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Developmental Changes of Muscle Synergies in an Infant's Walking

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Abstract— **Primitive stepping is one of the primitive reflexes in newborns in response to external stimuli. It is known that primitive stepping disappears about two months after birth, but its role and the relationship with voluntary gait acquired later are still unknown. In this study, we extracted muscle synergies, spatiotemporal coordination patterns of muscle activities, from EMG measured in one infant during growth (4-18 weeks of age) using non-negative matrix factorization (NMF). We found that a synergy changed before and after the disappearance of the primitive stepping, and others maintained the recruited muscles but changed the onset timing of the activations.**

I. INTRODUCTION

Newborns exhibit a variety of primitive reflexes related to the lower extremities. When the newborn is picked up, the bottom of the foot is placed on the floor, and a positive supporting reflex occurs, in which the lower limbs extend to raise the body in the vertical direction. Leaning forward from this upright position elicits a gait-like movement in which both lower limbs are alternately extended, i.e., primitive stepping reflex.

Forssberg reported that eliciting primitive stepping reflex becomes increasingly difficult after the first month of life and is almost absent by the second month [1]. Okamoto et al. examined the developmental changes after two months of age [2]. They found that infants around 3-4 months old begin to perform active leg extension movements before landing the feet, which newborns do not show. They speculated that voluntary movements involving the cerebral cortex began to join the primitive stepping reflex of the neonatal period [3]. Some studies investigated developmental changes in primitive stepping reflex by analyzing electromyograms (EMG) and suggested that some patterns of muscle activity were common to adult gait. Others were markedly different [1, 2, 4]. Some of them also suggested that the muscle activity patterns of the primitive stepping reflex disappear once but reappear at the acquisition of gait around one year old [1, 3, 4].

Many studies discuss vertebrates controlling their musculoskeletal system, which has redundant degrees of freedom, by combining a small number of movement patterns [5, 6]. The spatiotemporal coordination patterns of muscles and joints are called synergies. Various studies have quantitatively analyzed synergies and suggested their existence. However, many unresolved aspects remained in synergies' expression and developmental process.

Dominici et al. analyzed muscle synergies extracted from EMG data during primitive stepping in neonates and walking in toddlers, preschoolers, and adults. They suggested the existence of synergies common to all stages and synergies acquired with growth [7]. However, few studies have investigated the expression and changes of synergies during individual developmental stages. The ultimate goal of this study is to reveal the process of gait development and the role of the primitive stepping reflex through quantitative analysis of synergies.

In this paper, we extracted muscle synergies using EMG data continuously recorded in one infant's gait development. By comparing synergies at each stage of development, we investigated how muscle coordination patterns change.

II. METHOD

A. Experiment

EMGs of one infant during walking were recorded at 4, 7, 10, 14, and 18 weeks old (at 26, 47, 68, 97, and 127 days after birth) [8]. The experimenter induced the primitive stepping reflex by supporting the infant under both arms and placing the infant's feet on the floor. In ages after the primitive stepping reflex disappeared, the walking behavior was induced by distracting the infant.

B. Measuring and preprocessing EMG signals

The skin was preprocessed so that the resistance at the measurement site was less than 5000 Ω. Surface EMG signals were measured in bipolar leads using a 5 mm diameter dish electrode and an 18-channel pen-writing electro-encephalograph (Sannei Sokki, 1A53 (60 mm/sec) with a gain at 12 mm/0.5 m V). The muscles measured were tibialis anterior (TA), gastrocnemius lateral (LG), vastus medialis (VM), rectus femoris (RF), long head of biceps femoris (BF), and gluteus maximus (GM).

We digitized EMGs from scanned images (2552 × 3504 pixels) of pen-written EMGs. The digitized EMGs corresponded to them measured with 296 Hz. We individually

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normalized the digitized EMGs for each muscle by dividing them by the standard deviation of all data within each week-old (WO) condition. The EMGs were then full-wave rectified and were low-pass filtered by a fourth-order Butterworth filter with a cutoff frequency of 4 Hz [9].

We defined one cycle as from the timing of right foot contact to the timing of the next right foot contact. We identified the foot contacts using video recorded from the lateral direction. The length of each cycle was resampled to 1000 time points.

C. *Extracting muscle synergies*

We performed muscle synergy extraction by applying non-negative matrix factorization (NMF) [10] to the filtered and resampled EMG signals [5]. That is, the preprocessed EMG $\boldsymbol{X}$ (with N rows and D columns) is divided into a synergy matrix $\boldsymbol{W} = [\boldsymbol{w_1}, \boldsymbol{w_2}, \cdots, \boldsymbol{w_K}]$ (with T rows and N columns) and a coefficient matrix $\boldsymbol{H} = [\boldsymbol{h_1}, \boldsymbol{h_2}, \cdots, \boldsymbol{h_K}]^{\boldsymbol{T}}$ (with K rows and D columns);

$$\boldsymbol{X} \approx \boldsymbol{W}\boldsymbol{H}.$$

Here, N, D, and K are the number of time samples, EMG channels, and synergies.

D. *Similarities of synergies and coefficients*

We use cosine similarity to evaluate the similarity of synergies and coefficients [5, 11] at each WO;

$$Sw_k^{ij} = \frac{\boldsymbol{w}_k^i \cdot \boldsymbol{w}_k^j}{\|\boldsymbol{w}_k^i\| \|\boldsymbol{w}_k^j\|},$$

$$Sh_k^{ij} = \frac{\boldsymbol{h}_k^i \cdot \boldsymbol{h}_k^j}{\|\boldsymbol{h}_k^i\| \|\boldsymbol{h}_k^j\|}.$$

w_k^i and w_k^j are k-th synergies of i-th and j-th WO.

III. RESULTS

At each week old (4, 7, 10, 14, and 18 WO), we collected 5, 4, 8, 7, and 3 cycles, respectively. We averaged EMG (normalized and resampled in II-B) over cycles at each WO and extracted muscle synergies by NMF. We performed NMF 10 times from random initial values because NMF has initial value dependence [10]. Fig. 1 shows the average and standard deviation of the cumulative explained variance over the ten times NMF when the number of synergies was 1~5. For all WO, using three synergies can explain 84-91% of the variance in the original EMG.

Fig. 2 presents the synergies and coefficient matrices extracted when the number of synergies was 3 for each age group.

Fig. 3 shows the similarity of the synergies $\boldsymbol{W}$ and the coefficient matrix $\boldsymbol{H}$ between 4 WO and 7-18 WO.

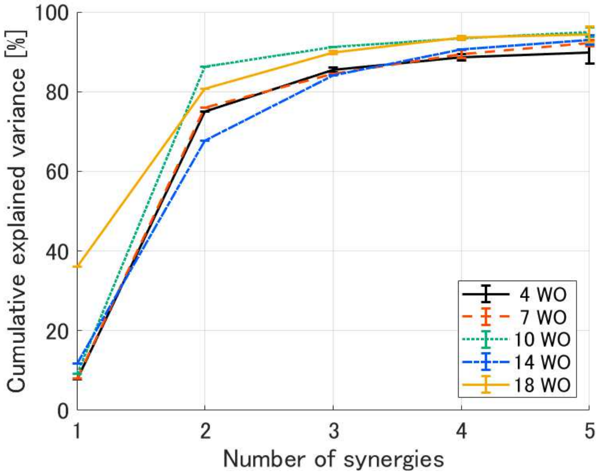
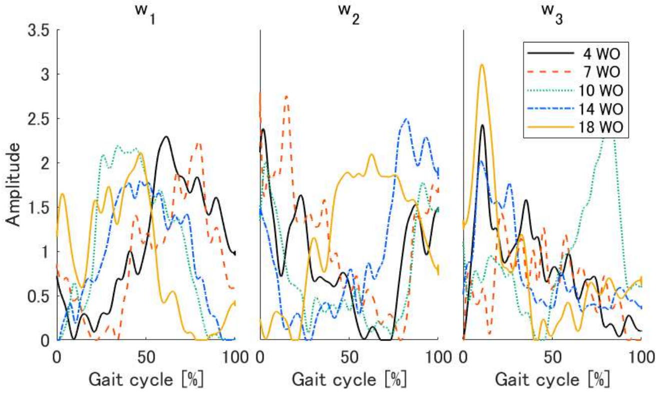
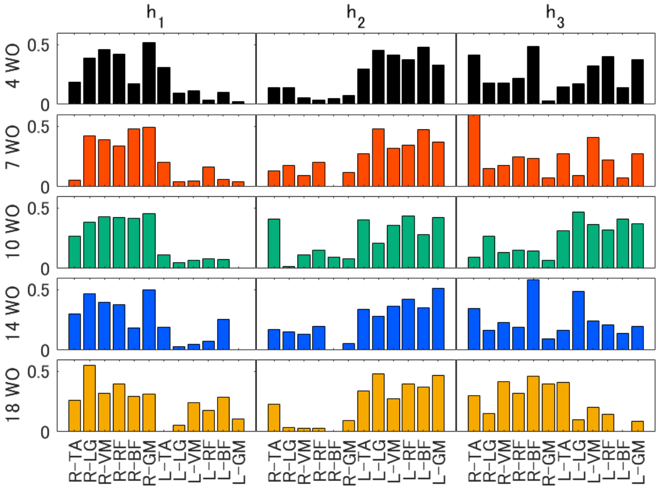


Fig.1 The number of synergies vs. cumulative explained variance



(a) Synergies $\boldsymbol{W}$



(b) Coefficient matrix $\boldsymbol{H}$

Fig. 2 The extracted synergies

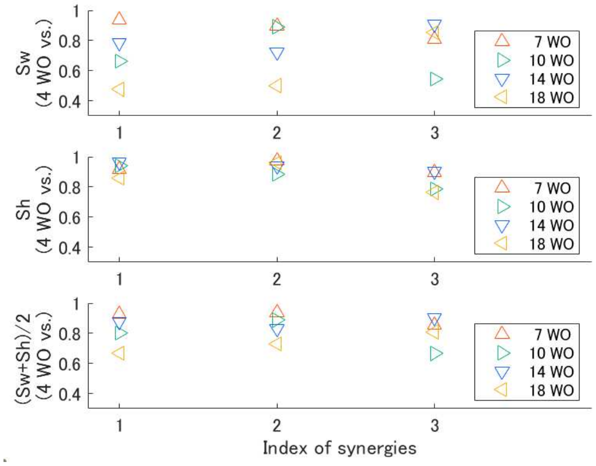


Fig. 3 The similarity of $\boldsymbol{W}$ and $\boldsymbol{H}$ between 4 and 7-18 WO

IV. DISCUSSION

In Fig. 3, 4 WO and 7 WO are highly similar in both $\boldsymbol{w}_k$ (time series profile of synergy activation) and $\boldsymbol{h}_k$ (muscles composing synergy). 4 WO and 18 WO are less similar than the others. $\boldsymbol{h}_k$ for the first and second synergies is similar between 4 WO and any WO (7-18). On the other hand, $\boldsymbol{w}_k$ shows a change with age in weeks. The first and second synergies correspond to the right (R-TA ~ R-GM) and left leg muscles (L-TA ~ L-GM). The onset timing of the activation of $\boldsymbol{w}_1$ and $\boldsymbol{w}_2$ is becoming earlier with the age of weeks. It may indicate that during the stance phase, which begins immediately after landing (0 and 100% of the gait cycle for the right leg and around 50% for the left leg), the infant is acquiring muscle coordination for pushing against the ground for supporting the body, and generating forward force.

Some previous studies showed that in the primitive stepping reflex of newborns, a flexion movement to raise the leg higher occurs during the stance phase [2, 7]. Okamoto et al. reported that more leg extensor activity appears around 3-4 months old. Our results (change in $\boldsymbol{h}$) do not show that each synergy changes from flexor dominance to extensor dominance. The standardization (we divided raw EMG by the standard deviation of all data within each WO condition) in preprocessing phase might influence the relative scale of the EMG amplitude.

In this paper, we defined one cycle as the interval at which the right foot makes contact with the ground. However, the gait rhythm of infants is not even. Thus, it might be necessary to define a gait cycle by normalizing the length of the swing phase and the support phase of each leg based on the left and right foot contact and foot-off [2, 3].

V. CONCLUSION

In this paper, we analyzed one infant's lower limb's EMG during primitive stepping reflex and supported walking at 4-18 weeks old to investigate the acquisition and development of muscle synergies during growth. We extracted three synergies and checked changes in the synergies with growth. The results suggest that two synergies maintained the recruited muscles and changed the activation timing, and one synergy substantially changed the timing and composition of the muscle. We plan to analyze EMG until around one year old to study the acquisition and development of synergies over a more extended period.

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