Study of Changes in the Fractality of Heart Rate Variability After Training in Athletes

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Abstract

This paper presents a study on the changes in fractal parameters of interbeat interval series in athletes following a training session. Fractal analysis of heart rate variability (HRV) provides crucial insights into the autonomic nervous system (ANS) and how the body regulates heart rhythm after physical exertion. The application of Detrended Fluctuation Analysis (DFA), Correlation Dimension, and the Hurst Exponent enables a detailed examination of these changes. DFA analysis measures long-term dependencies in the HRV signal, assessing the degree of scale-invariant self-similarity in the cardiac time series and whether it follows a regular or chaotic pattern. Correlation Dimension is one of the key methods for evaluating the fractal complexity of dynamic signals, such as HRV. It quantifies the extent to which the signal exhibits self-similarity at different scales and provides information about the number of independent processes governing HRV dynamics. The Hurst Exponent serves as an indicator of persistence or anti-persistence in HRV, where values greater than 0.5 suggest long-term dependence and predictability, whereas values below 0.5 indicate a chaotic or random behavior. A study was conducted on 24 athletes before and after exercise, with cardiac activity recorded using a Holter device for 10 minutes. Mathematical analyses revealed that before exercise, HRV exhibits high dynamism and complexity, characteristic of a well-regulated autonomic nervous system. The correlation dimension is high, indicating a chaotic yet adaptive cardiac rhythm. The Hurst Exponent is also high, suggesting that the HRV signal follows a persistent structure with long-term correlations, where values tend to maintain a trend rather than reverting to the mean. DFA analysis prior to exercise shows normal values for $\alpha 1$ and $\alpha 2$, reflecting a chaotic and flexible HRV signal.

Following physical exertion, HRV undergoes significant modifications, with reduced chaotic behavior and diminished predictability. This is attributed to the increased activity of the sympathetic nervous system (SNS), which temporarily reduces HRV complexity to stabilize the elevated heart rate induced by exercise. The correlation dimension decreases, indicating that the HRV signal becomes less chaotic and loses part of its dynamic complexity. Simultaneously, the Hurst Exponent slightly declines, reflecting a reduction in long-term dependencies as the sympathetic nervous system regulates heart rate. DFA $\alpha 1$ and $\alpha 2$ increase, meaning that the HRV signal becomes more structured and follows more defined trends. These changes represent a physiological adaptation, where the body mobilizes its internal mechanisms to achieve rapid stabilization and restore homeostasis. Recovery following exercise can be monitored through the gradual return of the fractal dimension and Hurst Exponent to higher values. If HRV remains excessively structured for an extended period (low fractal dimension, low Hurst Exponent, and high DFA values), this may indicate overtraining or incomplete recovery. Such analyses are highly valuable in sports physiology, allowing for personalized training load management and optimal monitoring of recovery processes.

Keywords

Athletes, Correlation Dimension, Detrended Fluctuation Analysis, Heart Rate Variability (HRV), Hurst Exponent.