FRACTAL DYNAMICS OF STRIDE INTERVAL FLUCTUATIONS: CHILDREN WITH SPASTIC DIPLEGIA

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ABSTRACT

The temporal fractal dynamics of gait in children with spastic diplegia were quantified, and the relationship between these fractal dynamics and mobility levels as measured by the Gross Motor Function Measure (GMFM) were investigated. A volunteer sample of 13 children with a mean age of 6.1 ± 0.97 years, with Spastic Diplegia participated in the study. Fluctuations in stride interval times were examined at different window sizes (scales), which characterized the fractal (statistical self-similarity) properties of the time series by a scaling exponent. Participants with Spastic Diplegia were found to have a mean scaling exponent value of 0.69 ± 0.12, deviating significantly ($p<0.05$) from published values for age-matched able-bodied children (0.92 ± 0.07). GMFM scores were poorly related to scaling exponent values. Fluctuations in the stride interval are believed to be governed by supraspinal neurological mechanisms. Deviations from scaling exponent values of able-bodied children suggest neurological pathology, the exact nature of which remains unknown.

BACKGROUND

The stride interval in human gait is defined as the time between consecutive heel strikes of the same foot. The stride interval fluctuates from one step to the next and this fluctuation was originally thought to be random. However, it has recently been shown that long-range fractal correlations exist between strides in a manner where fluctuations at one point are statistically correlated to fluctuations hundreds of strides earlier [2]. These long-range correlations are characteristic of normal human gait and have been shown to weaken in states of disease and advanced aging [1].

HYPOTHESIS

Due to the neurological impairment of children with Spastic Diplegia, it is anticipated that the fractal properties of gait will be altered and there will be a loss of long-range fractal correlations. The degree to which the long-range correlations decrease will likely correspond to the GMFM scores of each child.

METHODS/MATERIALS

A volunteer sample of 13 children diagnosed with Spastic Diplegia with a mean age of 6.1 ± 0.97 years participated in the study. Participants were asked to perform one unassisted walking trial of 10 minutes at a self-selected pace on a rounded indoor path. Heel strikes were measured using a force-sensitive resistor footswitch under the heel and an accelerometer placed at the level of the sacrum. The stride times were measured between successive heel strikes of the same foot and recorded on a portable data logger. Using detrended fluctuation analysis (DFA) [2], averaged wavelet coefficient method (AWC) [3] and surrogate data analysis [4], fluctuations in stride interval times (Fig. 1) were examined at different window sizes (scales), to characterize the fractal (statistical self-similarity) properties of the time series by a scaling exponent.

RESULTS

Using detrended fluctuation analysis, participants with Spastic Diplegia were found to have a mean scaling exponent value of 0.69 ± 0.12, deviating significantly ($p<0.05$) from published values for age-matched able-bodied children (0.92 ± 0.07). The average wavelet coefficient method yielded similar scaling exponent values (Table 1). The difference between scaling exponents for surrogate (shuffled) and original data was less significant (mean p=

0.245) than the difference between able-bodied values versus surrogate data (mean $p<10^{-6}$). Total GMFM scores and Walking GMFM subscores were poorly related (r^2= 0.1308 and 0.1242) to scaling exponent values (Fig. 2).

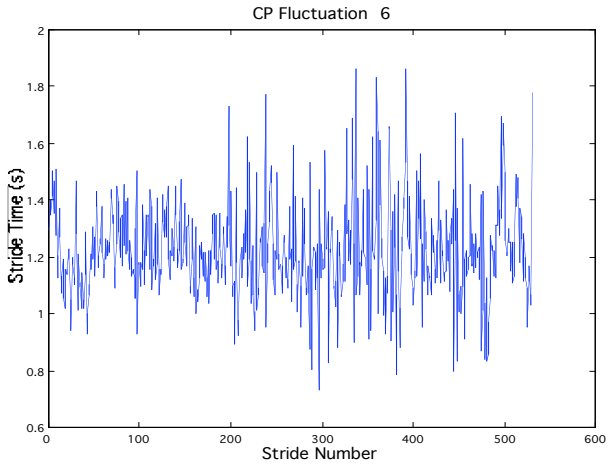

Figure 1 Stride interval fluctuation series for cerebral palsy (CP) subject 6

Table 1 Mean scaling exponent (alpha) values for cerebral palsy (CP) and control child (CC) populations determined via detrended fluctuation analysis (DFA) and averaged wavelet coefficient (AWC) methods

POPULATION	DFA	AWC
CP	0.69±0.1245	0.69±0.1255
CC	0.92±0.0737	0.90±0.0831

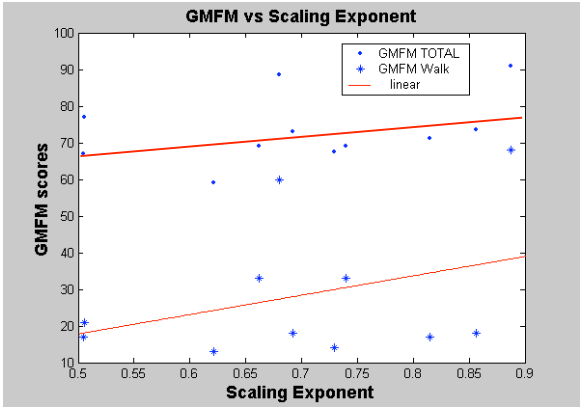

Figure 2 GMFM scores (total and walking dimensions) versus DFA-derived scaling exponents (alpha) for cerebral palsy subjects (GMFM Total r^2= 0.1308 & GMFM Walk r^2= 0.1242)

DISCUSSION

Determination of scaling exponent values through quantitative measurement of stride interval fluctuations reveals important properties of temporal gait dynamics. Scaling exponent values within the range of 0.5<alpha<= 1.0 are representative of long-range correlations, meaning that fluctuations at one point in the series are statistically correlated to fluctuations several hundreds of strides later. However, able-bodied individuals generally have values hovering near or towards 1.0, which corresponds to correlations extending well into the time series. Many pathological populations have values tending towards 0.5, which corresponds to random uncorrelated white noise. This shift towards uncorrelated randomness reflects an underlying temporal breakdown where long-term memory is lost or degraded in the pathological population. Scaling exponent values found in the cerebral palsy population point to a similar decrease in long-range correlations. These findings are consistent with literature findings in which other neuropathologies exhibit a loss of fractal long-range correlations in stride interval fluctuations. Differences between alpha values found for surrogate (shuffled) and CP data were less significant than differences between alpha values for surrogate and able-bodied data. This suggests that surrogate data representing static, nonlinearly transformed uncorrelated Gaussian noise, mimics to some degree the temporal characteristics of cerebral palsy time series. In other words, CP time series more closely resembles uncorrelated noise than able-bodied time series fluctuations. In Figure 2, it can be seen that children with similar GMFM scores (total and walk) had varying scaling exponent values indicating that measures of gross motor function are not sensitive to temporal variability during gait. This suggests that measuring long-range correlations may act as a more objective measure of gait dynamics and/or serve as a finer demarcation of cerebral palsy motor function. Quantifying the long-range correlations in stride interval time series serves to provide insight into the 'state' of the locomotor system and the mechanisms underlying its control and breakdown particularly with respect to the role of the central nervous system.

CONCLUSIONS

It was found that long-range fractal correlations are diminished significantly in the gait of children with Spastic Diplegia. In examining stride interval correlations, the scaling exponent is a useful quantitative measure of gait dynamics and may serve as an informative adjunct to the GMFM. Such a measure may aid in the understanding of how different pathological states alter human gait and to what degree. It may also serve to quantify the improvements in stride dynamics following treatment intervention and during the rehabilitation process.

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