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# Muscle synergy analysis in children with cerebral palsy

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## Abstract

**Objective.** To explore the mechanism of lower extremity dysfunction of cerebral palsy (CP) children through muscle synergy analysis. **Approach.** Twelve CP children were involved in this study, ten adults (AD) and eight typically developed (TD) children were recruited as a control group. Surface electromyographic (sEMG) signals were collected bilaterally from eight lower limb muscles of the subjects during forward walking at a comfortable speed. A nonnegative matrix factorization algorithm was used to extract muscle synergies. In view of muscle synergy differences in number, structure and symmetry, a model named synergy comprehensive assessment (SCA) was proposed to quantify the abnormality of muscle synergies. **Main results.** There existed larger variations between the muscle synergies of the CP group and the AD group in contrast with the TD group. Fewer mature synergies were recruited in the CP group, and many abnormal synergies specific to the CP group appeared. Specifically, CP children were found to recruit muscle synergies with a larger difference in structure and symmetry between two legs of one subject and different subjects. The proposed SCA scale demonstrated its great potential to quantitatively assess the lower-limb motor dysfunction of CP children. SCA scores of the CP group ( $57.00 \pm 16.78$ ) were found to be significantly less ( $p < 0.01$ ) than that of the control group (AD group:  $95.74 \pm 2.04$ ; TD group:  $84.19 \pm 11.76$ ). **Significance.** The innovative quantitative results of this study can help us to better understand muscle synergy abnormality in CP children, which is related to their motor dysfunction and even the physiological change in their nervous system.

**Keywords:** muscle synergy, cerebral palsy, surface electromyography

(Some figures may appear in colour only in the online journal)

## 1. Introduction

A fundamental question in the study of neuroscience is to understand how the central nervous system (CNS) organizes motor actions and movements. The brain is supposed to

coordinate the large number of degrees of freedom (DOFs) in the musculoskeletal system and overcome the complexity of limb dynamics to achieve a variety of behavioral goals [1, 2]. Muscle synergy is one of the many hypotheses attempting to offer solutions or models that deal with the DOFs problem [2]. The supporters of muscle synergies defined muscle synergy as a vector specifying a pattern of relative muscle activation, and the absolute activation of each synergy is presumed to be modulated by a single neural command signal [3]. Muscle synergies may represent the bottom of a hierarchical neural control framework. In this framework, higher neural centers manipulate task-related conceptual parameters

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via muscle synergies [4–8]. Under this hypothesis, the CNS controls muscle synergies, or groups of co-activated muscles, rather than individual muscles, to organize actions and movements. However, there exist some objections about this theory of motion control. The main critique is that muscle synergies reflect task constraints rather than neural control strategies [9–12].

In the past few years, muscle synergies have been extracted and discussed based on the analysis of sEMG signals recorded from muscles during different motor tasks in humans and other animals [2, 3, 13–17]. The study of the motor control of monkeys [18] and cats [19] showed that muscle synergies can be recruited by different neural pathways. Furthermore, muscle synergy analysis of the perturbed walking of humans revealed that locomotor muscle synergies can be recruited voluntarily and reactively [20]. These studies suggested that muscle synergies can be flexibly recruited by parallel descending neural pathways. The literature [21, 22] also provides direct support for the hypothesis that the CNS controls movements by adaptive combination of muscle synergies.

Under the muscle synergy framework, a few studies have been performed to understand the motor control of both healthy subjects and stroke survivors in the upper and lower limbs. In muscle synergy analysis of human locomotion, an average of four muscle synergies were extracted from sEMG signals recorded from multi muscles ([23]: 32 muscles, [24]: 8 muscles) involved in the human locomotion of healthy subjects during forward walking [23, 24], and these muscle synergies were considered to be sufficient to account for the variability of muscle activation from step to step and across speeds. In the locomotion of stroke survivors, a reduced number of muscle synergies were recruited, which resulted from merging of the muscle synergies observed in healthy controls [24]. And upper limb muscle synergies of severely impaired chronic stroke survivors were altered in structure from those in healthy controls [25]. Furthermore, muscle synergies in the upper and lower limbs of stroke survivors were observed to be significantly modified toward the chronic phase [26]. In the stroke-affected arms of stroke survivors, studies revealed preservation of normal muscle synergies in subjects with mild-to-moderate impairment while merging and fractionation in subjects with more severe impairment [27]. These muscle-synergy patterns may possibly be used as physiological markers of the status of patients with trauma and provide novel ideas for neural rehabilitation [26, 27].

Cerebral palsy (CP) is the term used for a group of non-progressive disorders of movement and posture caused by abnormal development of, or damage to, the brain. It is caused by events at or about the time of birth. Patients suffering from CP often suffer from neurological and physical abnormalities [28]. The gross motor function measure (GMFM) [29] is usually used to measure the gross motor function, particularly functional changes over time, of CP children. Based on the GMFM, the gross motor function classification system (GMFCS) [30] for CP was proposed to describe the motor function of children and youths with CP and has been used extensively [31]. On the other hand, many

researchers have recorded achievements in assessing abnormalities in the upper and lower extremities of CP subjects using sEMG signals. Some researchers provided methods for clinical gait analysis using sEMG signals based on cadence, symmetry or smoothness characteristics of the muscle activation pattern [32, 33]. And the mean frequency of sEMG was proven to be relevant to the functional muscle strength during gait in CP children [34]. As for the study of selective motor control in CP children, Esther observed that extensor synergy in CP was higher (0.95) than in healthy children (0.77), thigh synergy was almost equal in both groups, and the results supported the sensitive nature of EMG to represent an aberrant motor control in CP [35].

The diseases of stroke and CP originate from nervous system injury. In related researches, EMG data of CP children were decomposed using nonnegative matrix factorization to determine the relative weighting of muscles in each synergy. In a study the crouch gait of three CP children, researchers revealed that the muscle synergies of CP children show strong differences in contrast with healthy controls and strong similarities across patients [36]. Schwartz found that CP children recruited fewer synergies during gait than typically developing children which is similar to previous studies of synergies after stroke [37]. It suggested that CP children used a simpler neuromuscular control strategy during gait compared to unimpaired individuals. However, they did not obtain the specific neuromuscular control model during gait in CP children. The goal of this paper is to explore the muscle synergies of children with CP during forward walking. Because most research results on muscle synergy analysis were obtained from adults, muscle synergy comparison between healthy children and adults was made to explore if muscle synergies can also account for the complex movements of children. Subsequently, the similarities or differences in muscle synergies between CP children and healthy adults and children were analyzed.

## 2. Method

### 2.1. Participants

Participants including 10 healthy adults (AD group,  $24.5 \pm 1.08$  years), eight typically developed children (TD group,  $6.05 \pm 1.66$  years) and 12 children with CP (CP group,  $5.75 \pm 1.83$  years) were recruited in the experiment. Both the AD and TD groups were considered as two control groups in this study. Table 1 shows the gender and age of the control groups and the information on CP children is listed in table 2. Inclusion criteria for CP children included: (a) being diagnosed as having cerebral palsy; (b) having no history of other diseases that also lead to motor deficits; (c) exhibiting abnormal gait; (d) being able to walk independently or assisted; and (e) having no history of any kind of surgical therapy [38]. One should emphasize that ‘abnormal gait’ in (c) is used to describe symptoms, such as slow walking speed, scissor gait, foot eversion or dragging, of CP subjects originating from false control of the motor cortex or spinal cord to

**Table 1.** Subject information of the control groups.

Subjects	Gender	Age	step min <sup>-1</sup>	Subjects	Gender	Age	step min <sup>-1</sup>
AD1	M	25	48	TD1	F	7.6	57
AD2	M	23	55	TD2	M	6	60
AD3	M	24	56	TD3	F	4.5	63
AD4	M	25	48	TD4	M	6	60
AD5	M	25	46	TD5	M	4.6	42
AD6	M	26	51	TD6	F	9.2	63
AD7	M	26	48	TD7	F	4.5	54
AD8	M	24	47	TD8	M	6	52
AD9	M	24	50				
AD10	M	23	48				

**Table 2.** Physiological parameters of 12 CP children.

Subjects	Gender	Age	step min <sup>-1</sup>	TCP	GMFCS	WAP
CP1	M	7	56	HR	I	WI, SI
CP2	M	4	54	HR	I	WI, SI
CP3	M	9	60	DY	II	WI, SI
CP4	F	6	42	SQ	I	WI, SI
CP5	F	4	17	SQ	I	WA, SI
CP6	M	3.7	19	SQ	I	WI, SI
CP7	M	6	24	SQ	I	WA, SI
CP8	M	6	24	SQ	II	WA, SA, SG
CP9	M	5.5	18	SQ	II	WA, SA, SG
CP10	M	4.3	23	SQ	III	WA, SA
CP11	F	4.5	10	SQ	III	WA, SO
CP12	F	9	16	SQ	IV	WA, SA, SG

TCP: type of CP. GMFCS: scale of gross motor function classification system. High GMFCS scale means bad motor dysfunction. WAP: walking performance HR: hemiplegia right; SQ: quadriplegia; DY: dyskinetic; WI: walking independently; WA: walking with assistance; SI: standing independently; SA: standing with assistance; SO: standing with orthoses; SG: scissor gait; for subjects CP5, CP7–12, their guardians would hold their bilateral arms from behind in order to maintain the balance of left and right side during walking. Subject CP11 was asked to take off the orthoses during the experiment, and her guardian would also provide vertical support for her to walk more freely.

the skeletal muscle. The children were recruited with their guardians' written consent and this study was approved by the Ethics Review Committee of Anhui Medical University.

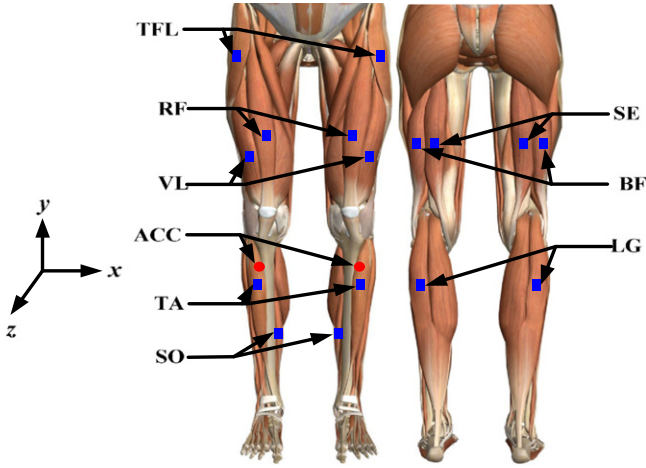
## 2.2. Experimental protocol

The subjects were instructed to walk for 50 consecutive strides on level ground along a straight line at a range of walking speeds comfortable for the subject. Four CP children (CP1–4) and AD1 were asked to walk at slow speed, self-selected comfortable speed and fast speed. Surface EMG signals of lower limb muscles and acceleration (ACC) data were collected simultaneously using a home-made multi-channel system including 16 sEMG sensors (each was a single-differential model constituting a pair of parallel bar-shape silver electrodes in a formation of 10 mm length and 1 mm width for each bar, and 10 mm spacing) and two 3D accelerometers. Taking the small size of muscles in the TD group and the CP group into consideration, surface EMG signals were recorded from eight muscles: *tibialis anterior* (TA), *soleus* (SO), *lateral gastrocnemius* (LG), *vastus*

*lateralis* (VL), *rectus femoris* (RF), *semitendinosus* (SE), *biceps femoris* (BF) and *tensor fasciae latae* (TFL) for each of the legs. Electrode placement was based on the guidelines of the Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) protocol [39]. Before electrode placement, the skin of each sEMG sensor site above the targeted muscle was shaved and cleaned with alcohol cotton. In this study, ACC signals were measured to detect gait cycles. Thus, for each leg, a 3D accelerometer was placed above the tibia and below the knee. The placement of all sEMG sensors and accelerometers was shown in figure 1. 16-channel sEMG signals were sampled at 1000 Hz, and 6-channel ACC signals were sampled at 100 Hz. All data were saved to disk for off-line analysis using Matlab 7.14 (Mathworks, Inc.).

## 2.3. Extraction of sEMG profiles

**2.3.1. sEMG pre-processing.** In order to extract sEMG profiles of the eight muscles for each leg, sEMG pre-processing was conducted first. In the pre-processing



**Figure 1.** The placements of the sEMG and ACC sensors. The anatomical picture of lower-limb muscles is reproduced from Google Body Browser. Rectangles: the sites of sEMG sensors; circles: the sites of the accelerometer. The three-dimensional Cartesian coordinate indicates the three axes of each accelerometer.

procedure, raw sEMG signals were polished by high-pass filtering (window-based finite impulse response filter, 50th order, cutoff of 50 Hz), demeaning, rectifying and low-pass filtering (window-based finite impulse response filter, 50th order, cutoff of 10 Hz) sequentially.

**2.3.2. Step detection.** In a successive walk, we defined that a gait cycle begins when the heel strikes ground and ends when the next strike happens. However, for CP children, walking posture is abnormal and their heels may not touch the ground. Considering the abnormal walking posture, we used the initial contact to segment the gait cycle of CP children [40]. During the foot's first contact with the ground, movement of the leg changes rapidly and leads to peaks in ACC signals. Thus, the gait cycles could be decided by identifying the time when peaks appear in the ACC signals. The peak points were detected using a windowed peak detecting algorithm as shown in figure 2(A). In the flow chart,  $L_{win}$  is the length of the sliding epoch window, which was an estimation of step length. We observed that the healthy subjects involved in our experiment had a gait cycle of approximately 1 s while CP subjects walked more slowly overall, requiring more time to take a step (ranging from 1 s to 7 s). The threshold  $Th$  could be given by

$$Th = \overline{ACC} + 0.5std(ACC). \quad (1)$$

$L_{win}$  zero points were added to both sides of the ACC respectively to ensure that the first and last peak of the ACC can be found. Gait cycles were decided by mapping the peak points of ACC to the polished sEMG signals of eight selected muscles. Then, the polished sEMG signal of each gait cycle formed a sEMG profile matrix. Each row of the data matrix corresponds to a muscle. For a subject, data for every stride were carefully inspected to eliminate the gait cycles with high-amplitude spikes arising from noise. In general, 20 gait cycles could be ensured at least.

Muscle synergy analysis focuses on the muscle activation pattern or how the muscles are coordinated, and information about the degree of muscle activation is not needed [41]. In order to ensure that the sEMG profiles are treated equally and the subsequent derivative muscle synergies are not biased into describing only the muscles with high amplitude, the data from each muscle was normalized to unit variance for the sEMG amplitude equalization between muscles [20, 25, 27]. And the sEMG amplitude difference resulting from electrode offset across trials and subjects would also be corrected.

Taking three gait cycles of RF muscle as an example, figure 2(B) shows the whole procedure of sEMG-profile extraction. Polished sEMG (figure 2(B).II)) was the result of pre-processing of the raw sEMG (figure 2(B).I)). Profiles of three gait cycles (figure 2(B).IV)) were produced by mapping the peak points of ACC (figure 2(B).III)) red points) to polished sEMG. For a gait cycle, eight data vectors of the eight selected muscles formed a sEMG profile matrix (figure 2(B).V)) in the order TA, SO, LG, VL, RF, SE, BF and TFL.

## 2.4. Muscle synergy analysis

**2.4.1. Non-negative matrix factorization.** We extracted muscle synergies from the sEMG profile matrix of the gait cycle using a non-negative matrix factorization (NMF) algorithm [42]. This algorithm has previously been used for muscle synergy analysis [23, 24, 27]. The technique assumes that a muscle activation pattern ( $M$ ) is comprised of a linear combination of a few muscle synergies recruited by a time-varying coefficient ( $C$ ). The recruitment coefficient represents the neural command that specifies how that synergy is modulated over time, and how much each synergy contributes to a muscle's total activity pattern [3]. Assuming that  $W$  represents the muscle-synergy matrix with each column representing a muscle synergy, muscle activation pattern  $M$  can be expressed as:

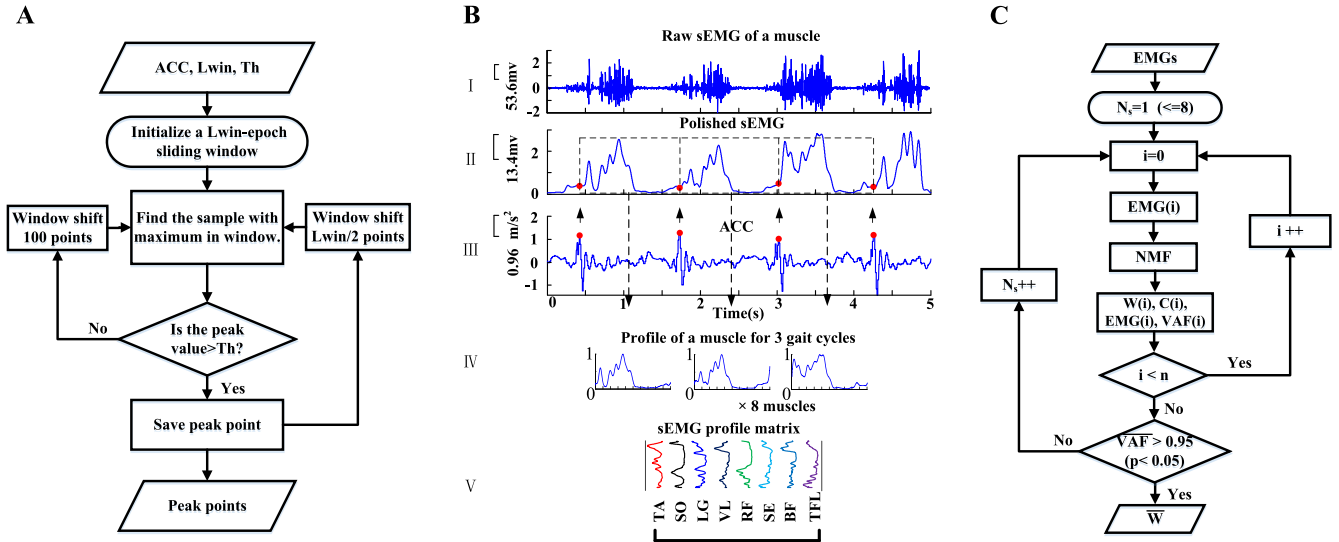
$$M^{m \times n} = W^{m \times s} C^{s \times n} \quad (2)$$

$$M = \begin{bmatrix} M_1(t) \\ \vdots \\ M_m(t) \end{bmatrix}, \quad W = \begin{bmatrix} W_{11} & \cdots & W_{s1} \\ \vdots & \ddots & \vdots \\ W_{1m} & \cdots & W_{sm} \end{bmatrix},$$

$$C = \begin{bmatrix} C_1(t) \\ \vdots \\ C_s(t) \end{bmatrix},$$

where  $m$  is the number of muscles,  $n$  is length of muscle activation pattern and  $s$  is the number of muscle synergies. In the process of factorization,  $W$  and  $C$  were initialized to be random values first, and the sEMG profile of a gait cycle was decomposed to be converged matrix  $W^*$  and  $C^*$  after multiple iterations using updating rules [43] given in equation (3). Then a reconstructed muscle activation pattern can be





**Figure 2.** (A) The flow chart of step detection. (B) Extraction of sEMG profiles. (I) Raw sEMG of RF muscle during walking for five seconds. (II) The polished sEMG after pre-processing. (III) The peak points (red dots) of the vertical ACC were detected by our algorithm. The peak points of ACC were then mapped to the polished sEMG (red dots in (II)). (IV) Profiles of RF muscle for three gait cycles according to (II). (V) Profiles of eight muscles for a gait cycle forming a profile matrix. (C) Flow chart of muscle synergy extraction. EMGs: profile matrices for  $n$  gait cycles selected; EMG( $i$ ): profile matrix for the  $i$ th gait cycle;  $N_s$ : number of muscle synergies;  $n$ : number of EMG profile matrices.

obtained by  $M^r = W^*C^*$ .

$$W_{ij} \leftarrow W_{ij} \frac{(MC^T)_{ij}}{(WCC^T)_{ij}}$$

$$C_{jk} \leftarrow C_{jk} \frac{(W^TM)_{jk}}{(W^TWC)_{jk}}$$

$$W(i) \leftarrow \frac{W(i)}{\|W(i)\|} \quad \forall \text{ column } 'i'. \quad (3)$$

**2.4.2. Determining the number of muscle synergies.** The number of muscle synergies was decided by calculating the variability accounted for (VAF, ranges from 0 to 1) [24] between the original profile (EMG<sub>o</sub>) and the reconstructed one (EMG<sub>r</sub>). For each subject,  $n$  ( $n > 20$ ) gait cycles were selected for muscle synergy extraction. The number of muscle synergies was set to 1 initially and increased sequentially. For each number, VAFs between EMG<sub>o</sub> and EMG<sub>r</sub> were calculated for the  $n$  cycles. When the mean of the  $n$  VAFs was larger than 0.95 (student's t-test at a significant level of  $p < 0.05$ ), the number of muscle synergies was determined and the muscle synergy extraction process was aborted. Lastly, the muscle-synergy matrices were averaged across  $n$  gait cycles for each subject. Figure 2(C) shows the whole process of muscle synergy extraction.

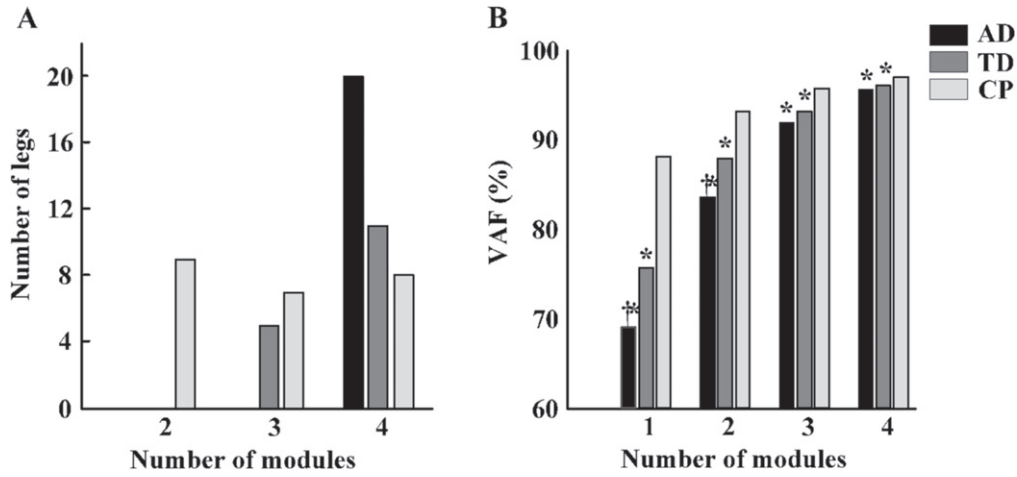
**2.4.3. Similarity between synergies.** In order to compare synergies derived from different subjects, structure similarity between muscle synergies was quantified by Pearson's correlation coefficient ( $r$ ) [20], which can be calculated by

equation (4). Two muscle synergies with  $r > 0.9$  are considered to be similar. Moreover, the similarity between two muscle-synergy matrices with the same number of synergies could also be determined using the 2D correlation coefficient ( $R$ ).

$$r = \frac{n \sum_i^n x_i y_i - \sum_i^n x_i \sum_i^n y_i}{\sqrt{n \sum_i^n x_i^2 - \left(\sum_i^n x_i\right)^2} \sqrt{n \sum_i^n y_i^2 - \left(\sum_i^n y_i\right)^2}}. \quad (4)$$

## 2.5. Synergy comprehensive assessment (SCA)

Based on the muscle synergy analysis, a model called synergy comprehensive assessment (SCA) was proposed to quantify the deficit of lower-limb motor function during forward walking. It was reported in previous studies that muscle synergy derived from healthy people during walking is quite consistent in number and structure [24, 44]. This was also the case for the AD group in our study (as reported in the following results). Therefore, the muscle synergies, which were commonly shared by the AD group, were averaged as a set of standard synergy templates  $Temp = [Temp_1, \dots, Temp_{N_t}]$ , where  $N_t$  is the number of standard templates. Assuming  $W_r$  and  $W_l$  are the extracted muscle synergy sets from the right leg and left leg of a subject respectively, and  $N_r$  and  $N_l$  represent their size. The number and structure similarity score  $S_r$  ( $s_l$ ) between  $W_r$  ( $W_l$ ) and  $Temp$  can be expressed as equations (5) or (6), where  $A = 100/N_t$ . Since four standard templates were selected,  $N_t$  and  $A$  in equations (4) or (6) were valued 4 and 25 separately in the following analysis. The structural score is equal to the average of  $S_r$  and  $s_l$ . The symmetry score between two legs can be calculated using equation (7), where  $B = 100/\max(N_r, N_l)$ . Finally, the SCA score can be computed



**Figure 3.** (A) Number of extracted muscle synergies. Of the 36 healthy legs (AD and TD group) measured, 31 required four modules and 5 needed three. Of the 24 paretic legs (CP group) measured, 8 required four modules, 7 required three modules and 9 needed two. Significantly fewer modules were needed for the CP children. (B) The VAFs corresponding to different number of muscle synergies. For each number of modules, the VAFs of the control group were significantly lower than the CP group (\* $P < 0.001$ ).

according to equation (9). As depicted in equation (8),  $f(X, y)$  is a function to calculate the similarity between muscle synergy  $y$  and muscle synergy set  $X$ . Based on the above definition, the SCA score ranges from 0 to 100, and a large value means less difference in muscle synergy and reflects better walking performance.

$$s_r = \sum_{j=1}^{N_r} Af(Temp, W_{rj}), \quad (5)$$

$$s_l = \sum_{j=1}^{N_l} Af(Temp, W_{lj}), \quad (6)$$

$$sym = \begin{cases} \sum_{i=1}^{N_l} Bf(W_r, W_{li}), & N_l \leq N_r \\ \sum_{i=1}^{N_r} Bf(W_l, W_{ri}), & N_l > N_r \end{cases}, \quad (7)$$

$$f(X, y) = \max \left[ r(X_i, y) \right]_{i=1}^{\text{size}(X)}, \quad (8)$$

$$SCA = (s_l + s_r + sym)/3. \quad (9)$$

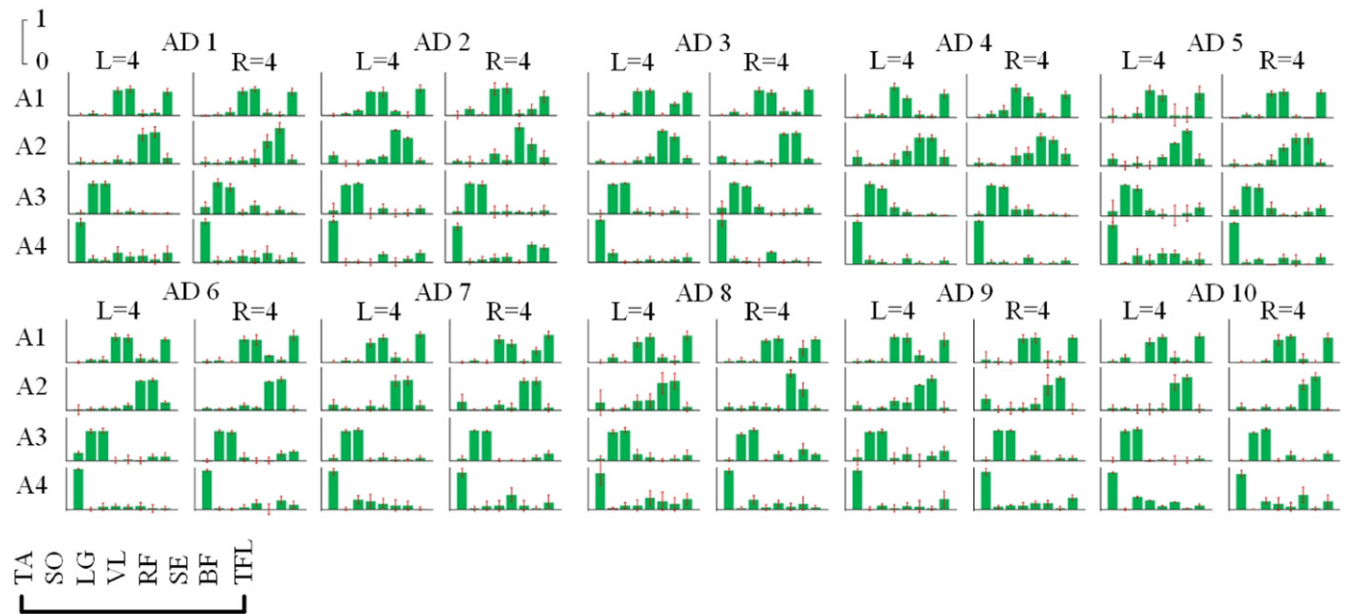
### 3. Experimental results

#### 3.1. Synergies of control group

Of the 36 healthy legs (AD group and TD group) measured, 86.1% required four synergy modules and 13.9% needed three (figure 3(A)). For 10 AD subjects, the results of muscle synergy analysis are shown in figure 4. It can be found that each subject in the AD group recruited four synergies (A1 to A4) for each leg to perform on-ground forward walking. These muscle synergies not only show good symmetry between the two legs of each subject, but also reflect the high number and structure similarity among the ten subjects ( $R = 0.9618 \pm 0.016$ ). Therefore, the averages of A1, A2, A3

and A4 across 10 subjects were computed and labeled as *Temp1*, *Temp2*, *Temp3* and *Temp4* respectively. The synergy *Temp1* is dominated by VL, RF and TFL; *Temp2* is dominated by SE and BF; *Temp3* is dominated by SO and LG; and *Temp4* is dominated by TA. These four synergies derived from the AD group were named mature muscle synergies and selected as the standard templates in the SCA model in the following analysis.

For the TD group, the results of muscle synergy analysis are shown in figure 5. Of the eight healthy children, two (TD1–TD2) have synergies similar to those of adults. By contrast, although three subjects (TD3–TD5) recruited the same number of synergies as AD subjects, the structure of some synergies appears to differ from those in the AD group. Specifically, TD3 and TD4 showed just one or two different structures of synergies in one leg which were different from those found in the AD group, whereas this number of different synergies was found to be two and four for the left and right legs of TD5 respectively. Also, muscle synergies derived from the right leg of TD6 are consistent with those in the AD group, but the number of synergies derived from the left leg decreased to three. Further, all of the remaining two TD subjects (TD7–TD8) recruited three muscle synergies for both legs, among which only one muscle synergy (T3) could be found in the AD group. By all accounts, although there exist some differences in muscle synergies in both number and structure between the TD group (figure 7(A)) and the AD group, a high level of symmetry of muscle synergies could still be found for both legs of each of the TD subjects (figure 7(B)). Moreover, high levels of similarity between subjects in the TD group also were found (synergy matrices with four synergies:  $R = 0.92 \pm 0.07$ ; synergy matrices with three synergies:  $R = 0.84 \pm 0.07$ ). For the two control groups, structural scores of the AD group are significantly higher than the TD group ( $^+P < 0.001$ ) (figure 7(A)), and symmetrical scores showed no difference ( $P > 0.05$ ) (figure 7(B)). This



**Figure 4.** Synergies extracted from 10 healthy adults. AD<sub>i</sub> represent the *i*th adult subject. For each subject, column one lists synergies in left leg and column two lists synergies in right leg. A<sub>i</sub> represent four synergies, where *i* ranges from 1 to 4. Muscle synergies in the same row (marked with A<sub>i</sub>) have  $r > 0.9$  to each other. In each subplot, bars of different height represent relative muscle activation.

means that the control group has good symmetry between right and left legs.

### 3.2. Synergies of the CP group

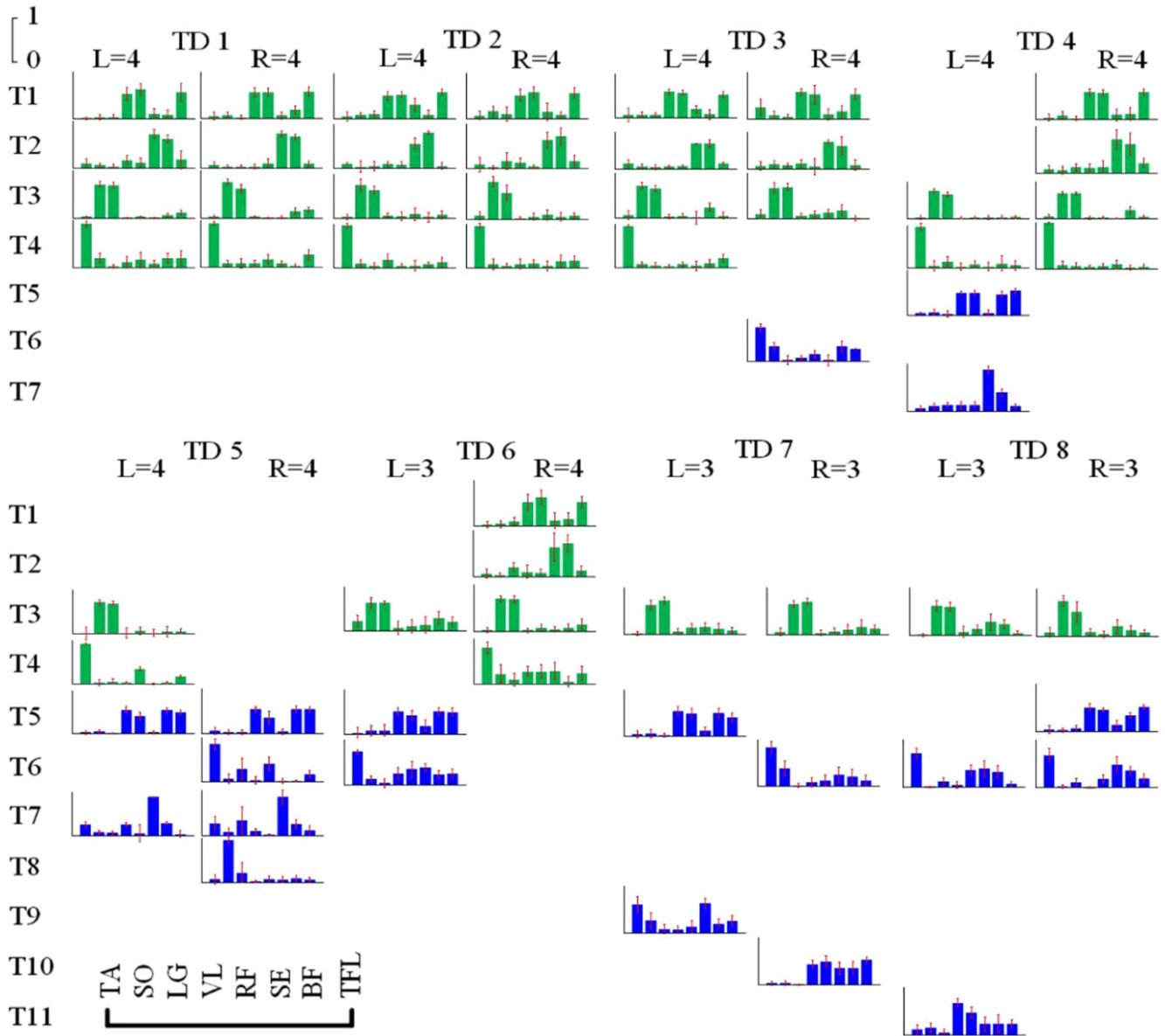
Of the 24 paretic legs (CP group) measured, 33.3% required four modules, 34.3% required three modules and 32.4% needed two (figure 3(A)). This means that CP children recruited fewer synergies during gait than the TD group. This result is consistent with the research of Schwartz [38]. Meanwhile, the VAFs corresponding to each number of modules extracted by NMF were always significantly lower in the control group ( $P < 0.01$ ) than that of the CP group (figure 3(B)). Lower VAF for a particular number of modules indicates that muscle control patterns are more complex during walking. The structures of muscle synergies of the CP group are shown in figure 6. CP1–7 except CP3 were classified as Grade I using GMFCS. CP1–4 were able to walk and stand independently. In each leg, CP1–4 recruited four muscle synergies. For CP1, four muscle synergies (C1–C4) in his left leg and one muscle synergy (C2) in his right leg were similar to that of healthy subjects while the other three muscle synergies (C6, C13, C14) were specific to the CP group. CP1 and CP2 have hemiplegia right, and the muscle synergies (C2, C6, C13, C14) in the right leg of CP1 and CP2 were similar. The similarity between CP1 and CP2 might be caused by the same type of cerebral palsy, and the lack of mature synergies might contribute to the dysfunction of CP1 and CP2 in their right leg. For the left leg of CP2, only one muscle synergy (C4) was similar to healthy subjects and the other three muscle synergies (C6, C7, C15) were specific to the CP group. For the dyskinetic patient CP3, all the muscle synergies (left: C7, C10, C12, C16; right: C6, C10, C11, C14) were specific to the CP group. For spastic quadriplegia CP4–12,

only CP4 and CP6 were able to walk and stand independently. Four muscle synergies were recruited in each leg, and one muscle synergy (left: C2) of CP4 was similar to healthy. For CP6, a total of five muscle synergies were recruited in his two legs, which is less than CP4 (eight muscle synergies). Three muscle synergies (C1, C2, C3) in his left leg were similar to healthy subjects while the two muscle synergies (C9, C11) in his right leg were specific to the CP group. The other subjects (CP5, CP7–CP12) could not walk independently, and only CP5 and CP7 could stand independently. Three muscle synergies were recruited in each leg of CP5 and two were recruited in each leg of CP7. Some synergies (C2, C3 of CP5; C3 of CP7) were similar to healthy controls. Comparing figures 5 and 6, we found that C5 (or T10) was shared by CP children and TD8 in the TD group. This meant that C5 belonged to normal synergy. Thus, CP5 and CP7 recruited more than half of the normal muscle synergies. In contrast to CP5, CP10 recruited three muscle synergies in both legs but with none of the mature synergies. For the rest of subjects (CP8–12, except CP10), the total number of muscle synergies was small and most of synergies were specific to the CP group. In brief, larger variation exists between the muscle synergies of the CP group and the AD group compared to the TD group.

### 3.3. Assessment of muscle synergy abnormality

To further demonstrate the muscle synergy differences between CP children and healthy controls in number, structure and symmetry in both legs, structural scores, symmetrical scores and SCA scores of all the subjects are given in figures 7 and 8. From figure 7, we can observe that the structural scores and symmetrical scores of the control group (AD group and TD group) are significantly higher than those





**Figure 5.** Synergies extracted from eight typically developed children. Synergies in accordance with those of adults in figure 5 are marked in green. Other synergies are marked in blue.

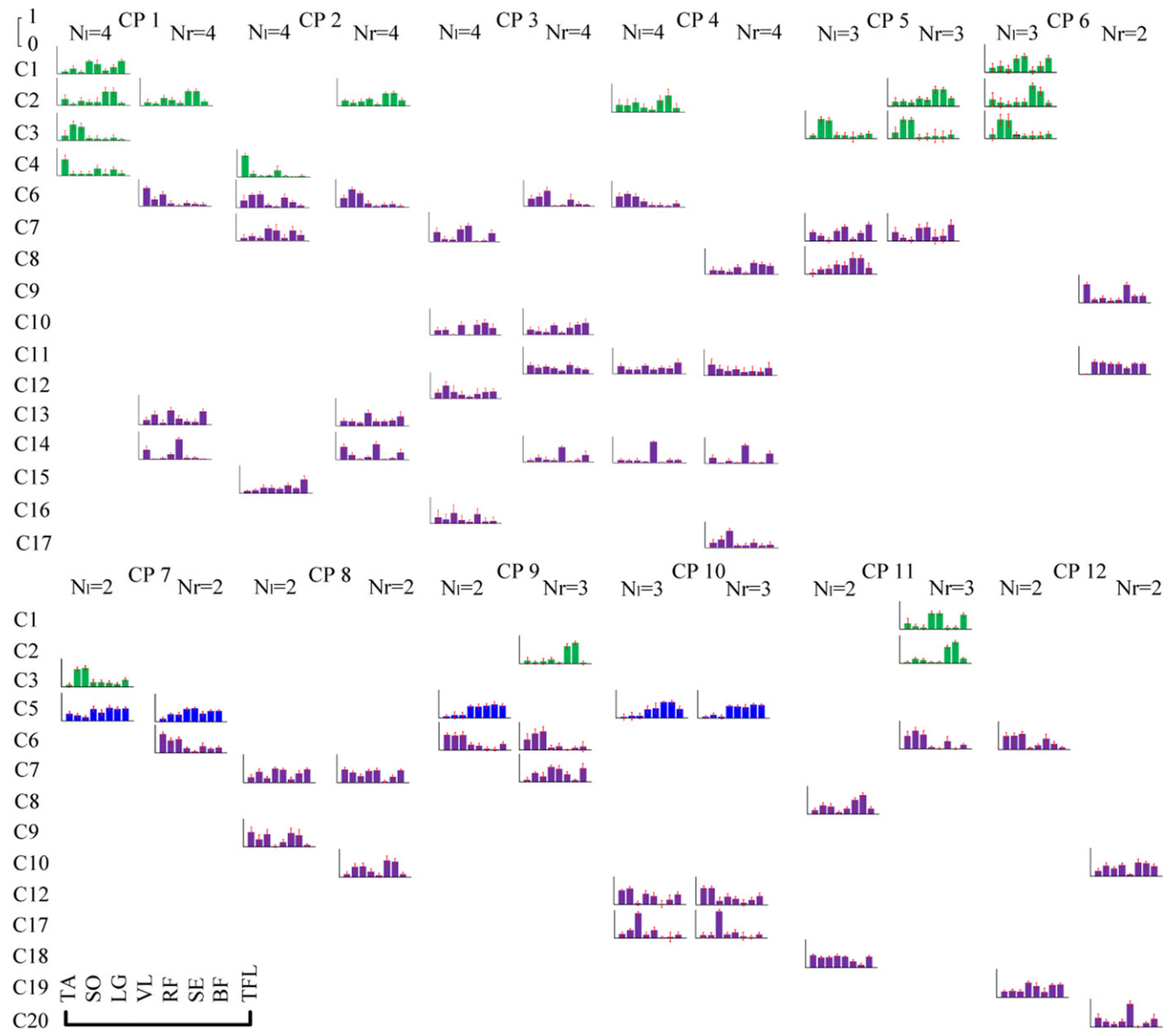
of the CP group (\* $P < 0.001$ ). As figure 8 shows, the SCA scores of CP subjects ( $SCA = 57.00 \pm 16.78$ ) are significantly less than that of the AD group ( $SCA = 95.74 \pm 2.04$ ,  $p < 0.001$ ) and TD group ( $SCA = 84.19 \pm 11.76$ ,  $p < 0.001$ ). AD1–AD10 and TD1–TD4 have SCA scores greater than 92. TD5–TD8 get lower SCA scores ( $69 < SCA < 81$ ) because they have fewer muscle synergies or less synergy symmetry. These results demonstrate that SCA score can quantify muscle synergy difference in number, structure and symmetry effectively and may be used to assess the physical abnormality of CP children.

### 3.4. Robustness of muscle synergy across walking speeds

All the subjects walked at different self-selected speeds as tables 1 and 2 show. The mean value of the AD group is

$49.9 \pm 3.5$  step  $\text{min}^{-1}$ ; the TD group is  $56.4 \pm 7$  step  $\text{min}^{-1}$ ; and the CP group is  $30.25 \pm 17.70$  step  $\text{min}^{-1}$ . In previous studies [20, 24], researchers found muscle synergies with each subject to be robust across walking speed. In order to verify whether the speed could impact the structure of muscle synergies, AD1 was asked to walk at slow speed (25 step  $\text{min}^{-1}$ ), self-selected comfortable speed (46 step  $\text{min}^{-1}$ ) and fast speed (78 step  $\text{min}^{-1}$ ). We found that the extracted muscle synergies of the subject walking at different speeds were similar to standard synergy templates ( $R_{\text{slow}} = 0.92$ ,  $R_{\text{self}} = 0.95$ ,  $R_{\text{fast}} = 0.90$  respectively) and the SCA scores were 93.21, 95.89 and 91.18 respectively. These results are consistent with previous studies [20, 24] and prove that the difference in speed has less effect on muscle synergies.

To verify whether the speed could impact muscle organization in pathological subjects, four CP children (CP1–4)



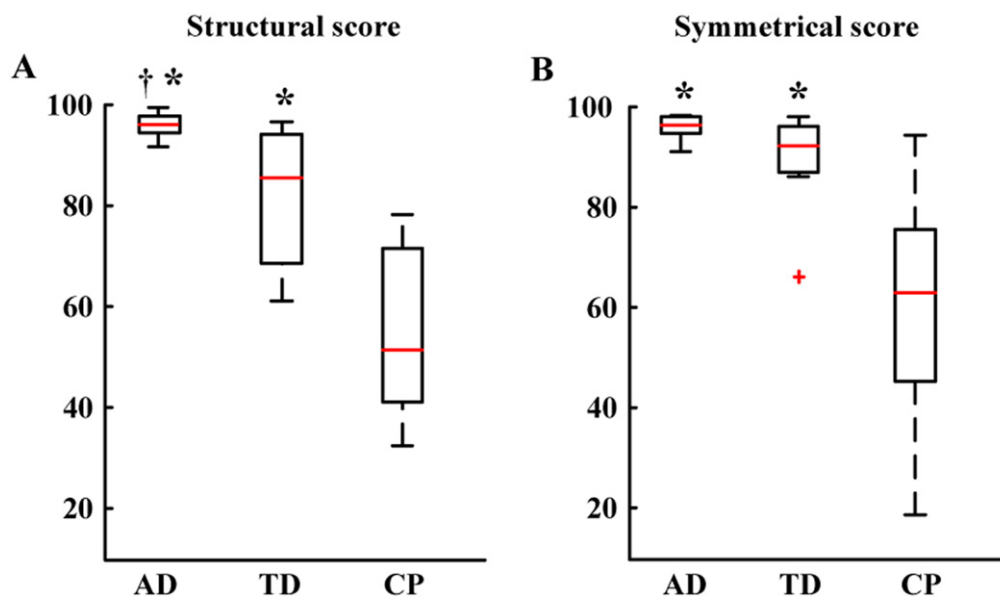
**Figure 6.** Synergies extracted from 12 CP children. Synergies that are of high similarity ( $r > 0.9$ ) to the control group in figures 5 and 6 are colored in green. And synergies that are specific to CP group colored in purple.

were asked to walk at slow speed, self-selected comfortable speed and fast speed. The walking speed of the CP children is listed in table 3. We extracted the muscle synergies of the CP children walking at different speeds and calculated Pearson's correlation coefficient ( $R$ ) between them. For CP1, we found that the extracted muscle synergies (figure 9) walking at different speeds were similar (left leg:  $R_{slow-self} = 0.98$ ,  $R_{slow-fast} = 0.99$ ,  $R_{fast-self} = 0.99$ ; right leg:  $R_{slow-self} = 0.99$ ,  $R_{slow-fast} = 0.98$ ,  $R_{fast-self} = 0.99$ ). And the SCA scores were 76.8, 76.6 and 77.1 respectively. No difference in SCA scores was found under different speeds. Based on our experimental results, we found that the number of muscle synergies extracted from four CP children with different speeds was four and the structures of synergy were similar (table 3). Meanwhile, the change of speed has less effect on muscle synergies and SCA scores. This means that the muscle

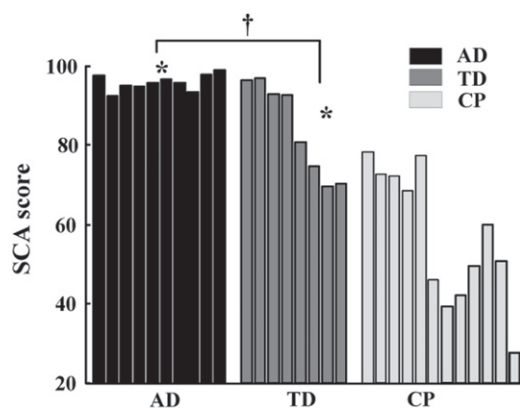
synergy of the CP children is robust under different walking speeds.

#### 4. Discussion

Since alternations of muscle synergy in aspects of number and structure can be used to examine various pathological changes in the CNS, muscle synergy analysis has been suggested as a metric for motor assessment [45]. In many previous studies, muscle synergy analysis of forward walking has been conducted on both post-stroke hemiparetic subjects and healthy controls [24]. Stroke patients were found to recruit fewer muscle synergies for muscle activation during walking in contrast to healthy controls. It has been reported that the reduced number of muscle synergies can be used to explain



**Figure 7.** Structural scores and symmetrical scores of all the subjects involved in our study. (A) Structural score (mean value of double legs). The structural scores of the control group (AD group and TD group) were significantly higher than that of the CP group (\* $P < 0.001$ , independent samples t-test). The TD group had a lower score than the AD group († $P < 0.001$ ). (B) Symmetrical score. The symmetrical scores of the control group were significantly higher than that of the CP group (\* $P < 0.001$ ). The TD group and the AD group showed no difference ( $P > 0.05$ ), but subject TD6 was abnormal.



**Figure 8.** SCA scores of subjects involved in this study. The SCA scores of the control group (AD group and TD group) were significantly higher than the CP group (\* $P < 0.001$ ). The TD group had a lower score than the AD group († $P = 0.007$ ).

the abnormality in muscle activation patterns [46, 47]. Taking advantage of its great potential in revealing motor control strategy of the CNS, the current study applied the muscle synergy analysis to individuals with a different nature of neurological disorder from stroke, i.e. CP. Moreover, the muscle synergy results derived from the control group, including both healthy adults and typically developed children were also reported for the purpose of comparison, in order to better understand the results derived from the children with CP.

#### 4.1. The development of locomotor patterns

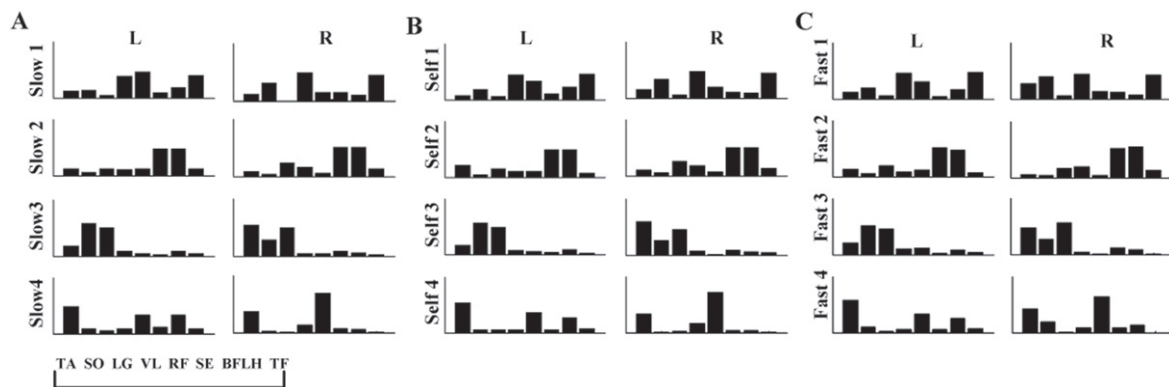
It could be observed from the experimental results that subjects in the AD group recruited four muscle synergies with a

high level of similarity over all individuals for both legs during forward walking. Such a result indicates good consistency of the mature muscle synergies in healthy adults and is consistent with a previous study [24]. One important finding of the current study is that the process of development could affect muscle synergy, which was suggested by the comparison between the TD and AD group. Of the eight TD children, two TD children showed exactly four mature synergies which were consistent with the AD group, whereas others exhibited some alternations in the number and structure of resultant muscle synergies. This result is in accordance with the study of Dominici [48] on the development of locomotor patterns. Dominici and his collaborators found that the same four primitives (muscle synergy activation signal) underlie locomotion in toddlers, preschoolers, and adults, while only two primitives underlie locomotion in neonates. It is possible that some locomotor patterns are inborn while other locomotor patterns are learned based on specific task requirements [49]. For the TD group, there were in total seven specific synergies (T5–T11) different from mature synergies, and three of them (T5–T7) were widely shared across most TD children. The reason for explaining the difference in muscle synergies between the AD and TD groups may be that children's CNSs can gradually reach maturity with their muscle synergies being learnt and updated to be mature ones like those of adults during the process of development. In this regard, the degree of CNS maturity for a child can be roughly reflected by the muscle synergy difference between the child and adults. However, not only age but also other physical and psychological factors can influence the CNS maturity during the process of development. We also found that for the TD children, the degree of differences in muscle synergy was not positively correlated to their age. For example, three TD

**Table 3.** Speed information of CP children.

Subjects	Number		Slow	Self	Fast	$R_{slow-self}$		$R_{slow-fast}$		$R_{self-fast}$	
	L	R	(step min <sup>-1</sup> )	(step min <sup>-1</sup> )	(step min <sup>-1</sup> )	L	R	L	R	L	R
CP1	4	4	42	56	66	0.98	0.99	0.99	0.98	0.99	0.99
CP2	4	4	38	54	70	0.90	0.89	0.86	0.86	0.89	0.90
CP3	4	4	48	60	66	0.87	0.95	0.91	0.94	0.89	0.96
CP4	4	4	28	42	48	0.93	0.94	0.92	0.89	0.90	0.88

Number: The number of muscle synergy of each leg. R: The Pearson's correlation coefficient between different speeds.

**Figure 9.** Synergies extracted from CP1 with different speeds. (A) Slow speed; (B) self-selected comfortable speed; (C) fast speed.

children with ages ranging from 6 to 7.6 years have access to mature synergies while others from 4.5 to 9.2 years have not acquired mature synergies. Jacobs concluded that gait patterns in 3- and 5-year-old children were not fully mature [50]. Assaiante found that the oldest children and adults also showed lower activation levels of hip and knee muscles but higher activation at the ankle level and the kinematic [51]. Based on our results, it can be inferred that CNS maturity takes place over a wide range of ages, which is inconsistent with Sutherland's study [52] reporting that CNS maturity takes place at approximately 4 years of age. Nevertheless, it should be acknowledged that the CNS is always updated and adjusted adaptively for healthy individuals. Such a development factor needs to be taken into account when understanding the muscle synergy results derived from CP children.

#### 4.2. Abnormal muscle synergy in CP

Many previous studies reported that changes in muscle synergy structure may affect the co-activation pattern of muscles and may suggest changes in neural connectivity or excitability after stroke or spinal cord lesions [53, 54]. Our study reveals consistent findings in CP children, suggesting that the application of muscle synergy analysis can also be expanded from adults with various neurological disorders to children with CP. By the muscle synergy analysis applied to CP children, large variations in muscle synergy between the CP group and the control group (including AD and TD subjects) were found, in terms of reduced synergy number, altered synergy structure and degenerated level of symmetry between two legs. In contrast to the muscle synergies derived from the control group, such large alternations in the number

and structure of muscle synergies derived from the CP group may reflect the pathological changes of the CNS control strategy underlying the CP. Specifically, the recruitment of mature muscle synergies can also reflect the motion performance of children suffering from CP. Among all CP children, CP1–2 and CP4–CP7 were classified as Grade I using GMFCS. Except CP5 and CP7, other subjects were able to walk and stand independently. In each leg, CP1–4 recruited four muscle synergies which was the same number as the AD group. CP1 with relatively low GMFCS scale exhibited the most of mature synergies. CP5–6 recruited more than half of normal muscle synergies. Most muscle synergies recruited by CP8–12 were abnormal and the total number was less than six. CP12 with the highest GMFCS scale exhibited no mature synergy. Based on the results, the number of muscle synergies can reflect the degree of movement disorders. Therefore, we supposed that a greater number of muscle synergies and normal mature synergies reflected better motor function with low GMFCS scale.

Additionally, special dyskinesia such as toe-walking may be responsible for specific synergies. For example, CP8, CP9, CP11 and CP12 used toe-walking, and figure 6 shows that CP9, CP11, CP12 recruited specific synergy C6 (with high contributions from TA, SO, LG) in common. Thus, we concluded that the contribution of three muscles (TA, SO, LG) weightings were high in CP children with toe-walking. Of course, more investigations regarding the neuropathology underlying the CP need to be done to explain this phenomenon. Besides, the muscle synergies derived from CP children show larger inter-subject variability than the control group. Furthermore, few mature synergies but many specific synergies can be found in CP children.



#### 4.3. Effect of walking speed and assistance on muscle synergy

Previous research results in the literature showed that the walking speed did not impact on muscle synergy structure and number [44]. However, Clark *et al* showed that the locomotor output complexity (number of independent modules) in the paretic leg of post-stroke persons was associated with speed difference between self-selected and fast walking [24]. In their study, they showed that the speed of walking changed under different numbers of modules. Similarly, CP children with different level self-selected speed were found to recruit different numbers of synergies during forward walking in our study: four muscle synergies for  $53.0 \pm 7.7$  step  $\text{min}^{-1}$ , three muscle synergies for  $36.5 \pm 19.2$  step  $\text{min}^{-1}$  and two muscle synergies for  $21.0 \pm 4.6$  step  $\text{min}^{-1}$ . However, Clark *et al* did not show whether the modules of the same subject change with walking speed. To verify whether the speed could impact muscle organization in pathological subjects more intuitively, four CP children were asked to walk at slow speed, self-selected comfortable speed and fast speed. Because it is difficult for most CP children to control their speeds well, we selected four CP children who were able to walk independently. Based on the experimental results, we found that the number of muscle synergies extracted from the same subject with different speeds was four and the structures of the extracted synergies were similar (table 3). This means that muscle synergy of CP children is robust under the control walking speed. So we supposed that the differences in the self-selected speeds of three groups may impact the synergies, but the influence is quite small.

In our study, two kinds of CP children (walking independently and walking with assistance) were involved. The structure scores, symmetrical scores and SCA scores of muscle synergies between 18 healthy subjects (AD1–10 and TD1–8;  $St = 89.43 \pm 11.91$ ,  $Sy = 92.95 \pm 7.64$ ,  $SCA = 90.60 \pm 9.70$ ) and seven CP children walking with assistance (CP5 and CP7–12;  $St = 45.03 \pm 12.82$ ,  $Sy = 58.44 \pm 27.23$ ,  $SCA = 49.50 \pm 15.93$ ) showed significant difference ( $P < 0.05$ ). The three scores between 18 healthy subjects and five CP children walking independently (CP1–4 and CP6;  $St = 68.85 \pm 11.40$ ,  $Sy = 64.83 \pm 16.94$ ,  $SCA = 67.51 \pm 12.55$ ) also showed significant difference ( $P < 0.05$ ). Symmetrical scores showed no significant difference ( $P > 0.05$ ) between CP children walking independently and walking with assistance. However, SCA scores and the structure scores of CP children walking independently were significantly higher than CP children walking with assistance. Based on the above results, we can conclude that symmetry abnormality between the two legs existed both in CP children walking independently and walking with assistance, but CP children walking independently recruited the same number of muscle synergies as healthy subjects and more mature synergies than those walking with assistance.

#### 4.4. Assessment of muscle synergy abnormality

Inspired by the above findings regarding the association between muscle synergies and motor deficiency under CP, we proposed the SCA scale to quantitatively assess muscle

synergy abnormality in terms of muscle synergy number, structure and symmetry between two legs. It was noteworthy that muscle synergy analysis results derived from CP children were generally consistent with their functional impairment level, as manifested by the GMFCS scale. As discussed in part B of this section, CP children with low GMFCS scale recruited a greater number of muscle synergies and normal mature synergies. SCA has a similar ability as the GMFCS to depict motor function disorder. For instance, CP1 with the lowest GMFCS scale obtained the highest SCA score ( $SCA = 78.65$ ) in all CP children, and CP12 with the highest GMFCS scale got the lowest SCA score ( $SCA = 27.61$ ). Not only that, but SCA has a more powerful ability to evaluate gait abnormality than GMFCS. Take CP1 and CP2 as an example, there was no difference between them from the perspective of the GMFCS scale (Grade I) and the type of CP (hemiplegia right). However, the motor coordination of CP1 was better than CP2 according to the assessment of a professional doctor, and this coordination difference also can be found in the results of the muscle synergy analysis (as shown in figure 6, CP1 recruited four normal mature synergies but CP2 recruited only one). In this case, SCA gave better a evaluation result (CP1: 78.65; CP2: 72.42) than the GMFCS. Another example is CP6 and CP10. From figure 6, we can observe that CP10 recruited three synergies in each leg and high symmetry existed in his two legs. Although CP6 recruited three normal mature synergies in his left leg, only two synergies specific to CP were extracted from his right, and there was no symmetry between the two legs. The GMFCS scale of CP10 (Grade III) was higher than CP6 (Grade I), but the SCA score of CP10 ( $SCA = 60.07$ ) was much higher than that of CP6 ( $SCA = 46.07$ ). Obviously, the SCA score depicted more accurately the muscle coordination of gait in this condition. Based on such results, muscle synergy analysis combined with the proposed SCA scale demonstrated its great potential to assess quantitatively the lower-limb motor dysfunction of a CP patient.

#### 4.5. Limitations

Our study sheds light on the motor function assessment of CP children, but there are a few limitations awaiting further study. Firstly, the method used to compare the synergies heavily depends on the threshold that was set to 0.9. A different threshold will make different evaluation results of synergy similarity. A high similarity threshold with rigorous restraint will lead to additional synergy structure while a lower one will lead to less synergy structure. Taking subject TD3 for example, the fourth synergy of the right leg (T6) is different according to the criterion but the synergy is somewhat similar to that of the left leg with dominance of the TA muscle contribution (T4). However, this drawback cannot affect motor function quantification with the SCA model. Secondly, a VAF-based muscle synergy extraction method was used in this study. It should be pointed out that the number of muscle synergies may vary when a different VAF threshold is used. Thirdly, although the speed does not drastically change synergies, it still affects spatiotemporal



EMG patterns and may contribute to variability of the resultant muscle synergies. Fourthly, in human locomotion, a lot of skeletal muscles are coordinated by the nervous system, which makes movement complex. However, we only take the role of the eight lower-limb muscles into consideration in this study, which may hinder the understanding of the strategy of how the nervous system organizes movements of the whole body. Some studies suggested that including more muscles in muscle synergy extraction may significantly affect the structure and the number of muscle synergies [55, 56]. Furthermore, some CP children need assistance in walking. We are not sure whether gait assistance in these CP children contributes to inter-subject variability. Crosstalk in EMG recordings in small children may also be a factor for reported inter-subject variability. In future work, these factors would be considered in more detail. Finally, the CP subjects involved in this study have in fact been receiving months of rehabilitation. As a preliminary study, we did not quantitatively assess the effect of the rehabilitation. Although rehabilitation can change the walking performance, it is unknown how muscle synergies in CP children change over the process of rehabilitation. Changes in muscle synergies in the aspects of number, structure or symmetry may be used to assess the changes of motor function and help the therapist or doctor to develop customized rehabilitation therapies for patients with cerebral palsy. In future work, experimental protocol will be improved by taking more skeletal muscles into consideration, and more CP subjects will be recruited to make our conclusion more convincing. Thus, further study will be conducted to assess the effect of rehabilitation treatment over chronic rehabilitation.

## 5. Conclusion

In this study, muscle synergy analysis was applied to CP subjects. Reduced number or symmetry and varied structure of muscle synergy implied motor dysfunction in CP children, which demonstrated the physiological changes in their nervous system. To quantify those changes in muscle synergies, the model of synergy comprehensive assessment was proposed. The results suggested that the SCA model could quantify the abnormality of muscle synergies effectively. This will help us understand how the nervous system organizes motor actions and movements, and also provide guidance for the development of rehabilitation strategies for CP subjects.

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