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Review

The Coupling Behaviors Between Nervous and Cardiopulmonary Circulation Systems Underlying Motor Function: A Review

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ABSTRACT Motor function relies not only on the effective execution of neuromuscular system but also on the dynamic coupling between nervous and cardiopulmonary circulation systems. During movements, the nervous system generates and transmits motor commands to muscles, while the cardiopulmonary circulation system continuously provides sufficient energy for neural and muscular activities. This "neuro–cardio–pulmonary–circulation coupling" (NCPCC) constitutes one of the critical physiological foundations for motor function. Previous studies have explored the coupling mechanisms among multiple physiological systems such as corticomuscular coherence (CMC) and neurovascular coupling (NVC), however, the coupling behaviors between nervous and cardiopulmonary circulation systems during movements remain poorly understood. From the perspective of motor execution, this paper summarized the recent research on NCPCC and proposed a concept of "brain–cardiopulmonary axis" (BCA). Based on a multi-level analysis framework that integrated the local regulation between neural activity and hemodynamic responses together with the global bidirectional regulation between nervous and cardiopulmonary systems, the characteristics and functional significance of neurovascular, neurocardiac, and neurorespiratory couplings were reviewed in detail. Furthermore, current challenges and future research directions were discussed. In summary, this review aims to provide a theoretical foundation for elucidating multisystem interaction mechanisms underlying motor function, thereby facilitating precision diagnosis and targeted intervention for motor function rehabilitation.

KEYWORDS Motor function; Neuro; Cardiopulmonary circulation; Functional coupling; Rehabilitation

1 Introduction

Motor function represents a fundamental capability through which humans adapt to and interact with the environment, reflecting the coordinated integration of the nervous, musculoskeletal, and cardiopulmonary systems. Previous research on motor function has primarily focused on neuromuscular coordination, whereby motor commands are formed within motor-related cortical regions [1], such as the supplementary motor area and primary motor cortex, and transmitted via descending pathways to spinal motor neurons and neuromuscular junctions, finally driving skeletal muscle contraction to accomplish intended actions. This analytical framework has provided an essential foundation for elucidating the mechanisms underlying motor function [2]. However, physiological motor behavior extends beyond neuromuscular activity. In addition to precise neural regulation and musculoskeletal execution, support from the cardiopulmonary circulation system is indispensable. By delivering oxygen and removing metabolic waste, this system ensures a continuous supply of energetic substrates and facilitates the metabolic clearance [3]. Therefore, the multilevel interactions among neural networks, skeletal muscle, and cardiopulmonary circulation system synergistically determine motor performance. Within this integrated framework, skeletal muscle serves as the executor of motor output, whereas coordinated regulation between the nervous and

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cardiopulmonary circulation system provides more fundamental support for motor execution by forming motor commands and ensuring adequate energy supply. Elucidating this interaction between the two systems is therefore essential for a comprehensive understanding of motor function.

In this context, the concept of "coupling" from systems science provides a valuable framework for analyzing the "neuro–cardio–pulmonary–circulation coupling" (NCPCC) underlying motor function. Within the field of physiology, coupling between the nervous and cardiopulmonary circulation system is reflected in coordination among neural electrophysiological, hemodynamic changes, and rhythmic regulatory activities [4–6]. Representative forms include neurovascular coupling (NVC), where increased neural activity in specific brain regions induces dynamic adjustments in local cerebral blood flow (CBF) and oxygenation [7]; neurocardiac coupling (NCC), where neural activity is coordinated with cardiac rhythm and output to match cardiovascular dynamics with metabolic demands [8]; and neurorespiratory coupling (NRC), where neural activity synchronizes with respiratory rhythms, thereby modulating gas exchange and neural oscillatory dynamics [9]. Together, these coupling behaviors constitute the essential forms of interactions between the nervous and cardiopulmonary circulation system during motion, and have emerged as a major focus of research in motor neuroscience and rehabilitation medicine. Furthermore, advances in multimodal physiological monitoring technologies, including electroencephalography (EEG) [10], electrocardiography (ECG) [11], functional magnetic resonance imaging (fMRI) [12], functional near-infrared spectroscopy (fNIRS) [13], and electron microscopy [14], have provided powerful tools for investigating the NCPCC. The synchronous acquisition and integrated analysis of these multimodal signals allow simultaneous capture of central neural electrophysiological activity, CBF and oxygenation, cardiac rhythms, and respiratory regulation, thereby revealing cross-system dynamic coupling features that are inaccessible through single-modality measurements. Such multimodal coupling analyses not only enhance the understanding of coordinated regulation between the nervous and cardiopulmonary circulation system but also provide a foundation for developing integrative physiological markers. Emerging evidence further suggests their clinical relevance in neurological disorders and motor-impaired populations, with potential applications in early diagnosis, functional assessment, and targeted intervention [15,16].

Despite these advances, the multisystem coordinated behaviors involved in motor function remain to be further elucidated. The recently proposed "brain–heart axis" concept [17] has provided an important theoretical model for understanding the bidirectional regulation between the central nervous and cardiovascular systems, while also offering novel insights into the mechanisms of multisystem functional coupling. However, considering the extensive interactions and coordinated regulation among the cardiopulmonary and circulation systems during movement, we proposed the "brain–cardiopulmonary axis" (BCA) as a multilevel analytical framework for elucidating the regulatory mechanisms underlying motor function. Based on the framework, this review summarized recent advances in the interactions between the nervous and cardiopulmonary circulation systems underlying motor function, including the NVC, NCC, and NRC. We further analyze the characteristics of coupling and decoupling behaviors and discuss their clinical implications for diagnosis and motor rehabilitation interventions. Finally, we outline current limitations and propose future research directions to advance the understanding of multisystem coupling in motor function and its applications.

2 Literature Search and Selection Strategy

A comprehensive literature search was conducted using IEEE Xplore, PubMed, Web of Science Core Collection, and Scopus, with Google Scholar used as a supplementary search tool to identify additional relevant studies and cross-check key references. The search covered publications from 2015 to 2025, with earlier seminal studies included when necessary to provide historical context or explain fundamental mechanisms. The search strategy combined controlled vocabulary and free-text keywords, including "neurovascular coupling", "neurocardiac coupling", "cardiac–brain interaction", "brain–heart axis", "neurorespiratory coupling", "respiratory rhythm", "cardiopulmonary system", "motor function", "motor control", "exercise", "rehabilitation", "EEG", "ECG", "fNIRS", "fMRI", together with their related terms and Boolean operators (AND/OR).

After removing impurities and duplicates, the remaining studies were screened according to the predefined inclusion and exclusion criteria. The screening process was conducted in two stages. In the first stage, the retrieved studies were independently screened based on titles, abstracts, and keywords. In the second step, the full texts of the studies that met the initial screening criteria were further evaluated for eligibility. Priority was given to high-quality original research articles, systematic reviews, and landmark studies published in peer-reviewed journals. Additional relevant references were

identified through manual searches of the reference lists of key publications. The eligibility criteria were defined as follows. Studies were included if they: (1) investigated interactions between the nervous system and cardiopulmonary circulation systems; (2) focused on mechanisms of neurovascular, neurocardiac, or NRC during motor control, exercise, or motor rehabilitation; or (3) reported advances in multimodal physiological monitoring, computational analysis, or clinical applications relevant to multisystem coupling. Conference abstracts without full-text availability, duplicate publications, non-peer-reviewed reports, and studies lacking sufficient methodological information were excluded. Following the screening process, a total of 108 publications were included in this review. The included literature encompassed studies directly addressing NCPCC, along with relevant publications that provided essential background information, historical context, and insights into future research directions.

3 Multisystem Coupling Underlying Motor Function

Bidirectional information transfer and functional coordination between the nervous and the cardiopulmonary circulation system constitute the BCA, which represents a crucial physiological foundation for the execution of motor function. Within the BCA, the nervous system serves as the core for motor information processing and regulation, while simultaneously modulating cardiovascular and respiratory activities through autonomic neural pathways. Meanwhile, endogenous physiological rhythmic signals generated by cardiopulmonary circulation system are continuously conveyed back to the central nervous system (CNS), thereby contributing to the maintenance of systemic homeostasis during motor execution. Based on the concept of BCA, NCPCC further characterizes the multilevel information transfer and coordinated interactions between nervous and cardiopulmonary circulation systems, representing a critical mechanism through which the BCA supports motor function. According to regulatory scale and functional scope, NCPCC can be conceptualized into two pivotal dimensions. The first dimension involves local regulation between nervous and the circulation system, namely neurovascular coupling. In this process, increased neural activity induces localized increases in CBF, thereby maintaining dynamic matching between neural metabolic demands and cerebral perfusion. The second dimension involves global bidirectional regulation between the nervous and cardiopulmonary systems, encompassing NCC and NRC. Through autonomic neural pathways, CNS regulates cardiac function, including heart rate and cardiac output, as well as respiratory dynamics such as breathing rhythm and ventilation, in order to meet metabolic demands during movement. Meanwhile, endogenous physiological signals arising from cardiac oscillations and respiratory rhythms can feed back to modulate neural activity, forming a dynamic information transfer network between the nervous and cardiopulmonary circulation systems. The content structure of remaining part and brief coupling relationships are illustrated in Fig. 1.

3.1 Local regulation between nervous and circulation systems: NVC

During the generation and transmission of motor commands, the activation of critical cortical regions such as the prefrontal and primary motor cortex, and the supplementary motor area is enhanced [1]. This process induces changes in regional CBF. The coordinated interaction between neural activity and regional hemodynamic regulation is termed NVC [18,19]. The NVC represents not only a fundamental physiological mechanism supporting brain function but also a prototypical case of coordinated regulation between the nervous and circulatory system. Contemporary NVC research has evolved into two major aspects: (1) cellular and molecular level studies focus on the microscopic mechanisms, aiming to elucidate how neural activity regulates vascular response through signaling pathways; (2) signal level studies examine the spatiotemporal correlation characteristics between neural activity and hemodynamic responses based on multimodal physiological signals. The schematic diagram of NVC at both cellular and molecular level and signal levels is illustrated in Fig. 2.

3.1.1 Cellular and molecular level

The cellular and molecular level research can be traced back to 1890 [20], when it was first observed that metabolic byproducts released during cerebral asphyxia (hypoxia/hypercapnia) dilated the cerebral vasculature. This observation led to the proposal of the metabolic feedback hypothesis, which suggests that increased neural activity elevates local metabolic demand, resulting in the accumulation of metabolites (CO_2 [21], lactate (Lac) [22], and H^+ [23]). These metabolites act on vascular smooth muscle cells to induce vasodilation, thereby increasing regional blood flow to satisfy the metabolic requirements of active neurons. In addition to supporting neuronal energy demands, NVC facilitates the

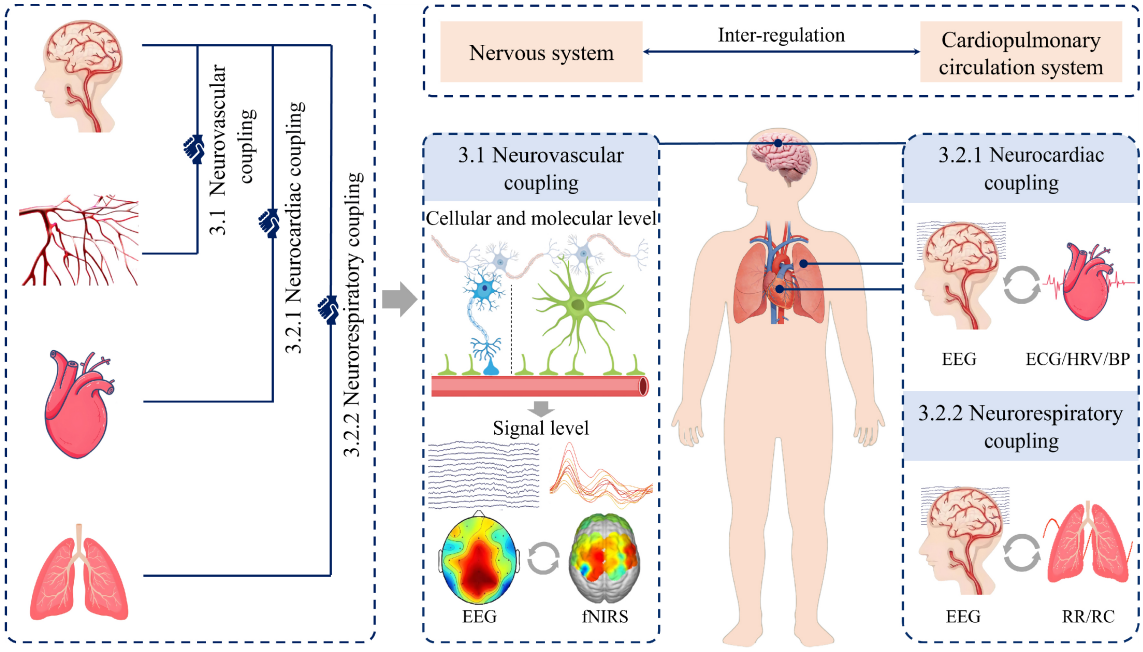

Fig. 1 The relationship of multisystem coupling and the content structure

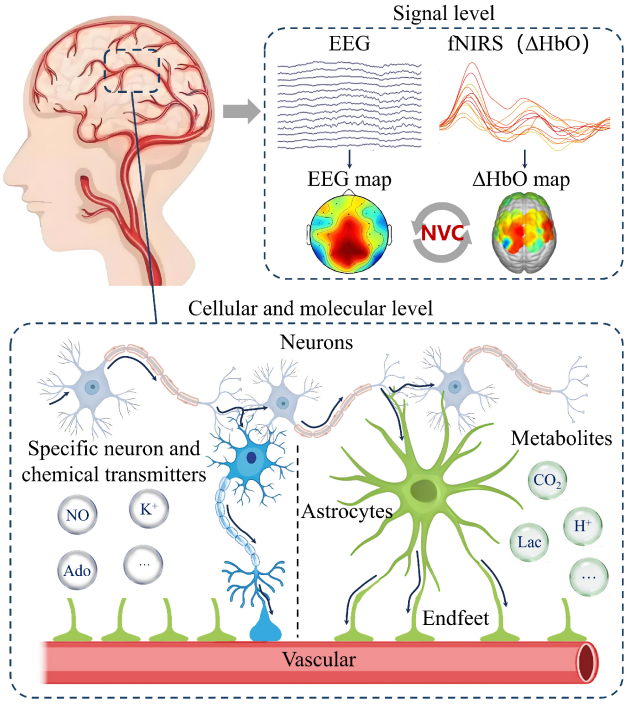

Fig. 2 Neurovascular coupling at the cellular/molecular level and signal levels.

clearance of metabolic waste [24,25] and contributes to multiple physiological processes, including proteostasis, neuroimmune trafficking, and brain temperature regulation [18,26]. However, advances in neuromodulation and imaging technology [27–29] have challenged the traditional metabolic feedback hypothesis of NVC [30]. Evidence indicated that activity-induced increases in CBF are not strictly confined to activated cortical regions [31] and do not always correspond to local oxygen and glucose demands [32]. Moreover, baseline cerebral perfusion may already be sufficient to support neural activity [33]. These observations have prompted the proposal of activity-dependent nonmetabolic feedforward hypothesis.

According to this feedforward hypothesis, increases in regional CBF are actively and rapidly triggered by neural activity itself [34–36], rather than by secondary metabolic byproducts resulting from energy consumption. A variety of chemical transmitters, such as nitric oxide (NO) [37,38], adenosine (Ado) [39], K^+ [40] can also influence vascular smooth muscle cells through multiple signaling pathways, thereby triggering vascular responses. Recent studies have further revealed the NVC regulating experience-induced neurogenesis: hippocampus-engaged behaviors rapidly increased microvascular blood flow velocity in the dentate gyrus, a process actively modulated by pre-existing newborn dentate granule cells through parvalbumin-expressing interneurons [41]. In addition, emerging evidence suggests that the glutamatergic neurons can directly regulate arterial smooth muscle cells through pseudo-synaptic connections, inducing vasodilation and functional hyperemia [42]. These findings complement existing models of CBF regulation and provide new insights into the rapid and precise modulation of CBF, with potential implications for therapeutic strategies targeting ischemic hypoperfusion. Specifically, a reverse signaling pathway was revealed in NVC. Changes in blood or pressure can alter the vascular tension of parenchymal arteriole, leading to modulation of the resting activity of cortical pyramidal neurons [43]. This information flow from blood vessels to astrocytes and subsequently to neurons, termed vascularneuro coupling, represents a reversal of the classic NVC direction and enables neurons to dynamically adjust their activity according to cerebral perfusion levels, thereby serving a potential neuroprotective function against energy supply-demand mismatch.

Building on the two perspectives discussed above, another view suggests that, at the cellular and molecular level, CBF regulation induced by neural activity may involve both metabolic feedback and nonmetabolic feedforward hypotheses, depending specifically on the duration and intensity of the neural activation. During the initial phase of neural activity, the feedforward signaling may predominate, enabling rapid and excessive vascular responses [44]. As activity persists, the accumulation of metabolic byproducts engages feedback pathways [45], thereby refining vascular responses to better match local metabolic demands. An overview of these cellular and molecular mechanisms of NVC is summarized in Table 1.

3.1.2 Signal level

Signal level investigations of NVC primarily rely on the synchronous acquisition and integrated analysis of multimodal electrophysiological and hemodynamic signals. By analyzing the temporal relationship, spectral characteristics, and information transmission of these signals, the dynamic relationships between neural electrical activity and cerebral hemodynamic responses are revealed. Regarding multimodal signal acquisition, EEG provides non-invasive measurements with high temporal resolution [46], enabling the characterization of rapid neural dynamics, whereas hemodynamic information is typically obtained using fMRI or fNIRS, which offer advantages in spatial resolution and experimental feasibility, respectively. The integration of EEG with fMRI enables the association of neural electrical activity with hemodynamic response, thereby elucidating the spatiotemporal relationship between neural activation and CBF regulation [47,48].

Table 1 Summary of different mechanisms of NVC at cellular and molecular level.

Reference	Mechanism	Method	Main finding
[21]	Metabolic feedback	fMRI and Fast scan cyclic voltammetry	The results suggest that CO_2 mediates signaling between neurons and the cerebral vasculature to regulate brain blood flow
[22]		cAMP analysis in brain slices, etc.	The lactate can act as a volume transmitter that links neuronal activity, cerebral energy metabolism and energy substrate availability
[24]		Two-photon imaging	Functional hyperemia boosts not only the supply of metabolites but also the removal of metabolic waste
[25]		Two-photon imaging	Functional hyperemia may serve to increase metabolite clearance from the arteriolar paravascular space
[34]	Nonmetabolic feedforward	Two-photon imaging	Capillary-associated microglia are involved in CBF regulation
[35]		Two-photon imaging	Arteriolar endothelial cells have an active role in mediating NVC
[36]		Two-photon imaging	Endothelial cell TRPA1 channels initiate microvascular vasodilatory responses
[37]		Laser doppler	Endothelial NO contributes to NVC
[39]		Laser doppler	Adenosine activates K_{ATP} channels to increase CBF
[41]		Ca^{2+}/blood imaging	NO signaling is involved in the regulation of microvascular blood flow
[42]		Two-photon focal optogenetics	Glutamatergic neurons can directly act on arterial smooth muscle cells and induce functional hyperemia in the brain
[43]	Other	Ca^{2+} imaging + electrophysiology	Blood flow/pressure-induced changes in parenchymal arterioles can alter the resting activity of cortical pyramidal neurons

Meanwhile, simultaneous EEG-fNIRS acquisition is particularly suitable for studies involving motor execution because of the tolerance to motion artifacts and freedom from magnetic constraints [49,50]. Increasing evidence suggests that combined EEG-fNIRS acquisition and analysis improve the accuracy and feasibility of characterizing neural activities during motion-related task compared to single-modal data [51,52]. Mechanistic studies have further revealed the coupling patterns between EEG rhythmic modulations and hemodynamic responses [53]. During motor execution, increases in oxyhemoglobin concentration (HbO) are accompanied by reductions in the amplitude of alpha [54,55] and beta [56] rhythms (event-related desynchronization, ERD), while hemodynamic responses exhibit a delayed onset relative to neural motion-related electrical activity and return to baseline levels several seconds after motion termination. Methodological advances in signal analysis have further enabled the characterization of the directional and nonlinear properties of neurovascular interactions. The time-frequency analysis captures the changes in non-stationary physiological signals, revealing frequency variations over time, whereas transfer entropy effectively quantifies nonlinear and bidirectional information transfer between neural and hemodynamic signals. EEG-fNIRS studies employing these methods have shown that, during motor execution, information transfer entropy from HbO changes to EEG is significantly stronger than the reverse direction, suggesting that hemodynamic changes exert a stronger feedback effect on neural activity [57]. Compared with the prefrontal cortex, this directional coupling is more pronounced in the motor cortex. Additionally, this pattern is further amplified under resistance training conditions, suggesting that movement load modulates the strength of neurovascular information transfer [58].

From both functional and clinical perspectives, signal-based investigations of NVC have demonstrated significant potential for clinical applications. Functional brain controllability analysis can be used to quantify post-stroke motor control impairments, revealing significantly reduced modal controllability within executive control networks in stroke patients [59]. This provides new insights into understanding stroke-induced motor control deficits. In addition, studies focusing on neurovascular decoupling highlight its diagnostic and rehabilitative potential across neurological disorders. Subject-specific NVC modeling demonstrates that faster finger-tapping speeds enhance hemodynamic activation and strengthen NVC [60], suggesting that quantification of task-dependent neurovascular responses may facilitate individualized rehabilitation assessment and treatment monitoring. Additionally, bilateral motion tasks reveal an increasing reliance on contralesional compensatory strategies to accomplish the task. Concurrently, fNIRS reveals enhanced hemodynamic responses in the sensorimotor cortex, whereas EEG activity remains comparable to that of healthy controls, reflecting an asymmetry between neural and vascular responses. This means that stroke patients may need to recruit additional neural resources to achieve performance levels similar to neurologically intact individuals [61]. Attenuation of such asymmetry, together with progressive motor improvement, may therefore represent a mechanistic substrate for post-stroke motor rehabilitation. Collectively, these findings indicate that signal level NVC metrics provide objective markers for assessing motor function and monitoring rehabilitation progress [62]. The signal level studies of NVC are summarized in Table 2.

3.2 Global bidirectional regulation between the nervous and cardiopulmonary systems: NCC and NRC

The cardiopulmonary system is extensively involved in motor function through multimodal coupling processes with the CNS. On the one hand, the cardiopulmonary system is itself regulated by the CNS, enabling adaptive cardiovascular and respiratory responses that ensure sufficient oxygen and substrate delivery during motor activity. On the other hand, emerging evidence has shown that cardiopulmonary activity is not merely passively regulated by sympathetic and parasympathetic pathways. Instead, intrinsic physiological rhythms, including cardiac and respiratory oscillations, actively interact with central neural dynamics and modulate neural excitability. Specifically, cardiac oscillations, as reflected by heart rate variability (HRV), exhibit robust phase-amplitude coupling with neural oscillations across canonical EEG frequency bands. Combined with the predominance of heart-to-brain Granger causality, these findings suggest that cardiac rhythms actively modulate cortical oscillatory amplitude [63]. Similarly, the respiration cycle modulates alpha-band activity, a reliable marker of cortical excitability, and dynamically influences beta-band corticomuscular coherence, thereby regulating the efficiency of sensorimotor communication [64,65]. These bidirectional interactions form the physiological basis of NCC and NRC, highlights the cardiopulmonary system as an active participant in the integrated regulation of motor function rather than merely a supportive subsystem. The schematic diagram of the global bidirectional regulation relationship between nervous and cardiopulmonary circulation system is shown in Fig. 3.

Table 2 Summary of NVC in motor function at signal level.

Reference	Subject	Paradigm	Main finding
[49]	Healthy individuals	Right/Left arm raising + hand gripping	The EEG-fNIRS based system discriminates a set of motor tasks with higher accuracy than individual system (EEG or fNIRS)
[51]		Three types of bimanual cyclical tasks	The decrease in μ band power was accompanied by the increase in HbO, and the EEG-fNIRS bimodal features could more accurately characterize neural activation patterns
[54]		Continuous walking, Isolated gait phase task, and single-limb stance	There is a significant ERD in alpha-band during the motion task, accompanied by an increase in HbO response.
[56]		Tapping computer mouse button with right finger	The increases in HbO were accompanied with a reduction in the amplitude of alpha- and beta-band
[57]		Voluntary/FES-induced wrist extension	The TE from HbO to EEG is larger than that for the opposite direction
[58]		Upper/Lower-limb exercises and Upper-Lower limb linked exercise	Limb movement is shown to significantly enhance information transmission or coupling relationships
[59]	Stroke patients	Left/Right-hand clenching tasks	The modal controllability of stroke patients in the executive control network and the supplementary motor cortex was significantly lower than that in healthy people
[60]		Finger-tapping task at 1/2 Hz	NVC varies under different speeds, with higher-frequency movement can induce stronger NVC
[61]		Paced-reaching task and circular steering task	Stroke patients showed elevated HbO in bilateral SM1 and reduced beta ERD when using the paretic hand, indicating excessive brain activation and motor compensation.
[62]		Left/Right-hand clenching tasks	The task-evoked strength at ipsilesional primary somatosensory cortex was significantly lower in stroke patients compared with healthy controls.

3.2.1 Neurocardiac coupling

The heart is not only a powerful organ sustaining systemic circulation but also an active participant in homeostatic regulation through continuous bidirectional communication with the CNS [66]. During motor execution, neural regulation of cardiac function is mediated by a feedforward mechanism known as “central command” [67], which enables anticipatory cardiovascular adjustments prior to or simultaneously with motion. Through coordinated modulation of sympathetic and parasympathetic outflow, this mechanism regulates heart rate, myocardial contractility, and peripheral vascular resistance, thereby ensuring sufficient cardiac output and arterial pressure stability both at motion onset [68] and during steady-state motion conditions [69]. Meanwhile, the CNS continuously receives information regarding circulatory status and metabolic load from feedback provided by baroreceptors, chemoreceptors, and mechanoreceptors, and dynamically adjusts the intensity and pattern of central commands. This process helps maintain arterial blood pressure (BP) stability, prevent excessive sympathetic activation, and preserve cardiovascular safety during exercise [70].

Beyond this top-down autonomic regulation, current evidence indicates that cardiac activity also exerts a bottom-up influence on neural dynamics, highlighting the bidirectional nature of NCC. At rest, BP has been identified as a driver of cortical alpha- and beta-band oscillations, as well as HRV. During motor tasks, this coupling pattern is preserved, although with fewer connections, underscoring the central role of BP in systemic physiological coordination [71]. In addition, the phase of cardiac cycle itself modulates motor-related neural excitability. Cortical and corticospinal excitability are enhanced during systole compared to diastole, as reflected by increased hand muscle activation and stronger desynchronization of sensorimotor rhythms [72].

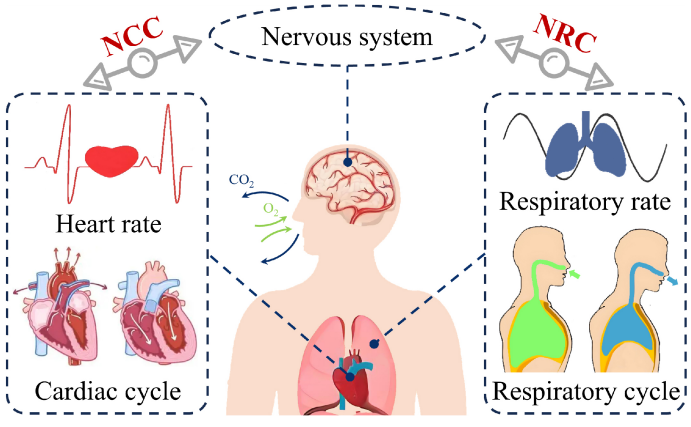

Fig. 3 Global bidirectional regulation between the nervous and cardiopulmonary circulation system.

Those findings suggest that phasic cardiac signals can regulate neural processing, potentially creating functionally distinct temporal windows within the cardiac cycle that differentially facilitate motor information processing and sensorimotor integration.

Collectively, these studies deepen the understanding of autonomic regulation mechanisms and provide a new conceptual framework for explaining how internal physiological signals are integrated into motor control, influencing individuals' response to the external environment. Disruption of this bidirectional neurocardiac coordination is increasingly recognized in neurological disorders, where impairments extend beyond central and peripheral motor control to include altered brain–heart interactions [73]. Such decoupling may contribute to secondary cardiac complications, including arrhythmias and heart failure [74], whereas concomitant cardiac dysfunction may exacerbate cerebral and muscular hypoperfusion, further constraining motor recovery [75,76]. Together, these observations highlight NCC as both a mechanistic substrate and a potential therapeutic target for optimizing rehabilitation strategies, reducing cardiovascular risk, and improving functional outcomes.

3.2.2 Neurorespiratory coupling

Neurorespiratory coupling refers to the interactions between respiration, the fundamental rhythmic activity sustaining gas exchange, and the CNS. This interaction plays a critical role in regulating cerebral oxygenation, neural excitability, and motor function [77]. The central respiratory control system exhibits a hierarchical organization. Brainstem respiratory nuclei, with the pre-Bötzinger complex as the core rhythm generator, are responsible for producing spontaneous rhythmic discharges and forming the basic respiratory rhythm [78]. Cerebral cortex, particularly the primary motor cortex, supplementary motor area, and premotor cortex, provides voluntary and feedforward modulation of respiratory activity [79], whereas subcortical structures such as the basal ganglia and hypothalamus integrate metabolic and autonomic information to shape respiratory regulation [80]. In addition, the CNS continuously receives afferent input from chemoreceptors, baroreceptors [81] and other peripheral sensors, enabling dynamic regulation of respiratory frequency and depth.

During motion, proprioceptive feedback arising from limb movements projects to the respiratory control centers, thereby augmenting ventilation in advance to meet the escalating metabolic demands of skeletal muscles [82] and maintaining oxygen supply-demand balance in both the brain and periphery. Beyond its role in gas exchange and homeostatic maintenance, respiration exerts a modulatory influence on neural oscillatory dynamics, which constitutes a core feature of NRC [83]. Alterations in respiratory depth and rate modulate low-frequency EEG activity, particularly within frontal and right parietal regions, where neural oscillations in the 0–2 Hz band exhibit close temporal and phase alignment with respiratory rhythms. Nonlinear analyses further demonstrate that spontaneous breathing reduces EEG sample entropy, indicating a shift toward a more ordered neural state [84]. This respiration-driven neural modulation plays a pivotal role in the dynamic coordination of motor function [85]. Motion has been shown to induce a global increase in cerebral oxygenation, particularly in regions associated with motor control, with the magnitude of this increase closely associated with respiratory rate and respiratory cycle phase [86]. Moreover, muscle force output and motor-evoked potentials amplitudes are significantly enhanced during rapid inspiration compared with normal breathing or rapid expiration phases [87,88], whereas voluntary deep breathing markedly enhances beta corticomuscular coherence during respiration-synchronized tasks [89]. Collectively, these findings suggest that respiratory rhythms can influence motor performance by modulating neural oscillations.

From a pathological perspective, neurological disorders mentioned in the NCC section, which cause impaired cardiac function, are also frequently accompanied by neurorespiratory decoupling, including respiratory muscle atrophy, abnormal breathing rhythms, and reduced gas exchange efficiency, ultimately leading to insufficient oxygenation [90,91]. Such impairments increase metabolic stress on the nervous system and limit patients' tolerance and effectiveness to motion training and rehabilitation interventions [92]. Therefore, a comprehensive elucidation of the mechanisms underlying coupling and decoupling between the neural and respiratory systems, together with the integration of respiratory and cardiac functions within a unified neuro-cardiopulmonary circulation regulatory framework, is essential. This integrative perspective provides a theoretical basis for developing multidimensional combined rehabilitation strategies aimed at enhancing the efficiency and outcomes of motor function recovery. The mentioned research of NCC and NRC is summarized in Table 3.

4 Discussion

The accurate execution of motor function depends on continuous information exchange and dynamic coordination among multiple physiological systems. Within this complex process, the synergistic regulation between the nervous and cardiopulmonary circulation systems constitutes a fundamental basis for motor

Table 3 Summary of NCC and NRC in rhythm regulation.

Reference	Types of Evidence	Paradigm	Main finding
[71]	Motor-related evidence	Computer mouse button tapping	BP exerted a predominant driving influence on the alpha and beta rhythm of the EEG and HRV
[72]		Motor pinch task	Systolic cardiac signals exert a facilitatory effect on motor excitability
[84]		Voluntary respiration task	There is a strong correlation between voluntary respiration and scalp EEG
[85]		Button-pressing under different conditions	There is a close relationship between respiration and readiness potential as well as voluntary action
[87]		Handgrip task with different conditions	The inspiration-motor coupling can effectively enhance endurance performance and the underlying mechanism may be related to respiratory modulation of neural system excitability
[88]		Knee extension task with different breathing conditions	Voluntary breathing increases corticospinal excitability of lower limb muscles during isometric contraction
[89]		Hand flexion and extension	Deep inspiration significantly enhanced beta CMC during respiration-synchronized tasks
[73]	Supportive/ pathological evidence	Rest state	Compared with healthy individuals, Parkinson's disease patients showed a reduction in the coupling of alpha and gamma connectivity with cardiac sympathetic dynamics
[75]		Rest state	In stroke patients, a reduced left ventricular ejection fraction may increase the risk of functional disability.
[76]		Rest state	There is a significant correlation between brain structure and markers of heart failure
[86]		Treadmill movements task	Exercise significantly and globally enhances cerebral oxygenation and the increase in oxygenation is closely related to respiratory rate and the phase of respiratory cycle

execution [18,66,77]. Traditional physiological research on motor function has primarily focused on the nervous and musculoskeletal systems. However, the execution of movement also relies on the coordinated involvement of the nervous and cardiopulmonary circulatory systems within the BCA. Coupling-based theory provides a novel perspective for investigating cross-system coordinated regulation in complex physiological functions. By characterizing the pathways [42] and mediators [22,40] of information transmission between different systems, as well as the synchrony, directionality, and nonlinear dependencies of information exchange [58,72,84], coupling analysis enables the delineation of hierarchical regulatory structures and cross-system information flow patterns, thereby supporting the elucidation of dynamic interaction mechanisms.

Within the context of motor function, NCPCC can be manifested at two levels. At the local level, NVC [26] describes the relationship between neural activity and hemodynamic responses. At the global level, bidirectional interactions between the nervous and cardiopulmonary systems, namely NVC and NRC [66,77], govern systemic coordination. This integrated local-global synergy ensures the generation and transmission of motor commands, energy supply during movement, and the maintenance of internal homeostasis. Analyzing motor function within the framework of NCPCC helps transcend the limitations of traditional single-system paradigms and reveals the integrative regulatory logic underlying motor execution. Particularly in motor rehabilitation, this system-level perspective provides a theoretical explanation for the limited efficacy of interventions targeting a single system and highlights the potential advantages of coordinated cross-system modulation strategies. Accordingly, this framework demonstrates broad application prospects across multiple fields of neurorehabilitation [93]. Nevertheless, despite increasing research interest in recent years, several critical limitations remain to be addressed:

(1) Neural pathway elucidation: The neural mechanisms underlying NCPCC remain in an exploratory phase. In particular, the dynamic coordination among cortical, subcortical, and brainstem nuclei involved in autonomic regulation (e.g., insula, anterior cingulate cortex, and hypothalamus) has yet to be systematically elucidated [17,94]. Furthermore, at the cellular and molecular levels, the specific neuronal populations involved in the BCA, as well as the neurotransmitters and signaling pathways underlying cross-system information transmission, remain to be further elucidated. Future research could integrate circuit-specific neuromodulation techniques, including optogenetics, chemogenetics, and genetically encoded fluorescent probe-based *in vivo* calcium imaging [95–97]. Under behavioral paradigms, these approaches will enable systematic dissection of the key neural circuits coordinating neural and cardiopulmonary circulation systems, exploration of the cellular repertoires and molecular signatures involved in multisystem regulation, and the establishment of a comprehensive research framework for the BCA. This will provide a robust mechanistic foundation for translating coupling theory into precise neuromodulation strategies.

(2) Signal acquisition and processing: Although advances in multimodal physiological monitoring, imaging and recording modalities remain limited in spatiotemporal synchronization across systems [98].

Most existing platforms are designed for single-modality recordings, with restricted channel capacity and limited inter-system compatibility. Meanwhile, signals from neural and cardiopulmonary circulation systems differ substantially in their temporal resolution, spectral characteristics, and noise profiles, posing significant challenges for multisource data integration. Conventional linear methods are inadequate for capturing directional, nonlinear, and time-varying coupling dynamics, and advanced approaches like transfer entropy remain largely confined to pairwise interactions [99,100], leaving higher-order, multisystem interaction structures insufficiently explored. Future efforts should prioritize high-synchronization multimodal platforms that leverage flexible bioelectronics and wearable technologies [101] to integrate data from neuro-cardiopulmonary circulation indices, such as electrophysiology, hemodynamics [102], and respiratory metrics, enabling continuous monitoring of multimodal physiological data. Furthermore, combining AI-driven network modeling techniques [103] can enhance the ability to extract complex patterns from high-dimensional datasets [104], revealing the hierarchical structure and adaptive characteristics of multisystem coupling.

(3) Model construction: Interactions between the neural and the cardiopulmonary circulation systems involve highly complex [30], and nonlinear processes influenced by multiple factors, including specialized function cells, multichannel regulation pathways, multiple timescales, and redundant mechanism. This complexity presents substantial challenges for establishing precise causal relationships and accurate models of physiological coupling. Existing frameworks often simplify these interactions, insufficiently capturing the bidirectional modulation between neural activity and cardiopulmonary dynamics or the cross-scale integration from electrophysiology to systemic hemodynamics. Future research should prioritize advancing from phenomenological correlations analyses to mechanism-driven multiscale modeling, particularly through the integration of the cardiopulmonary circulation system into established coupling models [105]. The integration of multisource physiological data with multimodal imaging techniques will facilitate more refined characterization of functional connectivity across systems and promote the development of comprehensive theoretical models incorporating electrophysiological, hemodynamic, and metabolic dimensions.

(4) Clinical application: Interindividual variability in physiological responses, such as vascular compliance and metabolic efficiency, lead to heterogeneous research findings. Furthermore, current evidence regarding the relationship between decoupling and disease remains insufficient [106], limiting accurate characterization of pathological stages and underlying mechanisms. Within the field of rehabilitation, the translation of NCPCC theory into clinically operational assessment and intervention tools remains underdeveloped. Existing rehabilitation evaluations rely on single-system metrics, lacking quantitative parameters that reflect cross-system integrative function. This limitation impedes comprehensive characterization of patients' overall functional status and the identification of critical rehabilitation targets. Future efforts should focus on establishing multidimensional assessment frameworks based on coupling mechanisms and developing novel multimodal physiological biomarkers and rehabilitation targets. In rehabilitation interventions, multisystem synergistic training paradigms should be integrated with AI and large-scale multimodal data analytics to enable individualized functional assessment and intervention planning [107,108], thereby advancing the development of precision rehabilitation. The current challenges and future directions of NCPCC research in motor function are summarized in Table 4.

5 Conclusions

The interactions between the nervous system and cardiopulmonary circulation system constitute one of the fundamental physiological bases for motor function. They not only ensure the generation and transmission of motor commands but also maintain metabolic homeostasis throughout motion. Based on the BCA, this review proposed a multilevel analytical framework centered on NCPCC, integrating local regulation with global bidirectional interactions. Within this framework, recent advances in NVC, NCC, and NRC during motor execution are synthesized. Future research should integrate circuit-specific neuromodulation techniques to explore neural pathways underlying the BCA. In parallel, the development of multimodal, spatiotemporally synchronized physiological acquisition techniques combined with artificial intelligence and complex network analyses will be essential for establishing multiscale and cross-system coupling models. Clarifying the causal relationships and mechanisms among neural activity, vascular regulation, and cardiopulmonary rhythms is crucial not only for elucidating the pathological basis of motor dysfunction, but also for advancing rehabilitation paradigms from single-system interventions toward multisystem coordinated regulation. In summary, the NCPCC-based analytical framework provides a new perspective for understanding the multisystem coupling mechanisms underlying motor function and offers a promising foundation for the precise functional assessment, early diagnosis, and the development of personalized rehabilitation strategies.

Table 4 Current challenges and future directions of NCPCC research in motor function.

Focus	Current challenges	Future directions
Neural pathway elucidation	● Dynamic coordination among cortical, subcortical, and brainstem autonomic networks has not been systematically elucidated ● The roles of neuronal population activity and neurotransmitter systems in multisystem regulation remain unclear	➢ Integrate circuit-specific neuromodulation techniques and genetically encoded calcium imaging with behavioral paradigms to elucidate the key neural circuits, cellular composition, and molecular mechanisms underlying the BCA ➢ Establish the multilevel regulatory research framework
Signal acquisition and processing	● Multimodal monitoring platforms have limited cross-system synchronization and compatibility ● Neural, hemodynamic, and cardiopulmonary signals differ substantially in temporal resolution, spectral characteristics, and noise profiles ● Conventional linear methods fail to capture directional, nonlinear, and time-varying coupling dynamics; advanced methods have not sufficiently explored higher-order interactions among multiple systems	➢ Develop highly synchronized multimodal acquisition platforms using flexible bioelectronics and wearable technologies, continuous and synchronized monitoring of electrophysiological, hemodynamic, cardiovascular, and respiratory signals ➢ Develop advanced analytical approaches for higher-order multisystem coupling ➢ Integrate AI-driven network modeling to reveal hierarchical organization and adaptive characteristics of multisystem coupling
Model construction	● Neuro-cardiopulmonary interactions are highly nonlinear and involve multiple regulatory pathways, timescales, and redundant mechanisms ● Existing frameworks often oversimplify the interactions, insufficiently capturing the bidirectional modulation and cross-scale integration from electrophysiology to systemic hemodynamics	➢ Advance from phenomenological correlation analyses to mechanism-driven multiscale modeling ➢ Develop mechanism-driven multiscale models by integrating multisource physiological signals, multimodal imaging, and the cardiopulmonary circulation system into established coupling frameworks
Clinical application	● Interindividual physiological variability leads to heterogeneous findings ● Evidence linking decoupling with disease progression remains insufficient ● Current rehabilitation evaluation mainly relies on single-system indicators and lacks quantitative measures of multisystem integration	➢ Establish multidimensional assessment frameworks based on coupling mechanisms ➢ Develop multimodal physiological biomarkers and rehabilitation targets ➢ Integrate AI with large-scale multimodal datasets to enable individualized assessment and intervention

Data availability No datasets were generated or analyzed for this work.

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Competing interests Ping Zhou is an Executive Editor-in-Chief, Yingchun Zhang is an Associate Editor, and Guanglin Li is an Editorial Board Member for ENGINEERING Health and Rehabilitation Engineering. They were not involved in the editorial review or decision-making process for this manuscript. All editorial decisions were made independently by other members of the Editorial Board who have no conflicts of interest. All other authors declare no conflicts of interest.

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