Fluctuations in gait force profiles versus stride-to-stride time analysis in patients with Parkinson's disease

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Objective

To study the fluctuations in gait, as expressed by the vertical ground reaction force profiles in patients with Parkinson's disease (PD) and in elderly subjects and to compare the results with stride-to-stride time series analysis.

Background

Gait analysis is used to augment the diagnosis and prognosis of various neurological diseases. Recently it has been shown that increased stride-to-stride variability is associated with PD [1]. Motivated by the high performance of form analysis in long-term ECG data sets [2], we study here another aspect of gait and its relation to PD by examining the shape of the force profile of the vertical ground reaction force during the stance phases of walking. By using Detrended Fluctuation Analysis (DFA), an analytical approach developed by statistical physicists to investigate complex systems, we investigate the fluctuations in the shape of consecutive force profiles recorded during walking. DFA enables us to study the fluctuations in different time windows ("scales"), where each scale represents the resolution at which we consider the fluctuations, and the correlations across time.

Methods

Subjects: 30 PD patients were compared to 24 healthy elderly subjects (ES).

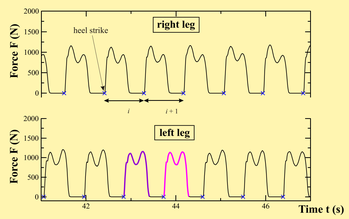
Gait Protocol: Subjects wore force-sensitive insoles that recorded the normal force exerted by the floor while stepping during a period of 2 minutes of comfortable walking.

Table 1: Characteristics of the study groups (Mean SD)

	AGE (years)	H&Y scale
PD	67 ± 7	2.3 ± 0.4
ES	64 ± 6	—
P value (t-test)	N.S.	—

Data preparation:

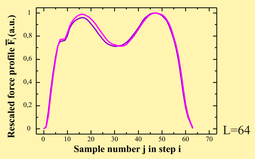
Fig. 1: Typical force profiles of right and left leg. The two coloured force profiles were selected to clarify rescaling and normalization procedure before analysis of the shape of the gait force profiles.



Analysis of the shape of gait force profiles vs. Stride-to-stride time analysis

Each step in the force profiles is rescaled in amplitude to the interval [0,1] and normalized in time to a fixed number of L data points. This process removes the stride-to-stride variations in stride timing.

Fig. 2: Corresponding force profiles from Fig. 1 after force rescaling and time normalization.

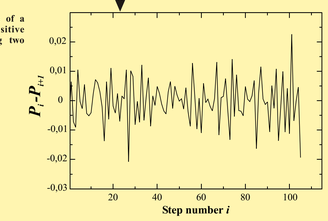


The resulting normalized data in time space were Fourier transformed. Since the few modes belonging to the lowest frequencies are most important for the signal shape, we characterize the morphology of the signal by summation over the power of a fixed band of four of the lowest frequencies:

$$P_i \quad \sum_{j=1}^{4} |\hat{F}_i(j)|^2$$

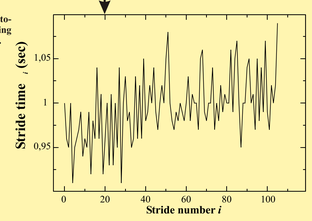
$\hat{F}_i(j)$ are the Fourier coefficients of $\overline{F}_i(k)$ ($j = 0, ..., L/2; k = 0, ..., L-1$)

Fig. 3: Increments of a typical form sensitive time series during two minutes of walking.



stride-to-stride time $_i$

Fig. 4: Typical stride-to-stride time series during two minutes of walking.



Methods (Cont.)

Detrended Fluctuation Analysis (DFA): This method was first introduced by Peng et al. [3] to improve on root mean square analysis of highly nonstationary data by removing their nonstationary trends. We apply DFA on the sequences $_i$ and P_i-P_{i+l} by calculating the fluctuation function

$$F(s) \quad \frac{1}{L_s} \sum_{1}^{L_s} F^2(\ ,s)^{1/2}$$

$L_s = int(L/s)$ ... total number of segments

length of the time series — scale ("time window")

... number of segment

According to Random Walk Theory one can estimate correlations and persistence in the data by extracting the Hurst exponent H from a double logarithmic plot of $F(s)$ versus scale s, since $F(s) \sim s^H$.
In order to study whether the DFA methodology can be used to distinguish between the gait of PD patients and the gait of healthy elderly subjects, we consider the scaling behavior of the fluctuations with window size (expressed by H; "scale invariant measure") as well as the size of the fluctuation function $F(s)$ at each scale separately ("scale dependent measure"). Since we study here short-time data sets, we use H as a short-term scaling exponent.

Results

Fig. 5: Mean and standard errors of the fluctuation function after analysis of form sensitive time series of the ground reaction waveform.

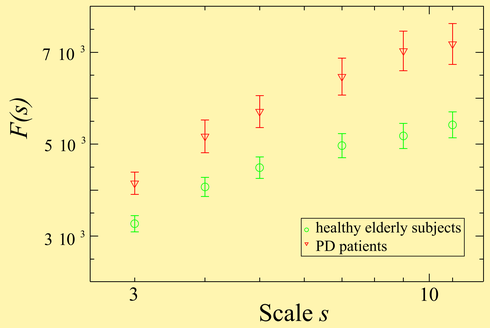


Fig. 6: Mean and standard errors of the fluctuation function after analysis of time series of stride times.

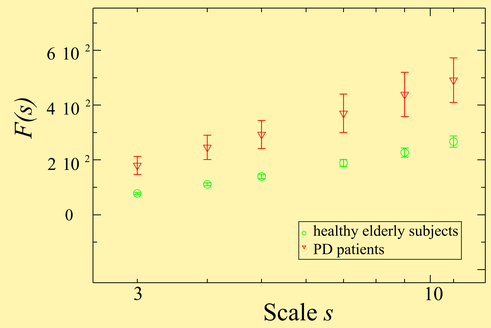


Table 2: Comparison of the fluctuations in the form of the ground reaction waveform in PD and elderly subjects at different time scales s. At all time scales studied, the waveform was more variable in the subjects with PD.

scale	$s = 3$	$s = 4$	$s = 5$	$s = 7$	$s = 9$	$s = 11$
P value (t-test)	0.005	0.01	0.005	0.003	0.0008	0.002

Table 3: Comparison of the fluctuations of the stride times in PD and elderly subjects at different time scales s. At all time scales studied, the stride time fluctuations were more variable (larger) in the subjects with PD.

scale	$s = 3$	$s = 4$	$s = 5$	$s = 7$	$s = 9$	$s = 11$
P value (t-test)	0.005	0.005	0.006	0.02	0.02	0.01

Table 4: Short term Hurst exponents of form sensitive time series (Mean Standard Error).

	Hurst exponent (Mean ± SE)
PD	0.41 0.01
ES	0.36 0.01
P value (t-test)	0.003

Table 5: Short term Hurst exponents of stride-to-stride time series (Mean Standard Error).

	Hurst exponent (Mean ± SE)
PD	0.77 0.03
ES	0.91 0.04
P value (t-test)	0.0096

Discussion and Conclusions

In summary, we present a new method for the statistical analysis of gait time series based on the shape of the ground reaction force profiles. This approach is complementary to the standard analysis based on stride-to-stride variability since stride-to-stride variations in step timing were removed by time normalization of every single step.
A fluctuation analysis of sequences derived from the shape of force profiles shows that PD lowers the consistency of the force profile. This reduced stability is not just a global phenomenon but can be found at different time scales. Thus, this measure appears to be a characteristic feature of PD that is independent of fluctuations in gait cycle timing.
The short term scaling behavior of form sensitive and heel strike time series, expressed by the Hurst exponent, is significantly different between healthy subjects and PD patients indicating that also scale invariant measures distinguish between the gait of both groups.
In the future, we will extend our approach, for example, by defining other measures of the shape of the signal that go beyond a characterization by a scalar quantity. Furthermore, it will be interesting to analyze cross-correlations between stride-to-stride time series and form-sensitive sequences and to examine how fluctuations in the waveform change with disease progression. It can be expected that such extensions will offer new possibilities for enhancing the quantification of the gait disturbances in PD and enriching the understanding of gait.

References

[1] J. M. Hausdorff et al.: *Impaired regulation of stride to stride variability in Parkinson's disease subjects with freezing of gait,* Exp. Brain Res. **149**, 187 (2003).
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