Cardiovascular and Cardiorespiratory Interactions – From Physiological Mechanisms to Clinical Applications
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Bridging Global and Local Causal Discovery in Physiology: From Observational Networks to Dynamic Cardiorespiratory Interactions

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Identifying causal relationships in human physiology and sports medicine is crucial for understanding complex systemic interactions and improving diagnostic strategies and designing personalized training patterns.

Traditional global causal discovery methods, such as the Greedy Fast Causal Inference (GFCI) algorithm, provide robust frameworks for mapping static variable dependencies in observational data [1]. For instance, applying data-driven GFCI modeling to physiological and physical assessments of youth soccer players, then knowledge-adjusted, successfully generated a directed acyclic graph (DAG) identifying non-dominant leg performance, or symmetry between strength achievable by dominant and non-dominant legs in general, as a potentially modifiable determinant linked to aerobic capacity, and proposing the prospective interventional study to assess the relationship [1].

However, while such "top-down" global models are effective for macroscopic physiological profiling, they average out dependencies over entire recording sessions or datasets [2]. This aggregation obscures the transient, short-term fluctuations inherent to non-stationary biological signals, limiting their applicability in dynamic cardiovascular assessment, where interactions are rarely static; the strength and directionality of couplings fluctuate continuously under the influence of the autonomic nervous system as well as changes in measurement conditions. To address

the limitations of static structural assumptions, we introduced *tempord*, an open-source Python framework designed to estimate local temporal orders and causal vectors (CV) directly from non-stationary time series [2]. Employing a "bottom-up" analytical strategy, *tempord* evaluates the short-term stability, directionality, and strength of links between signals within narrow sliding windows [2].

We demonstrated the capabilities of the *tempord* algorithm by evaluating cardiorespiratory coupling (CRC) dynamics. By analyzing continuous tidal volume and tachogram (RR intervals) data, the framework was able to parameterize local temporal stability and detect minor step changes during autonomic nervous system state transitions, such as the shift from spontaneous breathing to music-induced relaxation [2].

Ultimately, this transition from global observational networks to dynamic signal-level analysis allows for a deeper understanding of the transient mechanisms governing cardiovascular networks, supporting earlier diagnosis and risk stratification of cardiovascular diseases.

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