Supplementary materials

Prepared for the main article entitled:

**Long-lasting event-related beta synchronizations of electroencephalographic activity in response to support-surface perturbations during upright stance**

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**S1. Definition of the triple-inverted pendulum model**

We consider a triple-inverted pendulum model in the sagittal plane (Suzuki et al. 2012). See Fig. S1. The upper link of the model represents the head-arm-trunk (HAT). The lower link represents the leg. The foot-link is fixed on the support-surface as in Fig. S1. Distal end of the leg-link is connected to the foot by a pin joint, corresponding to the ankle joint. The distal end of HAT-link and the proximal end of the leg-link is connected by a pin joint, corresponding to the hip joint. Each link is considered as a rigid body with its mass distributed uniformly. The ankle and hip joint angles and body parameters are defined in Fig. S1.

**S2. Joint angles estimation**

The hip and ankle joint angles of each participant during standing were estimated using the inverted pendulum model described above and the marker positions attached to the ankles, the greater trochanters and the acromions of both of left and right sides of subject’s body. Positions of those markers were measured by the motion-capture system in the global coordinate system, which were projected on the sagittal plane and averaged to obtain the position data for each of the ankle ($x_{ANK}$, $y_{ANK}$), greater trochanter ($x_{GT}$, $y_{GT}$) and acromion ($x_{AC}$, $y_{AC}$) on the sagittal plane. See Fig. S1. Then, $\theta_a$ and $\theta_h$ were calculated using the following equations:
\[ \theta_a = -\arctan((x_{\text{ANK}} - x_{\text{GT}})/(y_{\text{ANK}} - y_{\text{GT}})), \]
\[ \theta_h = -\arctan((x_{\text{GT}} - x_{\text{AC}})/(y_{\text{GT}} - y_{\text{AC}})) - \theta_a, \]

in which the counterclockwise rotation (plantar flexion for the ankle joint and extension for the hip joint) was defined as the positive direction.

**S3. CoM estimation**

Horizontal position of the total body center of mass (CoM) in the AP direction during standing was estimated as

\[ COm = \frac{m_Lx_L + m_{\text{HAT}}x_{\text{HAT}}}{m_L + m_{\text{HAT}}}, \]

(1)

\[ x_L = \left(\frac{l_{\text{HAT}}}{2}\right) \sin \theta_a, \]

(2)

\[ x_{\text{HAT}} = l_L \sin \theta_a + \left(\frac{l_{\text{HAT}}}{2}\right) \sin(\theta_a + \theta_h), \]

(3)

where \( l_{\text{HAT}} \) and \( l_L \) represent the lengths of HAT- and leg-links, respectively. \( l_{\text{HAT}} \) and \( l_L \) were determined, respectively, by the mean distance between time series of two positions \((x_{\text{GT}}, y_{\text{GT}})\) and \((x_{\text{AC}}, y_{\text{AC}})\) and by that between \((x_{\text{ANK}}, y_{\text{ANK}})\) and \((x_{\text{GT}}, y_{\text{GT}})\), for each participant. We assumed that the CoM of each link is located at the middle point of the link. See Fig. S1.

**S4. CoP positions relative to the foot**

In the perturbed condition, the foot position shifted backward in response to every perturbation by the amount of the backward shift of the belt. Because the force plate and its local coordinate system were fixed in the global coordinate system independent of the moving belt, a time-profile of the recorded CoP position during the 7 min, denoted by \( x_{\text{cop}}(t) \) in the global coordinate system as a function of time \( t \), was the sum of a time-profile of the actual postural response \( x_{\text{cop}}^{L}(t) \) in the local coordinate system fixed on the belt (the CoP position relative to the foot) and a series of step-wise backward shifts of the belt that was measured as the position of the ankle joint \( x_{\text{ANK}}(t) \) both in the global coordinate
system, i.e., \( x_{\text{cop}}(t) = x_{\text{cop}}^L(t) + x_{\text{ANK}}(t) \). Thus, we could obtain the time series of CoP positions relative to the foot as \( x_{\text{cop}}^L(t) = x_{\text{cop}}(t) - x_{\text{ANK}}(t) \), which represents the actual postural response to the perturbation.

**S5. Equations of motion of the inverted pendulum model and inverse dynamics**

The equation of motions in the global coordinate system for each of the three links, namely, the HAT-link, the leg-link and the foot-link of the triple-inverted pendulum model, are as follows (Suzuki et al. 2012). See Fig. S1.

The HAT-link:

\[
\begin{align*}
  m_{\text{HAT}} \frac{d^2}{dt^2} x_{\text{HAT}} &= F_x \\
  m_{\text{HAT}} \frac{d^2}{dt^2} y_{\text{HAT}} &= F_y - m_{\text{HAT}} g \\
  l_{\text{HAT}} \frac{d^2}{dt^2} (\theta_a + \theta_h) &= (x_{\text{GT}} - x_{\text{HAT}}) F_y - (y_{\text{GT}} - y_{\text{HAT}}) F_x + \tau_h
\end{align*}
\]

The leg-link:

\[
\begin{align*}
  m_{L} \frac{d^2}{dt^2} x_{L} &= R_x - F_x \\
  m_{L} \frac{d^2}{dt^2} y_{L} &= R_y - F_y - m_{L} g \\
  l_{L} \frac{d^2}{dt^2} \theta_a &= (x_{\text{GT}} - x_{L}) (-F_y) - (y_{\text{GT}} - y_{L}) (-F_x) + (x_{\text{ANK}} - x_{L}) R_y - (y_{\text{ANK}} - y_{L}) R_x + \tau_a - \tau_h
\end{align*}
\]

The foot-link:

\[
\begin{align*}
  m_{F} \frac{d^2}{dt^2} x_{F} &= GRF_x - R_x \\
  m_{F} \frac{d^2}{dt^2} y_{F} &= GRF_y - R_y - m_{F} g \\
  l_{F} \frac{d^2}{dt^2} \theta_f &= (x_{\text{ANK}} - x_{F})(-R_y) - (y_{\text{ANK}} - y_{F})(-R_x) + (x_{\text{cop}} - x_{F}) GRF_y - (y_{\text{cop}} - y_{F}) GRF_x + \tau_a
\end{align*}
\]

\( I_{\text{HAT}} \), \( I_{L} \) and \( I_{F} \) are the inertia moments of the HAT-link, the leg-link, and the foot-link, respectively.
$F_x$ and $F_y$ are the forces applied at the hip joint from the leg-link to the HAT-link. $R_x$ and $R_y$ are the forces applied at the ankle joint from the foot-link to the leg-link. $m_{HAT}$, $m_L$ and $m_F$ are the masses of the HAT-link, the leg-link and the foot-link, respectively. They were estimated from the total body weight of each participant using the following statistical formula. $m_{HAT}$: $m_L$: $m_F = 0.62$: $0.35$: $0.03$ (Suzuki et al. 2012).

We performed the inverse dynamics analysis by eliminating unknown variables ($F_x$, $F_y$, $R_x$, $R_y$) from the equations of motion. Then, joint torques exerted on the ankle joint $\tau_a$ and the hip joint $\tau_h$ were estimated using

$$\tau_a = (x_{\text{cop}} - x_{\text{ANK}})G R F_y - (y_{\text{cop}} - y_{\text{ANK}})G R F_x + (x_F - x_{\text{ANK}})(-m_F g) - (x_F - y_{\text{ANK}})(-m_F a),$$

$$\tau_h = \frac{1}{6} m_L l_2^2 \ddot{\theta}_a - l_L \left( \frac{m_L}{2} + m_F \right) (g \sin \theta_a + a \cos \theta_a) + l_L (G R F_y \sin \theta_a + G R F_x \cos \theta_a) + \tau_a,$$

where we assumed that the foot-link is fixed on the moving support-surface with no translational and rotational movement ($\dot{x}_F = a$, $\dot{y}_F = 0$, $\dot{\theta}_F = 0$). Moreover, we assumed $(x_F - x_{\text{ANK}}) = 0.02$ m, $(y_F - y_{\text{ANK}}) = -y_{\text{ANK}}/2$ to compute $\tau_a$.

**S6. EEG signal preprocessing**

Preprocessing, denoising and analysis of EEG signals were conducted using EEGLAB (Delorme and Makeig 2004; Loo et al. 2019). First, EEG data were down-sampled to 1,000 Hz to reduce the computational time required for further processing. A zero-lag high-pass first-order Butterworth filter with a cutoff frequency of 1 Hz was applied to optimize signal-to-noise ratio (Winkler et al. 2015). We then removed data from noisy electrodes because we used the average reference potential method (Bigdely-Shamlo et al. 2015), for which a large noise in one electrode would affect the other electrodes. In this study, an electrode was considered as largely noisy if the correlation coefficients between the surrounding electrodes were smaller than 0.8. The average number of electrodes rejected in single
trials was 0.28 out of 32.

We performed the artifact subspace reconstruction (ASR), which is a method for denoising EEG signals using principal component analysis (PCA) (Mullen et al. 2015). Steps of the ASR processing are summarized as follows: (1) Find and extract less noisy time intervals from the 32-dimensional EEG time-series and apply PCA to the extracted data to define the template dataset with the basis vectors of the principal components (i.e., principal axes) for expressing other EEG signals in general. (2) Decompose all EEG time-series data within a time-window of 1.0 s into the principal axes to obtain the magnitude of variance for each principal axis. (3) Remove components if their variances were 20 times larger compared to those of the corresponding components for the template data, and reconstruct the EEG for this window using other remaining components. (4) Repeat the decomposition while shifting the time-window with 66% overlap (Mullen et al. 2015). After ASR, data for the removed electrodes were spatially and linearly interpolated using the data from the surrounding electrodes (Bigdely-Shamlo et al. 2015). Finally, re-referencing was performed based on the averaged potential of all electrodes, which eliminates a tendency for electrodes around CPz as the reference electrode to exhibit smaller amplitudes compared with the other electrodes.

To remove muscle-activity and eye-blinking related artifacts from the EEG data, the independent component analysis (ICA) was performed. Artifact components were defined using the method described by Bruijn et al. (2015). That is, any independent component (IC) was considered to be affected by EMG activities of muscles, if its average power in the frequency band between 50 to 100 Hz was larger compared to that of the alpha band (8 to 12 Hz) and/or the low-beta band (13 to 20 Hz). Moreover, any IC was considered to be affected by eye-blinking originated electrooculograms (EOGs), if its central frequency was under 3 Hz and the corresponding topographic-map-representation was distributed around the forehead. The mean number of removed EMG and EOG components for single
trials was 2.3 and 1.6 out of 32, respectively. After removing those artifact ICs, the remaining ICs were re-mapped onto the electrodes. The re-mapped EEG data in the time interval from 5 s before the perturbation until 15 s after the perturbation was then used as an epoch.

S7. Wavelet transformation for computing ERSPs

Outcomes of time-frequency analysis for each epoch for each electrode were summarized by averaging them over all epochs, for each participant as well as across participants to obtain ERSPs (Makeig 1993). For each epoch, we performed a time-frequency analysis using the wavelet transform with the Morlet wavelet \( \psi(t) \) defined as

\[
\psi(t) = \frac{1}{\sqrt{2\pi \sigma^2}} e^{-t^2/2\sigma^2} e^{i2\pi ft},
\]

where the number of cycles for the continuous wavelet transformation that defines \( \sigma \) was increased gradually from 3 to 24 corresponding to the range of 3 to 60 Hz, which covers all relevant EEG frequency bands, i.e., theta (3-7 Hz), alpha (8-13 Hz), low-beta (13-20 Hz), high-beta (20-30 Hz) and gamma (40-60 Hz).

S8. Responses of the perturbation in each subject

We confirmed that there was no outlier of ERSP by plotting an ERSP map for each trial and also averaged ERSP across trails within each subject (Figs. S2-S10). We also confirmed that beta rebound appeared within the frequency band of 20 - 30 Hz in all participants. As can be confirmed in Figs. S2-S10, the beta rebound sustained for a long period of time in ERSP of each participant, not only in the grand averaged ERSP over the participant as shown in the main text (Fig. 1). One of the limitation of this study was that we used a fixed perturbation parameter, and thus we had no EEG responses (ERSPs) for a different kind of perturbation to be compared with the ERSP that we obtained in this study. However, we found no obvious EEG responses that appeared before the onset perturbation, which
suggests strongly that no participant could make an accurate prediction of the next perturbation to brace for it.

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Figure S1. A triple-inverted pendulum with a foot-link fixed on the support-surface. The model consists of links of HAT, leg and foot with a pin joint at the ankle and hip. See text in S1, S2 and S3.
Figure S2. Event-locked average profiles of Subject 1 triggered by the perturbation-onset. (A) ankle and hip joint angles, (B) joint torques, (C) CoP and CoM positions, (D) CoP–CoM, (E) normalized iEMGs of Medial-Gastrocnemius and Soleus, (F) normalized iEMG of Tibialis Anterior, (G) magnification of (E), (H) magnification of (F), (I) ERP of Cz electrode, (J) ERSP of Cz electrode. The light color shaded area in each of (A)-(I) is the standard deviation, representing the distribution across all perturbed trials of Subject 1.
**Figure S3.** Event-locked average profiles of Subject 2 triggered by the perturbation-onset. (A) ankle and hip joint angles, (B) joint torques, (C) CoP and CoM positions, (D) CoP–CoM, (E) normalized iEMGs of Medial-Gastrocnemius and Soleus, (F) normalized iEMG of Tibialis Anterior, (G) magnification of (E), (H) magnification of (F), (I) ERP of Cz electrode, (J) ERSP of Cz electrode. The light color shaded area in each of (A)-(I) is the standard deviation, representing the distribution across all perturbed trials of Subject 2.
**Figure S4.** Event-locked average profiles of Subject 3 triggered by the perturbation-onset. (A) ankle and hip joint angles, (B) joint torques, (C) CoP and CoM positions, (D) CoP−CoM, (E) normalized iEMGs of Medial-Gastrocnemius and Soleus, (F) normalized iEMG of Tibialis Anterior, (G) magnification of (E), (H) magnification of (F), (I) ERP of Cz electrode, (J) ERSP of Cz electrode. The light color shaded area in each of (A)-(I) is the standard deviation, representing the distribution across all perturbed trials of Subject 3.
Figure S5. Event-locked average profiles of Subject 4 triggered by the perturbation-onset. (A) ankle and hip joint angles, (B) joint torques, (C) CoP and CoM positions, (D) CoP–CoM, (E) normalized iEMGs of Medial-Gastrocnemius and Soleus, (F) normalized iEMG of Tibialis Anterior, (G) magnification of (E), (H) magnification of (F), (I) ERP of Cz electrode, (J) ERSP of Cz electrode. The light color shaded area in each of (A)-(I) is the standard deviation, representing the distribution across all perturbed trials of Subject 4.
Figure S6. Event-locked average profiles of Subject 5 triggered by the perturbation-onset. (A) ankle and hip joint angles, (B) joint torques, (C) CoP and CoM positions, (D) CoP–CoM, (E) normalized iEMGs of Medial-Gastrocnemius and Soleus, (F) normalized iEMG of Tibialis Anterior, (G) magnification of (E), (H) magnification of (F), (I) ERP of Cz electrode, (J) ERSP of Cz electrode. The light color shaded area in each of (A)-(I) is the standard deviation, representing the distribution across all perturbed trials of Subject 5.
Figure S7. Event-locked average profiles of Subject 6 triggered by the perturbation-onset. (A) ankle and hip joint angles, (B) joint torques, (C) CoP and CoM positions, (D) CoP-CoM, (E) normalized iEMGs of Medial-Gastrocnemius and Soleus, (F) normalized iEMG of Tibialis Anterior, (G) magnification of (E), (H) magnification of (F), (I) ERP of Cz electrode, (J) ERSP of Cz electrode. The light color shaded area in each of (A)-(I) is the standard deviation, representing the distribution across all perturbed trials of Subject 6.
Figure S8. Event-locked average profiles of Subject 7 triggered by the perturbation-onset. (A) ankle and hip joint angles, (B) joint torques, (C) CoP and CoM positions, (D) CoP−CoM, (E) normalized iEMGs of Medial-Gastrocnemius and Soleus, (F) normalized iEMG of Tibialis Anterior, (G) magnification of (E), (H) magnification of (F), (I) ERP of Cz electrode, (J) ERSP of Cz electrode. The light color shaded area in each of (A)-(I) is the standard deviation, representing the distribution across all trials of Subject 7.
Figure S9. Event-locked average profiles of Subject 8 triggered by the perturbation-onset. (A) ankle and hip joint angles, (B) joint torques, (C) CoP and CoM positions, (D) CoP–CoM, (E) normalized iEMGs of Medial-Gastrocnemius and Soleus, (F) normalized iEMG of Tibialis Anterior, (G) magnification of (E), (H) magnification of (F), (I) ERP of Cz electrode, (J) ERSP of Cz electrode. The light color shaded area in each of (A)-(I) is the standard deviation, representing the distribution across all trials of Subject 8.
Figure S10. Event-locked average profiles of Subject 9 triggered by the perturbation-onset. (A) ankle and hip joint angles, (B) joint torques, (C) CoP and CoM positions, (D) CoP–CoM, (E) normalized iEMGs of Medial-Gastrocnemius and Soleus, (F) normalized iEMG of Tibialis Anterior, (G) magnification of (E), (H) magnification of (F), (I) ERP of Cz electrode, (J) ERSP of Cz electrode. The light color shaded area in each of (A)–(I) is the standard deviation, representing the distribution across all trials of Subject 9.