The Novel Cardiopulmonary Coupling Analysis Methods for Autonomic Nervous Function Assessment and the Application Prospect on Wearable Health Devices

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Abstract. Heart rate variability (HRV), derived from electrocardiogram (ECG) signals, has become a cornerstone in assessing autonomic nervous system (ANS) function and overall health status through R-R interval (RRI) analysis. Studies indicate that integrating respiratory signals with RRI time series enhances the precision of ANS activity estimation and provides a more detailed depiction of the dynamic interaction between the cardiovascular and respiratory systems. Cardiopulmonary coupling (CPC), which combines cross-power spectral analysis with coherence at shared frequency bands, has been refined through the Synchrosqueezing Transform (SST) introduced by Wang *et al.* (*IEEE JBHI*, 27(4): 1790-1800, 2023). This method enhances the time-frequency resolution of CPC spectrograms, improving the accuracy of sleep apnea detection when paired with machine learning classifiers. Li *et al.* proposed a cross-wavelet cardiorespiratory coupling analysis, revealing stronger coupling in younger individuals compared to older adults and demonstrating reduced vagal modulation during aging. This method was further applied to evaluate the therapeutic effects of breathing training on autonomic nervous function (*Chaos*, 33(12): 123106, 2023). Building on these findings, Ma *et al.* developed a novel quantification approach called multimodal coupling analysis (MMCA), which assesses respiratory sinus arrhythmia (RSA) strength across a broader respiratory frequency range. MMCA-derived RSA has been validated as an effective metric for grading heart failure severity and evaluating clinical outcomes in patients with severe arrhythmias (*BSPC*, 89: 105764, 2024). Cardiopulmonary interaction analysis, given its effectiveness and reliability in evaluating ANS function, holds significant potential in wearable health device applications. The proposed SST-CPC method, designed for lightweight sleep monitoring and sleep apnea detection, has already been deployed in elderly care service programs. Cardiorespiratory coupling methods further enhance the capabilities of wearable devices, offering promising applications in community health care, disease diagnosis, vital sign monitoring, and therapeutic efficacy assessment in clinical settings.

Keywords: Heart Rate Variability, Cardiopulmonary Coupling, Respiratory Sinus Arrhythmia, Autonomic Nervous System, Wearable Electrocardiogram Device

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