Spatiotemporal Cortical-Synergy Connectivity in the Gait Cycle

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ABSTRACT

This study employed electroencephalography (EEG), electromyography (EMG), and full-body motion capture to investigate body motion during walking. Challenges in EEG and kinematic analysis include signal delay and multisensory integration. Our results identified five types of synergies, each active in specific gait phases and following a circuit. Two synergies acted as primary drivers involving the premotor and primary motor cortices; one showed speed suppression, another showed brain lateralization, and one acted as a fine-tuning component, adjusting movements through the sensory cortex.

INTRODUCTION

Walking is a routine yet complex task that requires coordination between muscles and the brain. Analyses of electroencephalography (EEG) and kinematic parameters have been used to design rehabilitation programs, however, there is a delay between the two, and the motor process involves the brain's dynamic integration of visual, sensory, and vestibular signals to regulate motor areas for adaptive movements [1]. Therefore, brain-muscle coordination can improve targeted rehabilitation training.

Muscle synergy, as a fundamental unit of motor control, has been proposed as a mechanism by which the central nervous system (CNS) simplifies the control of multiple muscles. Studies have shown that descending commands from the cortex activate muscle synergies via the corticospinal tract. The brain uses synergies, rather than directly controlling individual muscles to layer movement control [2]. In particular, beta-band oscillatory activity has been shown to propagate along the corticospinal tract to spinal neurons [3]. Studies have indicated that during walking, connections are established in the sensorimotor, primary motor, and premotor areas [4].

However, previous studies have rarely associated muscle synergies with the biomechanical components involved in body movements, leaving the specific functions of synergies and their roles in motor control unclear. Therefore, this study has two objectives: (1) to collect real-time brain-body imaging data using synchronized EEG, electromyography (EMG), and full-body motion capture; and (2) to investigate the relationship between kinematics, muscle synergies, and cortical activity in the beta-band across six phases of the gait cycle.

2. MATERIALS & METHODS

2.1. Instrumentation & Data Collection

Three male participants were instrumented with the 32-channel EEG cap, surface EMG, and motion capture. The EEG cap follows the international 10-20 system. Surface EMG using wet bipolar electrodes was recorded from 4 sites bilaterally: tibialis anterior (TA), lateral gastrocnemius (LG), rectus femoris (RF), bicep femoris (BF) as shown in **Fig. 1**. Sample rate of EEG is 500 Hz, 100 Hz of EMG. The motion capture and 3D tracking system was setup around subjects including 4 cameras to form a rectangular field. All 2D pose shooting in the field would be fusing to produce 3D human pose estimation. Sample rate: 30 Hz.

Subjects were asked to stand still during the baseline period, indicated by a red bulb light. During this time, an event marker was sent to the dongle through the synchronous recorder. After 10 sec of baseline, the red bulb light started flashing for 10 sec to signal the subjects to begin walking. The bulb then turned green, and another event marker was sent to the dongle to mark the end of this phase. The time-synchronize of EEG, EMG, Motion Capture system would be complete through bulb light and corresponding event marker's alignment.

2.2. Data Preprocessing

3D positions were loaded into *OpenSim[5]* to align the body model with the skeleton for kinematic analysis to obtaining parameters. Heel velocity was used to identify heel strike (HS), heel-off (HO) and toe-off (TO) as motion events. Time synchronization was achieved using image recognition of bulb lights. In the study kinematic like knee angle, hip flexion, and heel velocity would be extract.

All preprocessing and analysis procedure were conducted using EEGLAB[6], FIELDTRIP[4] and MATLAB. EEG data is first time-synchronized using event markers and bandpass filtered from 0.5 Hz to 80 Hz (zero-phase 4th order Butterworth). Artifact subspace reconstruct (ASR) [6] is applied for high amplitude motion artifact removal using a 10-sec standing baseline for calibration, with a 500-ms sliding window based on the principal component analysis with a threshold of 10 standard deviation. Remaining data undergoes Infomax Independent Component Analysis (ICA) to further eliminate motion artifacts. The EMG signal is time-synchronized using an event marker, detrended, bandpass filter (40 to 400 Hz, zero-phase 4th-order Butterworth filter), down-sample to 500 Hz and then 9 Hz lowpass filter.

2.3. Muscle Synergy

Muscle synergy would extract through non-negative matrix factorization (NNMF) [7]. After temporal normalization, the EMG matrix (M) is structured as an 8 (muscle number) × 501 (time points number) matrices. This matrix is ultimately decomposed into spatial (W) and temporal (C) components, along with a residual.

$$M \cong WC + residual \#(1)$$

where M, W, C, residual is matrices of dimensions, $m \times t$, $m \times n, n \times t$ and $m \times t$. (m is the number of muscles, t is number of time point, n is number of synergy). Five synergies were determined by the Variance account for (VAF). In the study, we used (1) VAF≥ 0.9 and (2) ΔVAF ≤ 0.75 as criteria.

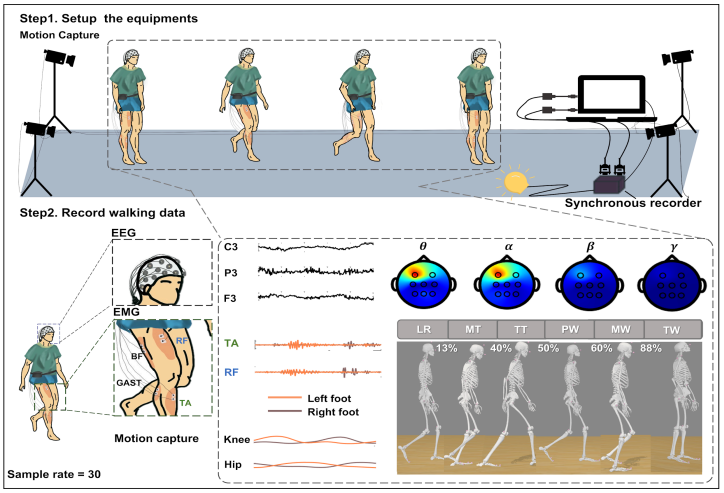

Fig. 1. Experimental setup for simultaneously EEG, EMG and Kinematic recording.

2.4. Cortical-Synergy Connectivity

To find out the location of cortical sources that present coherence with the muscle synergy, Dynamic Imaging of Coherent Sources(DICS) beamformers was used [4]. Forward model was first built by MRI template and EEG cap's electrode location. Later, coherence measures the synchrony between two signals in the frequency domain, using cross-spectral density ($S_{XY}(f)$) and auto-spectral density ($S_{XY}(f)$, $S_{YY}(f)$):

$$C_{XY}(f) = \frac{|S_{XY}(f)|}{\sqrt{S_{XY}(f) \cdot S_{YY}(f)}} \#(2)$$

where $C_{XY}(f)$ is the coherence of EEG signal *(X)* and muscle synergy *(Y)* at frequency f. The regularization parameter of the cross-spectral density matrix was set to 5% and using the filter that preserves real number.

2.5. Kinematic Analysis

Each gait cycle of kinematic, EEG, and EMG signal would be segment through HS to next HS signal and later clip into 6 phases: loading response (LS) by opposite TO, mid-stance (MT) by HO, terminal-stance (TT) by opposite HS, pre-swing (PW) by TO, mid-swing (MW) by opposite HO, terminal-swing (TS) by HS. All the gait cycle is clip from left heel strike. One-way ANOVA is used to evaluate the difference between the different phase of cortico-synergy coherence.

Centre of activation (CoA) is the polar angle(θt) of the motor primitive's center of mass, ranging from 0 to 2π over the gait cycle.

$$CoA = \begin{pmatrix} \sum_{t=1}^{k} \sin\theta_t K_t \\ \sum_{t=1}^{k} \cos\theta_t K_t \end{pmatrix} \#(3)$$

where k is the point count per transition cycle, and K indicates the activation vector's amplitude [8].

3. Results and Discussion

The synergy components are divided into 5 types as shown in **Fig. 2**. CoA reveal that *Syn1* is mainly active in the MT phase, *Syn2* in TT, *Syn3* in early MW, *Syn4* at the end of TW, and *Syn5* in late MW.

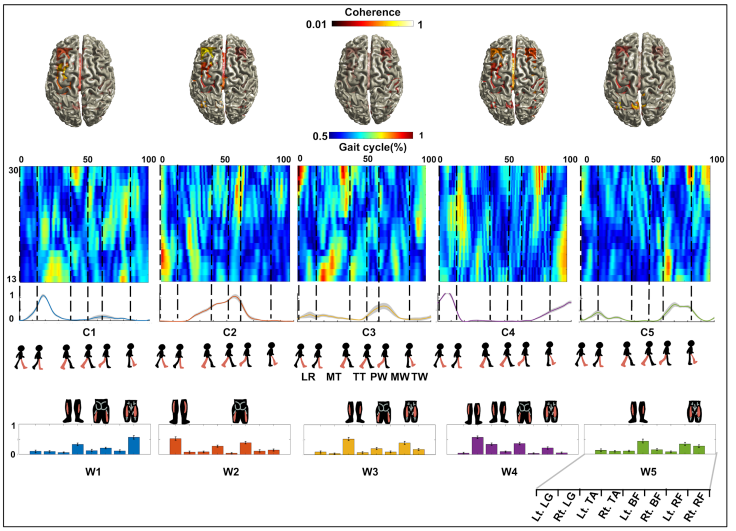

Fig. 2. The weights of muscle synergies (W1-W5) and cortical activation (C1-C5) with correponding cortico-synergy coherence spectrum of primary mortor cortex and source location. The spectrum and synergy activation are time locked from LHS to LHS.

Temporally, from synergy and kinematic perspectives as shown in **Fig. 3A**, *Syn4* activates in MW, engaging RF, BF, TA, and opposite-side GL, leading to knee extension, maximum hip flexion, and heel deceleration in TW. This influence continues into LR, when heel velocity drops to zero, and knee extension continues. *Syn1* activates during LR as the contralateral muscle module shifts to MT, involving opposite RF and TA, associated with propulsion. The model like *Syn1* is confirmed in previous study [9]. *Syn2* activates in MT, engaging GL and contralateral BF and TA, allowing knee re-flexion and hip extension in TT. Subsequently, *Syn3* activates before the PW, engaging RF and TA, causing sustained knee flexion, maximum hip extension, and increasing heel velocity, which may also reflect the influence of *Syn2*. In the MW phase, *Syn5* activates with major components in bilateral RF and contralateral TA. During this phase, the knee reaches maximum flexion angle, and the hip returns to flexion. Considering the muscle weighting and activation of *Syn5*, these changes are attributed to *Syn4's* influence, making *Syn5* a fine-tuning component after phase transitions. In summary, these may indicate that synergy activations precede kinematic parameters, with *Syn4* and *Syn2* identified as key synergies in the gait cycle, while *Syn5* appears to play a role in fine motor coordination during gait transition. *Syn3* is associated with the foot-lifting process, and *Syn4* may encompass inhibitory effects like gait deceleration. Based on this analysis, it can be assumed that the walking state transition follows the sequence of *Syn4*-(*Syn1*)-*Syn2*-(*Syn3*)-*Syn5*-*Syn4*. *Syn5* may reconnect to *Syn1* to re-enter the loop. The surmise has been proved in **Fig. 3B**.

From the perspective of synergy and cortical activity, the source localization results reveals most synergies are associated with the primary motor cortex (M1) as shown in **Fig.2**. Specifically, *Syn1* is lateralized to the left hemisphere, corresponding to the activation of right-side muscles. During the activation of *Syn1* and *Syn4*, coherence increases accordingly. *Syn2* and *Syn4* also show activity in the premotor area. The coherence spectrum indicates that *Syn2* exhibits active beta oscillations during the double-support phase, consistent with previous studies [4]. Beta band oscillations could help calibrate the sensorimotor system after movement [3]. *Syn5*'s activity in the sensorimotor cortex(S1) and the increase in pre-activation coherence seem to support the above findings, suggesting that *Syn5*'s motor coordination may be the product through communication between the sensorimotor and motor cortices. Additionally, when comparing different phases, the key synergy components mentioned earlier show significant differences in the terminal phase in both the sensorimotor and premotor cortical regions as shown in **Fig. 3C**.

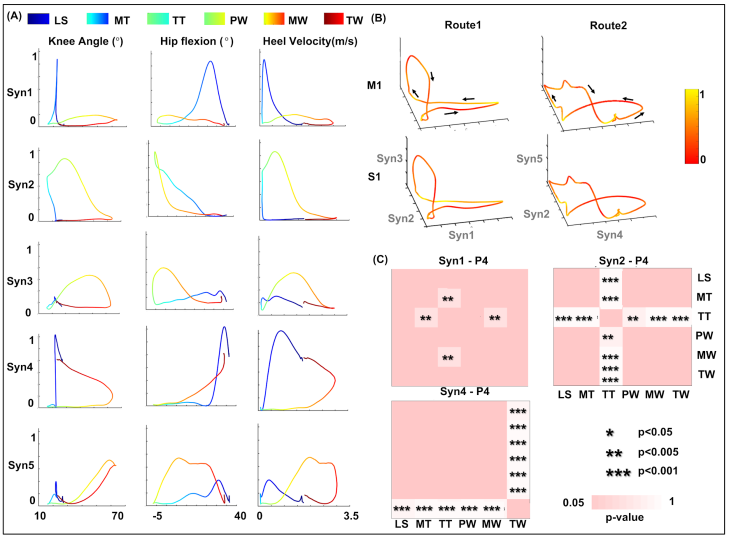

Fig. 3. Analysis during gait phase. (A) Synergy activation patterns (*Syn1*-*Syn5*)and corresponding kinematic parameters, including knee angle, hip flexion, and heel velocity, across six gait phases. (B) Synergy trajectory during gait cycle with corticol-synergy coherence. (C) showed significant differences in sensorimotor and premotor cortical regions in the transition states of gaiting (one-way ANOVA).

In conclusion, these findings support above analyses of synergy and motor parameters, as well as the relationships between cortical activity and synergy, indicating that synergy components may allow us to infer final motor parameters based on cortical information.

4. REFERENCES

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