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Non linear approach to study the dynamics of neurodegenerative diseases by Multifractal Detrended Cross-correlation Analysis—A quantitative assessment on gait disease

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HIGHLIGHTS

- Study of Neurodegenerative diseases using MFDXA.
- Study of both autocorrelation and cross correlation gives a better approach to the study of neurodegenerative diseases.
- Degree of correlation (γ) and degree multifractality (W) are studied.
- Both γ and W are more in control group compared to diseased set.
- Fundamental results from independent experiments are almost the same.

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ABSTRACT

This paper studies the human gait pattern of normal people and patients suffering from Parkinson's disease using the MFDXA (Multifractal Detrended Cross-correlation Analysis) methodology. The auto correlation and cross correlation of the time series of the total force under the left foot and right foot were studied. The study reveals that the degree of multifractality (W) and degree of correlation (γ) are generally more for normal patients than the diseased set. It is also observed that the values of W and γ are nearly same for left foot and right. It is also observed that the study of autocorrelation alone is not sufficient, cross correlations should also be studied to get a better concept of neurodegenerative diseases.

1. Introduction

Neuro-degenerative disease produces changes in neuromuscular control. Muscle movements control, muscle tone, involuntary movements and smoothness of movement are affected due to neuro-degenerative disease. One of the important diagnostic methods for determining neuro-degenerative disease is study of human gait [1]. Hausdorff et al. [2] have demonstrated strong connection between human walking and random walk. Though walking appears to be a periodic regular process the gait pattern reveals small fluctuations even under stationary conditions.

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Human gait is considered a complex, non-linear process [3–5] by which the locomotor system incorporates input from the cerebellum, the motor cortex, and the basal ganglia, as well as feedback from visual, vestibular, and proprioceptive sensors. Under healthy conditions, the locomotor system produces a stable walking pattern; the kinetics, kinematics, and muscular activity of gait remain relatively constant from one step to the next, even during unconstrained walking [3,6–10]. For this reason, most conventional biomechanical studies are based on the thorough analysis of a walking cycle. The data obtained are then extrapolated into the whole walking process. A number of studies, conducted using the non-linear dynamic approach, have revealed that gait patterns present fluctuations even under apparently stable conditions [11–14]. Thus, human gait dynamics have a complex behaviour that many studies have tried to elucidate [15] using practical applications mainly focusing on ageing and pathologies affecting human walking. There are several methods that have been used to study human gait for normal and diseased set [4,5,16–22].

Gait is basically the pattern of movement of limbs. Human locomotion can be described by three distinct stages: (i) Development stage (from resting position to some velocity) (ii) Rhythmic stage (at some constant velocity) and (iii) Decay stage (back to the rest position) [23]. A step in human has two distinct parts. The first part begins when the foot strikes the ground and ends when the foot is lifted. The second part begins when the foot is lifted and ends when it strikes the ground again. Various features can be extracted from these two steps that may lead to diagnosis of several neuro-degenerative diseases [1]. Scafetta et al. found the time series of human gait stride intervals to exhibit fractal and multifractal properties under various conditions. They analysed records obtained from subjects walking at normal, slow, and fast pace speed to determine changes in the fractal scalings as a function of the stress condition of the system. They also analysed subjects with different ages from children to elderly and patients suffering from neurodegenerative disease to determine changes in the fractal scalings as a function of the physical maturation or degeneration of the system. The authors presented a supercentral pattern generator (SCPG) model that correctly prognosticates that the decrease in average of the long correlation of the stride interval time series for children and for the elderly or for those with neurodegenerative diseases can be understood as a decrease in the correlation length among the neurons of the biomechanical motor control system (MCS) due to neural maturation and neurodegeneration, respectively [23].

There are several devices which analyse human gait complexity using pressure or force sensors [24,25] or hip and knee angles [26]. Many mathematical methods too have proven to be useful in examining the complexity of biological signals such as stride intervals [27,28], Detrended Fluctuation Analysis (DFA) [5,29,30], power law scaling by Fourier's method [4], the Lyapunov exponent [31,32] or entropy [33] to name a few.

Parkinson's disease (PD) is a chronic and progressive hypo-kinetic disorder of the central nervous system caused by basal ganglia dysfunction. Four major motor symptoms of PD are resting tremor of 4–6 Hz (the most manifest symptom), rigidity (stiffness in muscles), bradykinesia (slow physical movement), and postural instability (loss of postural reflexes) [34]. Other symptoms may include physical fatigue, festination, small shuffling steps, and decreases in both arm swing and walking speed [35].

To quantify kinetic, spatiotemporal, power spectral, and fractal parameters of the gait in PD, computer-aided analysis has been used in many studies [4,5,36–41]. The research group led by Sekine et al. [38,39] applied the wavelet-based fractal analysis and the time–frequency matching pursuit algorithm to the acceleration signals recorded from PD subjects during climbing stairs and walking along a corridor. The study of Sekine et al. [39] suggested that the acceleration signals of PD patients recorded from one gait cycle to the next would be altered into a more complex pattern, and the fractal dimensions of the body motion tend to be higher in PD. Morris et al. [42] observed that PD patients are able to modulate normal walking cadence, but they also reported that the averaged stride length is remarkably shorter in PD patients than in healthy subjects, which has been confirmed in recent studies [43–45]. Additionally, some related studies suggest that the fluctuation dynamics of stride interval are significantly increased in PD patients [37,40,46]. Hausdorff et al. [30,40], estimated the stride-to-stride fluctuations in healthy control subjects and in PD patients, respectively. Their results suggested that the coefficient of variation is increased in PD, and is also related to the degree of severity of disease [40]. They also studied the effects of external cueing using rhythmic auditory stimulation (e.g., by means of a metronome) on gait variability, and the results demonstrated that rhythmic auditory stimulation set to 110% of the step rate may improve mobility and reduce fall risk in PD patients [30]. Miller et al. reported increase of electromyographic (EMG) signal variability of gastrocnemius in PD patients [47]. Wu et al. used the Parzen-window method to estimate the probability density functions (PDFs) of stride interval and its two sub-phases (swing interval and stance interval), for healthy subjects and PD patients, respectively [35].

Ashkenazy et al. [48] presented a stochastic model of gait rhythm, based on transitions between different neural centres that reproduced distinctive statistical properties of normal human walking. By tuning one model parameter, the transition (hoping) range, the model described alterations in gait dynamics from childhood to adulthood-including a decrease in the correlation and volatility exponents with maturation. The model also generated time series with multifractal spectrum whose broadness depends only on this parameter. They also found volatility exponent to increase monotonically as a function of the width of the multifractal spectrum, which suggested the possibility of a change in multifractality with maturation. West et al. developed a Supercentral Pattern Generator (SCPG) model that developed both fractal and multifractal properties of gait dynamics [49]. Scafetta et al. [23] have observed that human stride interval in complex time series that is characterized by particular symmetries including fractal and multifractal properties using the SCPG technique. The randomness of the fluctuations is found to be higher in elderly or cases with neurodegenerative diseases. In this respect Hausdorff et al. [2] extended the detrending technique designed for monofractal series to multifractal formalism (Multifractal Detrended Fluctuation Analysis) MF-DFA. Long range correlation properties of the gait series have been given