peng, G. Yanli, and C. Lingling, "Design of walking gait cycle identification method based on electromyogram and experiment system," *Computer Measurement & Control,* vol. 19, pp. 1965-1967, 2011.

[16] L. Tang, "Research on motor dysfunction assessment in children with cerebral palsy," University of Science and Technology of China, University of Science and Technology of China, Hefei, China, 2017.

[17] A. Subasi, "Classification of EMG signals using PSO optimized SVM for diagnosis of neuromuscular disorders," *Computers in Biology & Medicine,* vol. 43, pp. 576-586, 2013.