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Effects on the Motor Cortex in Gamma Rhythm in Terms of Central Pattern Generator

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ABSTRACT The locomotion is one of the basic skills essential for animals' survival. It is a key research field where the locomotion is modulated by the motor cortex. It is shown by the investigation that the neural oscillations have key roles in neural communication. To assess the impacts on the motor cortex in gamma rhythm based on different frequencies central pattern generator (CPG), it is attempted to establish the model between the motor cortex and the CPG. The primary motor cortex and the primary somatosensory cortex are included in the motor cortex. The effects level is qualified using the power spectrum, spiking time histogram, rastergram, spectrogram in terms of the wavelet analysis and coherence between neural populations. The main findings include (1) The CPG with various frequencies under the gamma rhythm frequency can be embedded in gamma oscillation and the gamma power is modified by the CPG phase. (2) There is an optimal CPG with appreciate frequency and amplitude making the neural populations oscillate for the best action in the gamma band. Therefore, to process the neural population the appropriate stimulus is suitable. (3) When CPGs with different parameters are sent into the neural populations, the coherence difference mainly takes place in the gamma band. Therefore, there is an interaction between the internal dynamics with incoming stimuli providing a substrate for processing the complex information. A beneficial exploration can be provided by the investigation on the information process mechanisms in the motor cortex.

INDEX TERMS Central pattern generator, motor cortex, gamma rhythm.

I. INTRODUCTION

The motor cortex is a functional unit of cortex providing the spinal cord with input which defines the motor actions [1]. The direct and indirect inputs can be accepted by motor cortex from multiple cortical areas such as premotor, sensory and executive centers. It is considered that the output of motor cortex is determined by both external sensory and internal driven information [2], [3]. It was speculated that input from the primary somatosensory cortex to motor cortex contributes to information integration and is a key basis of motor cortex's output [4], [5]. Therefore, the working mechanism of information transfer between the external input and the motor cortex is deserved to investigate. At the same time, because of the contribution to effective corticospinal interaction and sub-serve the cognitive flexibility, the coherence among the neural areas is also deserved to study [6], [7].

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The neural rhythms are found across various spatial and temporal scales and it is thought that they are oscillations [8]. Within the researches, it is shown that neural oscillations can be indicated in different frequency bands, including alpha(8–12Hz), beta(15–30Hz), delta(1–4Hz), gamma(30–90Hz) and theta(4–8Hz). These bands are approximately correspondent to frequency ranges usually found in human electroencephalography investigations. Recent theories propose that these oscillations play important roles in neural communication, though they have been found over a long time [9], [10]. Many researchers investigated the gamma rhythm in these neural oscillations. Based on the gamma cycle studies, it was shown that it is an important computational mechanism for implementing a time-based coding scheme enabling quick processing and flexible routing of activity [11]. It was also attempted to investigate the cross-frequency coupling within the slow brain rhythms and the gamma oscillation and the cross-frequency coupling as a tool for transferring the data from large-scale neural networks to the local cortical [12]–[14]. At the same time, the gamma oscillation mechanism is also investigated by the researchers. Gamma rhythms can emerge via a pyramidal-interneuron gamma mechanism where the interneurons are activated by the excitatory input from the pyramidal neurons [15]–[17]. Hence, the pyramidal-interneuron gamma mechanism is used to generate gamma oscillator in the motor cortex in this paper.

The CPG is a micro neural circuit in the spine cord able to create cycle oscillations with no external information. Based on previous studies [18]–[21], the CPG controls the main rhythmic movements. The Matsuoka CPG model [22] was extensively utilized to the robot control, the modeling and simulating the human's motion, as a result of its effectiveness and simplicity [19]–[21], [23]. Simultaneously, in the neuroscience, it is concentrated on how the body's movement with the proprioception is caused by the activity of the neural system causes. The proprioception is the capability of understanding the positions of our body at all periods. The results show that the automatic movement was mostly understood at the spinal cord in terms of the proprioceptive feedback [24]. Moreover, the CPG is preserved as the proprioception applied in the humanoid robot's locomotion [25]. In the previous studies, the relationship between and the CPG and the neural network was studied and the results showed that the motor cortex involves equivalent modes with the CPG. The motor cortex has a stable state when the CPG is the limit cycle [18], [21].

The discriminatory directing of data within neocortical areas is essential for effective communication with a specific task. It is vital to improve the processing of the most appropriate data for the task since processing all the incoming sensory information is unbearable for the motor cortex [15]. Therefore, this paper is focused on the communication mode between the CPG and the motor cortex based on the neural rhythms. Moreover, the processing of sensory information and the coordination between the motor cortex and the CPG are enhanced. In this work, the CPG is preserved as proprioception that is the primary somatosensory cortex's input in the coupling model. The effects on motor cortex based on CPG and the coherence between the primary somatosensory cortex and the primary motor cortex are discussed.

This paper is organized as follows. In Section II, a novel model is presented representing the interaction between the motor cortex and the CPG based on the biological knowledge. Section III provides a detailed analysis of the CPG phase-modulated gamma power and the coherence between the neural populations in terms of the model between the CPG and the motor cortex. Section IV summarizes the contents of the paper and gives a discussion to compare the results of the paper with previous investigations. The final section deals with conclusions and future studies.

II. METHODOLOGY

Two connected neocortical areas are considered as the primary motor cortex and the primary somatosensory cortex, to establish the coupling model between the CPG and the motor cortex. They are coordinated by the CPG, at the same time. Each population is modeled as a local network of neurons sturdily interconnected, to investigate the communication between various cortical areas. There are 75 fast spiking interneurons, 25 low threshold spiking interneurons, and 400 regular spiking excitatory pyramidal neurons in each population [15], [26]. In the neural population, the connection of each neuron to all other neurons represents the robust connectivity of a local cortical population. Random noise current inputs are received by each neuron in the model that is uncorrelated between the neurons. To model the neuron, the Izhikevich model [27] is utilized with a suitable parameter set.

$$\begin{cases} \dot{v} = 0.04v^2 + 5v + 140 - u + I \\ \dot{u} = a(bv - u) \end{cases} \tag{1}$$

In the Izhikevich model, a reset circumstance exists: when v crosses 30mV, it is called an action potential and the variables are readjusted as follows

$$\begin{cases} vc \\ uu + d \end{cases} \tag{2}$$

where v denotes for the membrane potential of the simulated neuron, I shows the quantity of current flowing into the neuron and u represents a slow recovery variable, which can be interpreted as the inactivation of $Na+$ currents or action-potential induced activation of $K+$. The dynamical features of the neuron are determined by the parameters a, b, c and d. The values of these parameters are selected as in [15]. In the two connected neocortical areas, the average connection strengths between each neuron type and the noise parameters for various neuron kinds are also selected as in [15]. Later, the model between the CPG and the motor cortex is represented below.

In Figure 1, the upper portion of the model represents the motor cortex and the lower one shows the CPG model. The left part in motor cortex shows the primary somatosensory cortex and the right part represents the primary motor cortex. The motor cortex structure parallels to the anatomical structure. Each population includes inhibitory (I) and regular spiking excitatory (E) neurons. In this paper, the majority of the analysis is performed on the E population since it is thought that the currents leaving and entering neurons from the E population over synaptic inputs and spiking play role in the extracellular local field potential [15], [28].

The CPG model [21]–[23] is provided by.

$$\begin{cases} T_r \dot{x_1} + x_1 = -bx_2 - wg(x_3) + e \\ T_a \dot{x_2} + x_2 = g(x_1) \\ T_r \dot{x_3} + x_3 = -bx_4 - wg(x_1) + e \\ T_a \dot{x_4} + x_4 = g(x_3) \end{cases} \tag{3}$$

where $g(\cdot)$ is a piecewise linear function that describes the property of the neurons' threshold. This function could be expressed as $g(x) = \max(0, x)$. The membrane potential

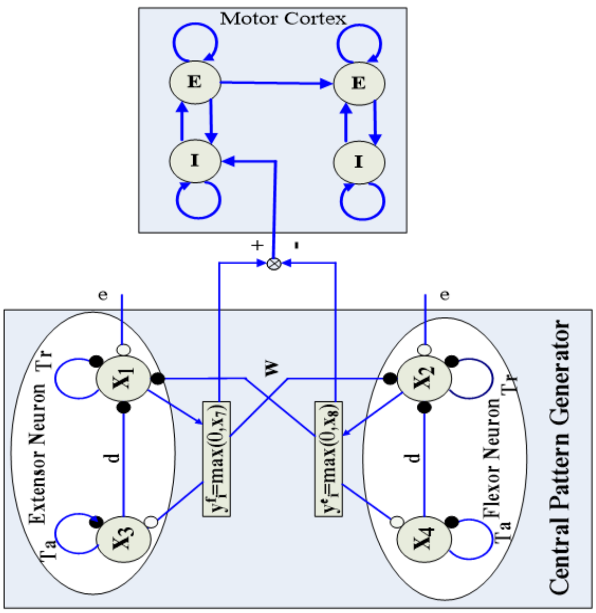


FIGURE 1. The model between the CPG and the motor cortex.

is represented by x_1 and x_3. The two variables x_2 and x_4 represent the adaptation and fatigue specification of the real neurons. The adaptation parameter e shows the continuous adaptation of the tonic input over the stimulation process. The action potentials are caused by this adaptation over the stimulation procedure. b and w, respectively express the self-inhibition and mutual strength. T_r and T_a denote for the time constants of x_1, x_3 and x_2, x_4, respectively.

Gamma oscillations emerge instinctively via a pyramidal-interneuron gamma mechanism [15] where the interneurons are activated by the excitatory input from the pyramidal neurons. In reply, the network is introverted by them for a period given by the time scale of fast GABAergic feedback. Then, with a frequency in the gamma band, the neural population oscillates.

In the paper, to show the frequency of the oscillator, the spike time histogram (STH) is used. The STH is determined as the whole number of firings of a neuron within a given time bin.

$$STH = \sum_i X_i(t) \tag{4}$$

In (4), $X_i(t)$ defines whether neuron i fired within the time bin at time t. And it is provided in (5).

$$X_i(t) = \begin{cases} 1, & f_j^i \in (t, t + \Delta t) \\ 0, & otherwise \end{cases} \tag{5}$$

where f_j^i is the time of the j^{th} spike of neuron i. The width of the time bin is $\Delta t = 1ms$.

Using wavelet analysis, we determined the coupling of the power of the gamma rhythm to external data. For obtaining a complex number labeling the power and phase for every frequency and time-step, the complex Morlet wavelets are convolved with the signal. The complex Morlet wavelet is described by.

$$\psi(t, f) = Ae^{-t^2/2\sigma_t^2} e^{2i\pi f_0 t} \tag{6}$$

where f_0 is the center frequency of the wavelet and σ_t represents the bandwidth factor of the Gaussian envelope. The complex wavelet bandwidth of the scaled with $1/f_0$. By convolving the signal $x(t)$ with the wavelet, the complex wavelet transform is found.

$$CWT_x(t, f) = \sqrt{\frac{f}{f_0}} \int_{-\infty}^{\infty} x(\tau)\psi^*(\frac{f(\tau - t)}{f_0})d\tau \tag{7}$$

where ψ^* shows the complex conjugate of the Morlet wavelet. Utilizing the complex wavelet transform, the power and phase of the signal at a particular frequency can be determined in a time-resolved mode.

$$\begin{cases} P_x(t, f) = |CWT_x(t, f)|^2 \\ \phi_x(t, f) = \arg(CWT_x(t, f)) \end{cases} \tag{8}$$

Following wavelet analysis, the cmor1-1 is selected as the mother wavelet.

The analyses of coupling model in the paper are carried out on the STH of the E population [28]. Data are averaged over 20 trials. The gamma oscillations are shown from the peaks in the STH and the oscillations are not regular. The gamma oscillations are produced in the motor cortex without input (Figure 2).

In Figure 2(a), a clear peak of the power spectrum shows the oscillator in the gamma band. In Figure 2(b), the rastergram of excitatory(red) and inhibitory(blue) neurons over the interval of 1000ms show the neural population oscillator also in the gamma band. The number of peaks in the STH also shows the period of the gamma band in the neural population, which is represented in Figure 2(c). The oscillator activity of E neurons in the primary somatosensory cortex is observed in Figure 2(d), as a red-yellow horizontal band in the interval of 1000 ms. Moreover, the frequency in the whole time interval exists in the gamma band. Hence, based on the diagrams of the power spectrum, rastergram, STH and power based on wavelet analysis, it is indicated that the oscillation exists in the gamma band indicating the effectiveness of the established motor cortex.

III. RESULTS

We apply a CPG input of different frequency with a fixed amplitude to the I population, to investigate the coupling relationship between the CPG and the emergent gamma oscillations. No CPG input current exists to the excitatory neurons, therefore, the impact of the modulation on the E population is supposed to be indirectly modified by the prediction of the I population to the E population. It is possible to interpret a CPG input to the cells in different frequency as a slow variation of the input currents. It is expected that the gamma power and frequency change with the CPG.

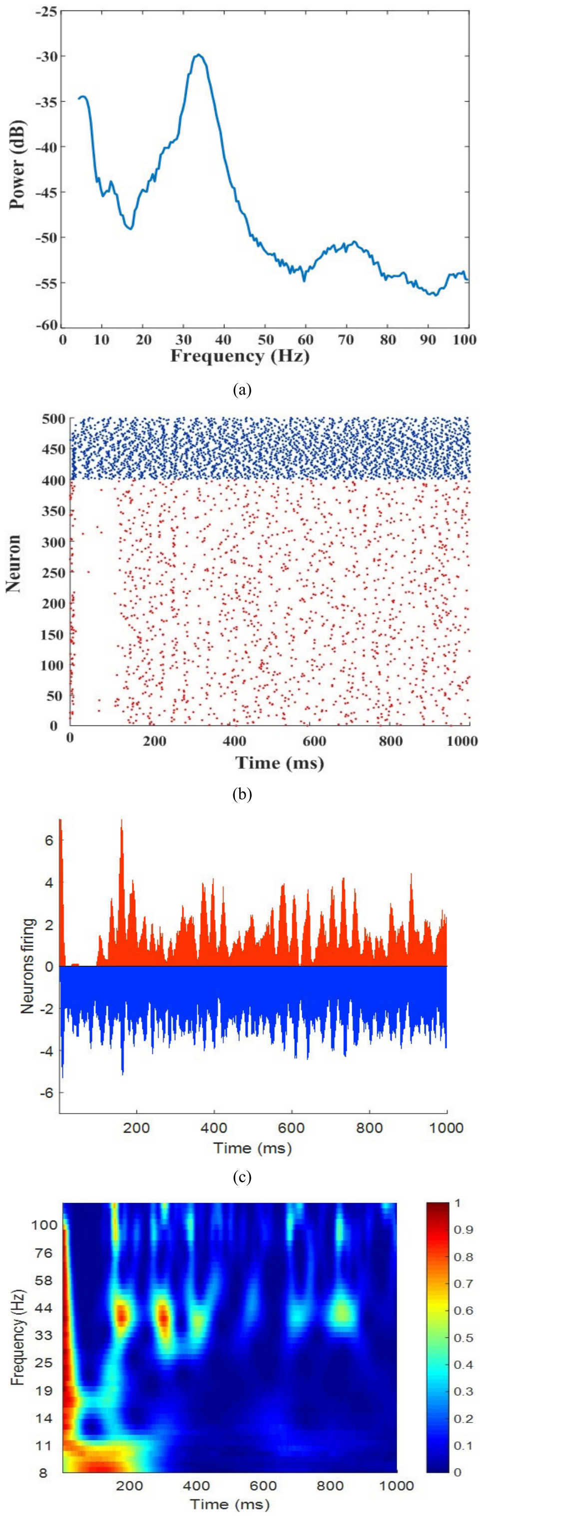


FIGURE 2. The gamma oscillations of the motor cortex without input. (a) The diagram of the power spectrum. (b) The rastergram of excitatory (red) and inhibitory (blue) neurons. (c) The STH of the primary somatosensory cortex. (d) The spectrogram of the primary somatosensory cortex.

To assess the dynamic characteristics of oscillation at the various frequency in the simulation, the power spectrum analysis is selected based on the CHRONUX toolbox [29]. The

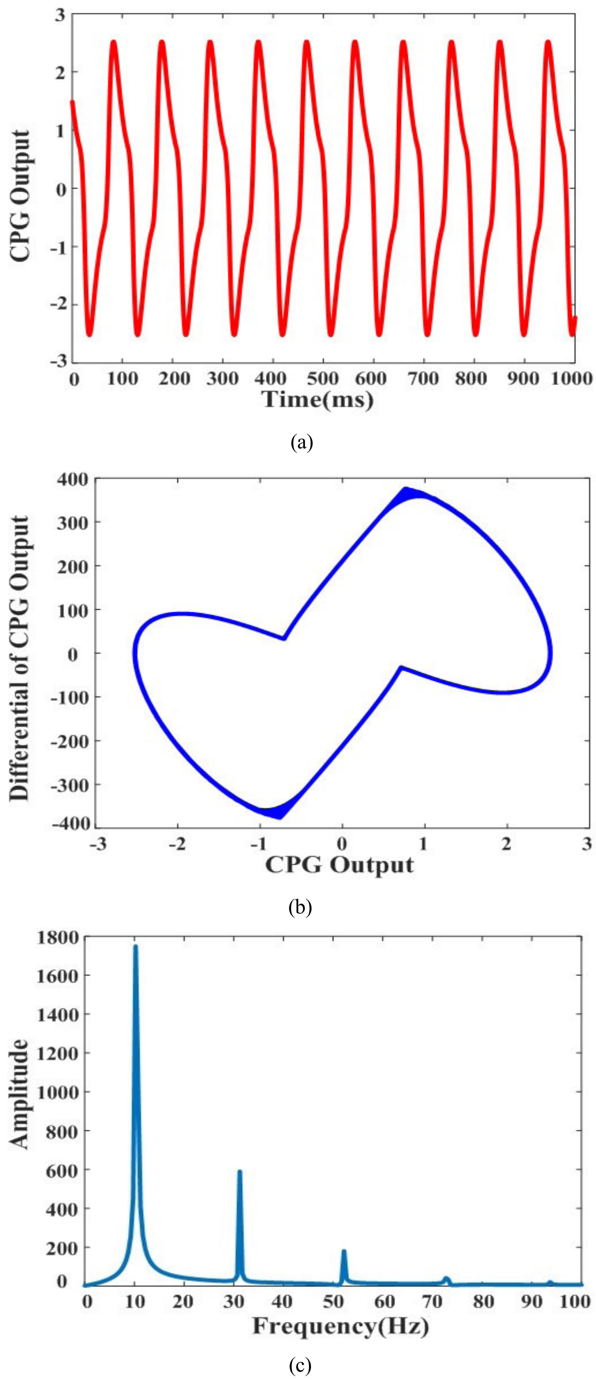


FIGURE 3. The features of the CPG model with 11Hz. (a) The CPG output. (b) The phase Diagram. (c) The diagram of the power spectrum.

factors of the Fourier transform are provided by.

$$X(f) = \sum_{i=1}^{N} x(i) e^{-\frac{2\pi(i-1)(f-1)}{N}} \tag{9}$$

where $x(i)$ is the i^{th} data point. f shows the frequency and N represents the number of data points.

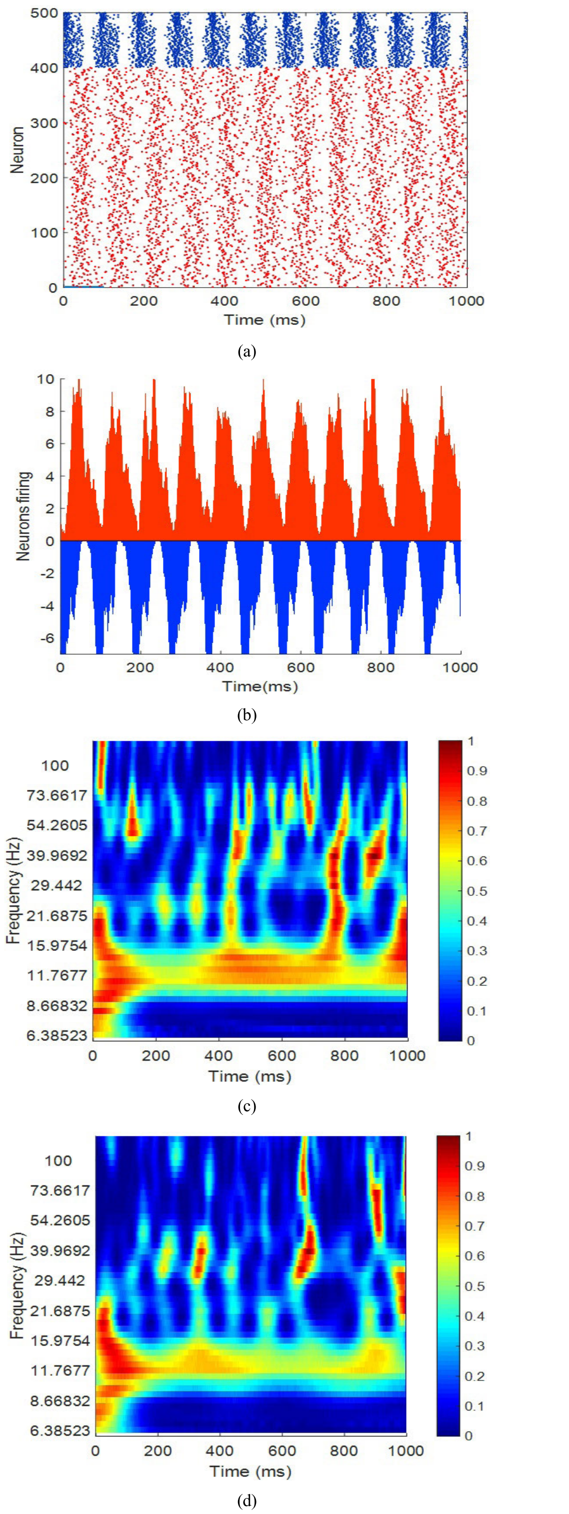


FIGURE 4. **The characteristics of coupling model in terms of CPG of 11Hz. (a) The rastergram of excitatory (red) and inhibitory (blue) neurons. (b) The STH of primary somatosensory cortex. (c) The spectrogram of the primary somatosensory cortex. (d) The spectrogram of the primary motor cortex.**

Then, the absolute values of the Fourier elements are obtained representing the power spectral density.

$$S(f) = |X(f)|^2 \tag{10}$$

The coherence is analyzed to quantify communication between the primary somatosensory cortex to the primary motor cortex. The coherence relies on the cross-spectral density and shown below.

$$C_{xy}(f) = \frac{\left|S_{xy}(f)\right|^2}{S_{xx}(f)S_{yy}(f)} \tag{11}$$

where $S_{xy}(f)$ represents the cross spectral density. $S_{yy}(f)$ and $S_{xx}(f)$ denote for the respective auto spectral densities [15], [29].

In the CPG model of (3), the parameters are adjusted as $T_a = 10T_r$, $w = 2$, $b = 2$ and $e = 2$. The primary value is [0 0 0 0.1]. The frequency of CPG output is determined by parameter T_r. The frequency of CPG output is 11Hz when the value of T_r is 0.004. The features of the CPG output are obtained and represented below.

The phase diagram in Figure 3(b) is the typical limit cycle of CPG corresponding to the cycle oscillation in Figure 3(a). In Figure 3(c), the power spectrum represents that the main frequency of CPG is 11Hz.

Based on the model between the CPG and motor cortex, the CPG output of 11Hz is directed into the primary somatosensory cortex. Then, the dynamics of the model is obtained and represented in Figure 4.

In Figure 4(a)-(b), the mixture of the CPG frequency and gamma band is represented by the rastergram and the number of the peaks in the STH. In Figure 4(c)-(d), the oscillator activity of E neurons is found as a red-yellow horizontal band in the primary somatosensory cortex and the primary motor cortex. Moreover, it is obvious that the oscillator is the mixture of the gamma band and CPG frequency.

Based on biological studies, the low-frequency rhythm entrained by external sensory and motor events can modulate the high-frequency brain oscillation [10], [12], [15]. The CPG frequency is chosen in the field of [1Hz, 19Hz] in the following simulations to show the modulation of gamma oscillator entrained by the CPG.

To observe the dynamic properties in the primary somatosensory cortex and the primary motor cortex in terms of various frequency CPG, the parameter T_r is chosen from 0.035 to 0.0022 correspondent to the frequency from 1Hz to 19Hz all indicating similar phenomena. In Figure 5, the obtained diagrams with the CPG output of 16Hz are represented.

Comparing Figures 4(a)-(b) with Figures 5(a)-(b), the rastergram and the STH of the E population, oscillations are displayed in a mixture of different frequency CPG the and gamma frequency. The peak is extended by the introduction of the CPG reflecting the variation of gamma oscillation frequency with CPG input. The CPG activity is observed as a red-yellow horizontal band in the spectrogram centered in power and frequency that are represented in Figures 4(c)-(d) and Figures 5(c)-(d). The red and the blue lines in Figures 5(e)-(f), represent the gamma power and the CPG phase, respectively. When the frequency is from 30Hz to 90Hz, the gamma power is the average value normalized into [0, 1].

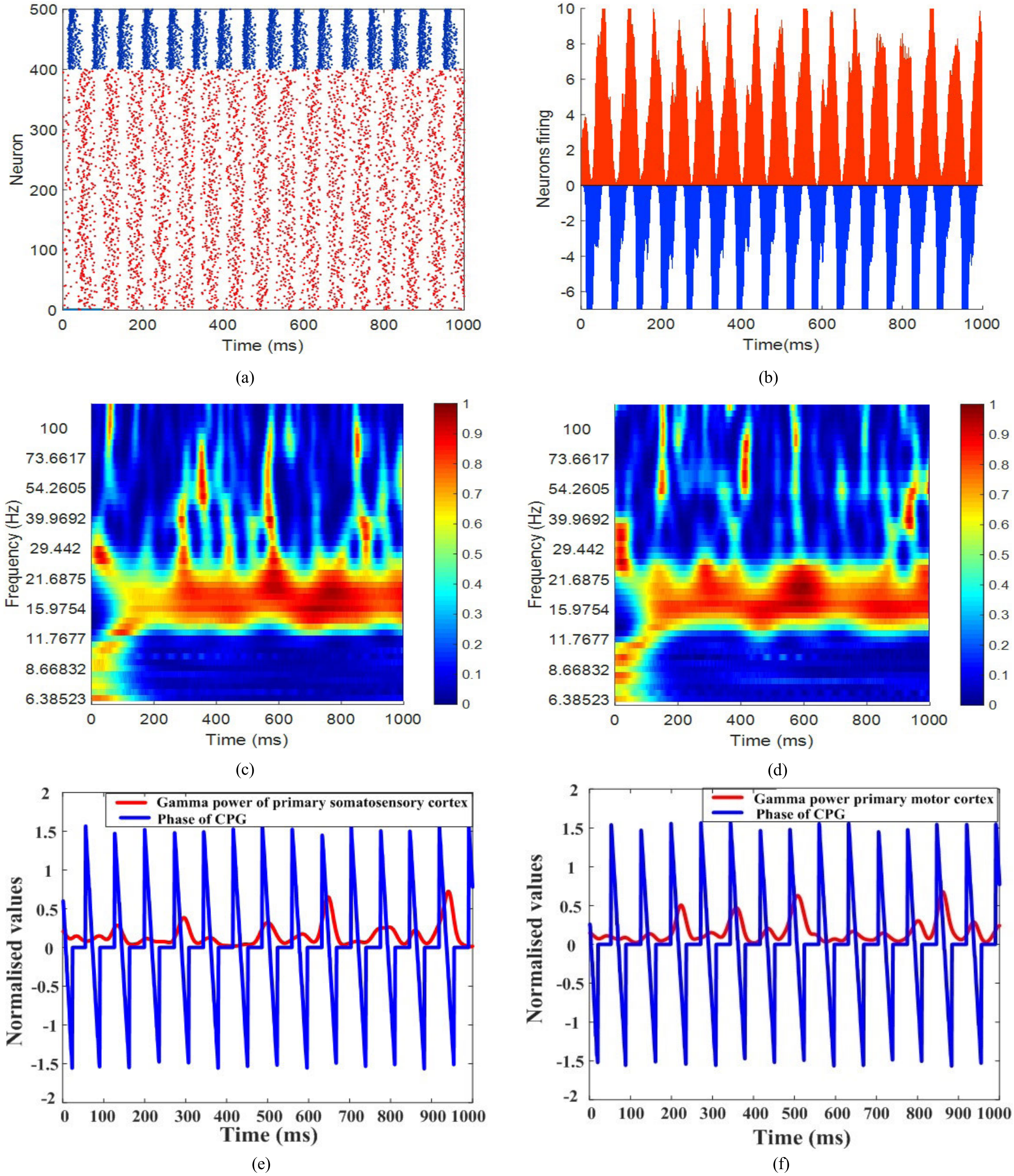
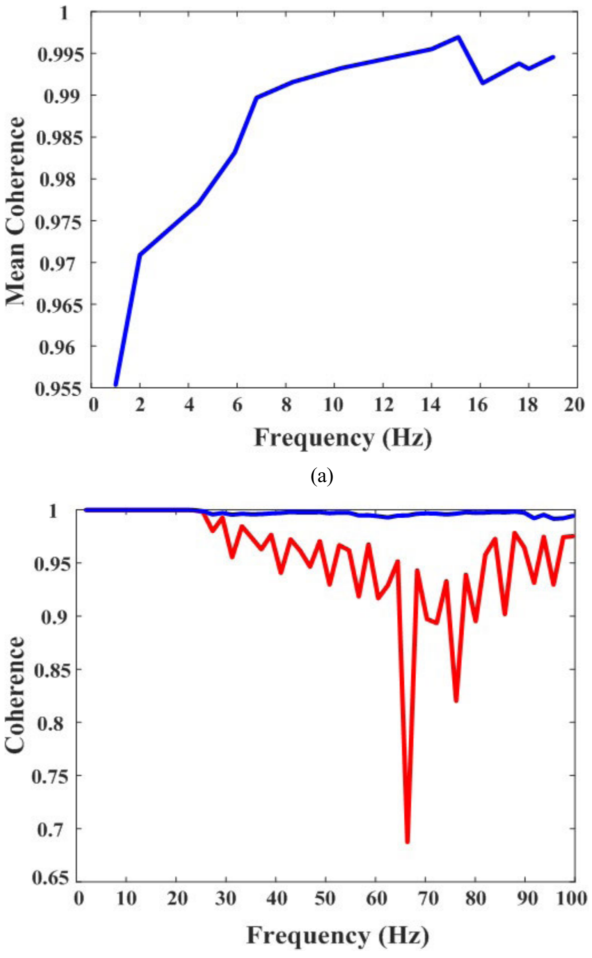


FIGURE 5. The characteristics of coupling model in terms of CPG of 16Hz. (a) The rastergram of excitatory (red) and inhibitory (blue) neurons. (b) The STH of primary somatosensory cortex. (c) The spectrogram of the primary somatosensory cortex. (d) The spectrogram of the primary motor cortex. (e) The CPG phase-modulated gamma power in the primary somatosensory cortex. (f) The CPG phase-modulated gamma power in the primary motor cortex.

Based on the results, it is indicated that the phase of the CPG modulates the gamma power. Moreover, the information can be transferred from the primary somatosensory cortex to the primary motor cortex.

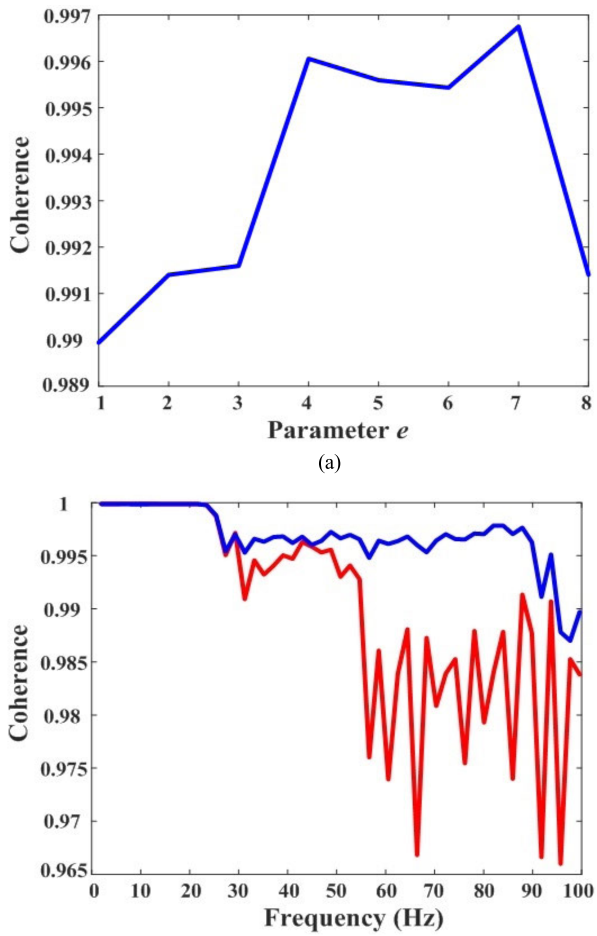
The gamma band coherence between the two populations is selected as an index for the level of information transmission, to investigate the communication between the frequency and amplitude of CPG modulate and the primary somatosensory cortex and the primary motor cortex. The frequency of CPG changes in the field of [1Hz, 19Hz]. Unchanging the amplitude of CPG, the mean value of coherence with the various frequency of CPG is found. Furthermore, the various



(a)

(b)

FIGURE 6. The coherence of neural areas in terms of various frequency CPG. (a) The mean value of coherence. (b) The coherence between the primary somatosensory cortex and the primary motor cortex at different frequencies.



(a)

(b)

FIGURE 7. The coherence of neural areas in terms of various amplitude CPG. (a) The mean value of coherence. (b) The coherence between the primary somatosensory cortex and the primary motor cortex in different amplitudes.

coherence between the maximum mean value and the minimum one is represented in the following figure.

In Figure 6(a), the maximum mean value of the conference is observed at 15Hz and the minimum one is observed at 1Hz. In Figure 6(b), the coherence between the primary somatosensory cortex and the primary motor cortex obtained at different frequencies are displayed by the red and blue lines. When the frequency of the CPG is maintained at 1 Hz, the coherence is displayed by the red line. The blue line is equivalent to the CPG frequency of 15 Hz. According to the results, the difference in coherence is obtained occurring in the gamma band.

Choosing the frequency of CPG as 15Hz, the amplitude parameter e in (3) changes from 1 to 8. Then, the mean value of coherence with CPG of various amplitude is found. The different coherence between the maximum and minimum mean values is shown below.

In Figure 7(a), the maximum mean value of the conference is observed when $e = 7$. And the minimum one is shown when $e = 1$. In Figure 7(b), the red and blue lines represent the coherence consistent with $e = 1$ and $e = 7$, respectively. According to the results, the difference in coherence is also found occurring in the gamma band.

IV. DISCUSSION

The locomotion control system includes the motor cortex, CPG, musculoskeletal system and environmental sensors, and each part plays an irreplaceable role in the system [19]. In order to better understand the functional organization and capabilities of the locomotion control system, the researchers have investigated the structure and the working mechanism of the locomotion control system based on the biological experiments [31], the neural encode principle based on bionics [32], and the coupling relationship between the CPG and the motor cortex [18], [23]. However, the information transfer in the locomotion control system is still an open problem. The previous studies suggest that the brain oscillations and their cross-frequency coupling play a functional role in neuronal computation and information communication [8], [12]. Inspired by the biological phenomena, we establish the model between the motor cortex and the CPG. Through simulations, the principle of information communication between different neural populations is shown in detail.

Comparing Figure 2 with Figures 4-5, it is found that the various frequency of CPG can have key roles in the primary somatosensory cortex and the primary motor cortex. They can cause the CPG frequency to insert in the gamma oscillation. The data indicate that the CPG phase modulates gamma power. Moreover, the information can be transferred from the primary somatosensory cortex to the primary motor cortex. To clarify the roles of cross-frequency coupling, the results can be utilized [12]. In Figures 6-7, there is an optimal CPG with appropriate amplitude and frequency causing the neural populations to oscillate for the best action in the gamma band. Therefore, the proper stimulus is suitable for processing the neural population and it corresponds to the biological phenomena. In Figures 6-7, the coherence difference mostly happens in the gamma band, when CPGs with various parameters are transferred into the neural populations. Consequently, the interaction of the internal dynamics with incoming stimuli provides a substrate for processing the complex information.

Comparing with the previous investigation[15], [18], [21], [23], the contents of the paper have much in common. Firstly, we use the pyramidal-interneuron gamma mechanism to generate gamma oscillations, and Matsuoka's model to simulate CPG. Secondly, the effects level is qualified using the power spectrum, spiking time histogram, rastergram, spectrogram in terms of the wavelet analysis and coherence between neural populations. However, there are many differences from the previous investigation. In previous studies [18], [21], [23], we only investigated the state change of the CPG and motor cortex and their corresponding relationship based on the model between the CPG and the motor cortex. In the paper, the investigation of the information transfer between the CPG and the motor cortex is innovative. The research indicates that the CPG with various frequencies exposed to the gamma rhythm frequency can be embedded in gamma oscillation and the gamma power is altered by the CPG phase. An optimal CPG exists with appreciate frequency and amplitude making the neural populations oscillate for the best action in the gamma band. Once sending the CPGs into the neural populations, the coherence principally occurs in the gamma band. The results are consistent with the previous research report where the gamma rhythm plays an important role in neuronal information processing [33] and the coherence between the neural population can enhance the neuronal communication [34]. At the same time, the phase-power coupling mechanism is a beneficial explore for the information transfer between the CPG and the motor cortex. The results open up a mechanism through which the information selection and processing can be achieved and the mechanism is a source for further investigation in the field of neuronal information communication.

V. CONCLUSION

Based on the numerical simulation and biological knowledge, the model between the CPG and the motor cortex is created. The periodic signal of CPG is employed to the primary somatosensory cortex while sending the data of the primary somatosensory cortex to the primary motor cortex. The impacts on the motor cortex in terms of the CPG in gamma band rhythm is assessed in the paper. The results help us to better understand the information process in the neural populations.

In the paper, we focus on the information transfer between the CPG and the motor cortex and simple motor cortex is used to investigate. Based on biological knowledge, the locomotion control system is a complex system [19], [35]. It is a limitation of the paper that there is no complete system established to analyze the neuronal information communication. At the same time, researchers [8], [30] indicate that physiological information is included in the waveform shape of neural oscillations reflecting specific points regarding the physiology of the brain region. In traditional assessment on the neural oscillations, it is not possible to comprehend the roles of the shape of neural oscillations comprehensively. Another limitation of the paper is that there is no investigation to analyze the roles of the waveform shape in neuronal information communication. Further investigations are required for these contents.

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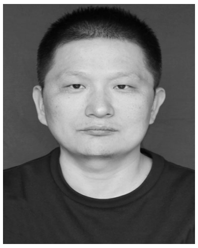

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