Developmental Changes of Muscle Synergies in an Infant's Walking

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Abstract

This study addresses the process of gait development and the role of the primitive stepping reflex. We analyzed muscle synergies (spatiotemporal coordination patterns of muscle activities) using electromyograms (EMGs) measured in one infant during growth (4-18 weeks of age). 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.

Introduction

Primitive stepping

- One of the newborn's **primitive reflexes** in response to external stimuli
- **Gait-like movement** in which both lower limbs are alternately extended to stimuli to the bottom of the foot

Previous studies on the development of walking

- **The muscle activity patterns** of the stepping reflex (Forssberg, 1985):
  - **disappearing once** at around two months after birth
  - **reappearing** at around one year old
- Some synergies† are common from neonates to adults, and others are acquired with growth (Dominici et al., 2011)

† Synergies: coordinated motor behavior (Bernstein, 1967)

Few studies investigated the expression and changes of synergies during individual developmental stages

Final goal:

- Elucidating the process of gait development and the role of the primitive stepping reflex

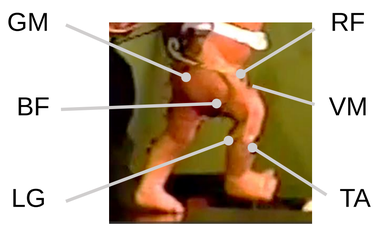
The goal of this paper:

- Investigating the **development of muscle synergies** in an infant's walking
  - Analyzing electromyographic (EMG) data recorded from one infant in developmental stages (4-18 weeks old) of walking
  - Extracting and comparing muscle synergies extracted in each stage

Methods

Experiments (Okamoto & Okamoto, 2016)

- Measuring EMGs from one infant during primitive stepping and walking at 4, 7, 10, 14, and 18 WO (weeks old)
  - 6 muscles in each leg (12 muscles in total)
    - Gluteus maximus (GM), Rectus femoris (RF), Biceps femoris (BF),Vastus medialis (VM), Gastrocnemius lateral (LG), Tibialis anterior (TA)



EMG Preprocessing (Buchanan et al., 2004)

- For converting from EMG to muscle activation

Normalized → Full-wave rectified → Low-pass filtered

Muscle synergy analysis (d'Avella et al., 2003)

$$X \approx W \times H$$

(X: $T \times D$, W: $D \times N$, H: $N \times T$)

Preprocessed EMG | Synergy matrix | Coefficient matrix

T: the number of time samples
$D\,(=12)$: the number of dimensions (muscles)
N: the number of synergies

Extracting muscle synergies by Non-negative matrix factorization (NMF)

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

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

w_k^i and w_k^j: k-th synergies of i-th and j-th WO

Evaluating the similarity of synergies and coefficients between each stage

Results

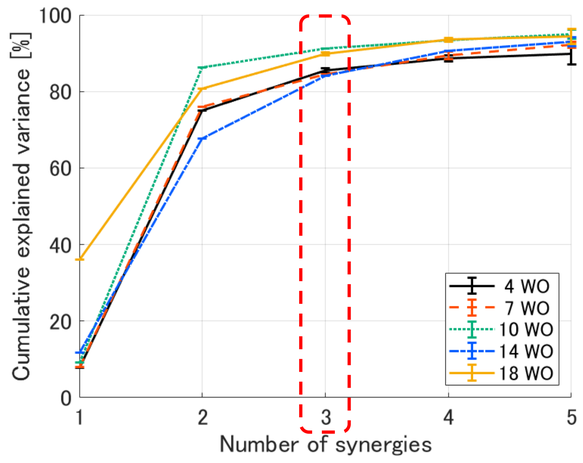
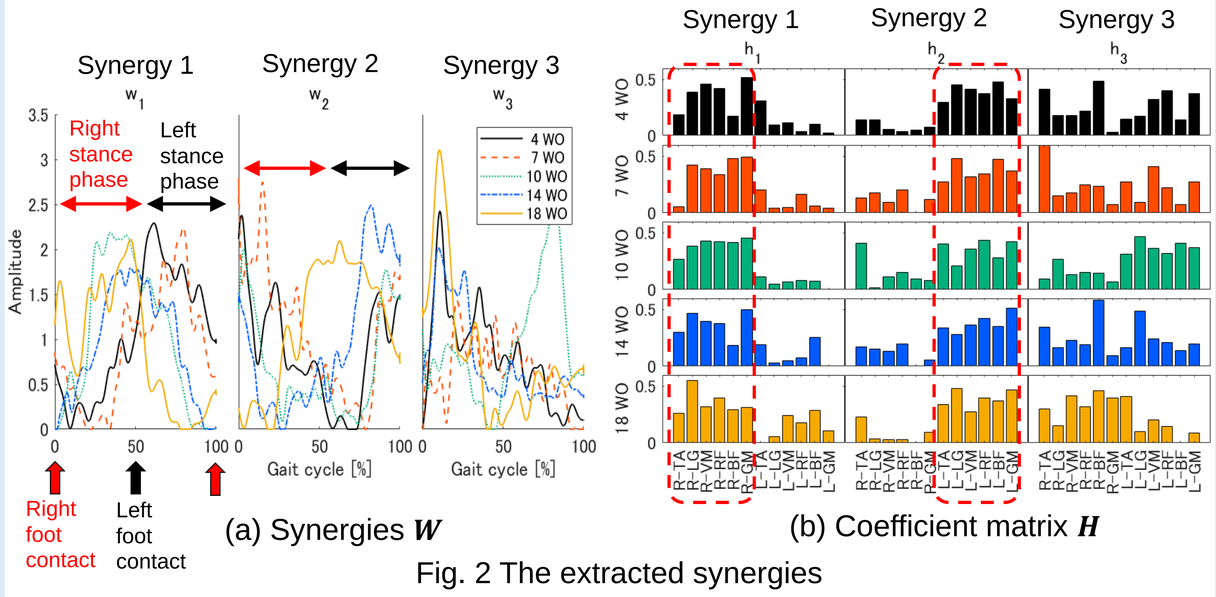


Fig. 1 The Number of Synergies

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.

Using **three synergies** can explain 84-91% of the variance



(a) Synergies $\boldsymbol{W}$ (b) Coefficient matrix $\boldsymbol{H}$

Fig. 2 The extracted synergies

Fig. 2 presents the synergies and coefficient matrices extracted when the number of synergies was 3.

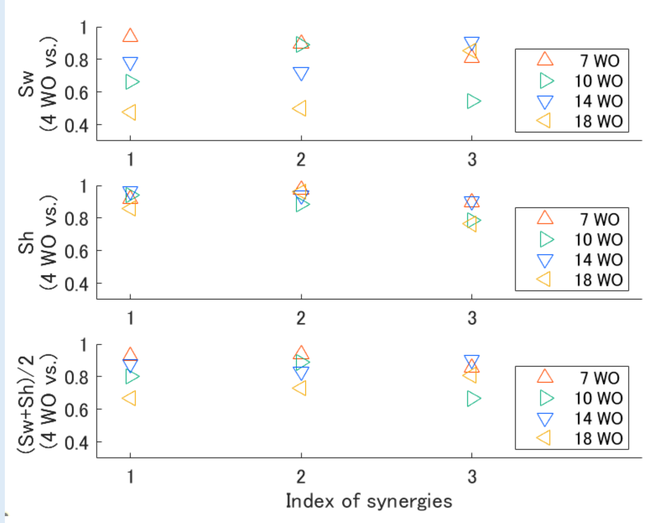


Fig. 3 The similarity of $\boldsymbol{W}$ and $\boldsymbol{H}$

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

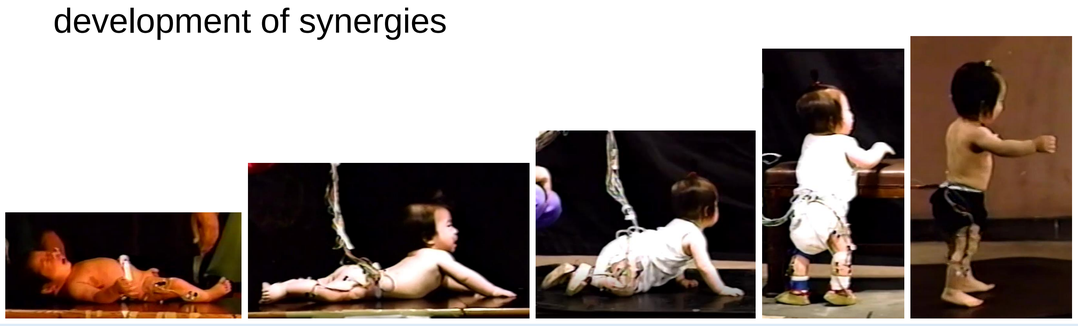
- $\boldsymbol{w}_k$ and $\boldsymbol{h}_k$
  - 4 WO and 7 WO are similar
  - 4 WO and 18 WO are less similar
- $\boldsymbol{h}_k$
  - $\boldsymbol{h}_1$ and $\boldsymbol{h}_2$ correspond to the right and left leg muscles (Fig. 2(b))
  - $\boldsymbol{h}_1$ and $\boldsymbol{h}_2$ are similar between 4 WO and any WO (7-18)
- $\boldsymbol{w}_k$
  - changes with age in weeks

Discussion

- Control of muscles in right and left legs congenitally separate
  - The synergies would be common to primitive stepping and voluntary walking
- The onset timing of the activation of $\boldsymbol{w_1}$ and $\boldsymbol{w_2}$ change with the WOs
  - to be activating in the stance phase for pushing against the ground to support the body, and generating forward force

Conclusion & Future Direction

- We investigated changes in extracted three synergies with growth
  - Two synergies maintained the recruited muscles but changed the onset timing
  - One synergy substantially changed the time profile and the recruited muscle
- We plan more investigation:
  - Analyzing EMG until around one year old to study the acquisition and development of synergies



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