Investigating the Dynamical Nature of Unipedal Balance

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Introduction

We would like to understand the dynamical nature of human unipedal balance. Time series typical of the anterior-posterior (A-P, front to back) and medial-lateral (M-L, side to side) jerk during the balance process were studied. Our interest is to classify features found in these measurements as indicative of subjects experiencing certain medical conditions. New data taken with a higher sampling rate and a more restricted filtering scheme (for better resolution and to deal with machine noise) revisits our earlier work in this area [1].

Our analysis suggests that these signals have a temporally evolving autocorrelation structure and time-frequency spectrum. We will use the term “nonstationary” for this behavior, although there is uncertainty as to the signal’s random nature. Many nonstationary signals can be broken down into stationary segments. However, we are unsure the that the data we study has this property. To informally check this, the signal was segmented into sequential windows and statistics were tracked locally in time. We further analyzed the data using recurrence plots, which examine the system’s propensity to revisit previous values [2].

Background

The COP (center of pressure) is the point of application of the net force vector on the floor, where the bottom surface of the foot is in contact with the ground. As weight shifts, so does the COP. A multi-axis force plate was used to collect data concerning the COP trajectory of a healthy adult attempting to remain still (unassisted) standing on one foot with eyes open, hands by their sides. (The noise profile of this force plate was taken into consideration.)

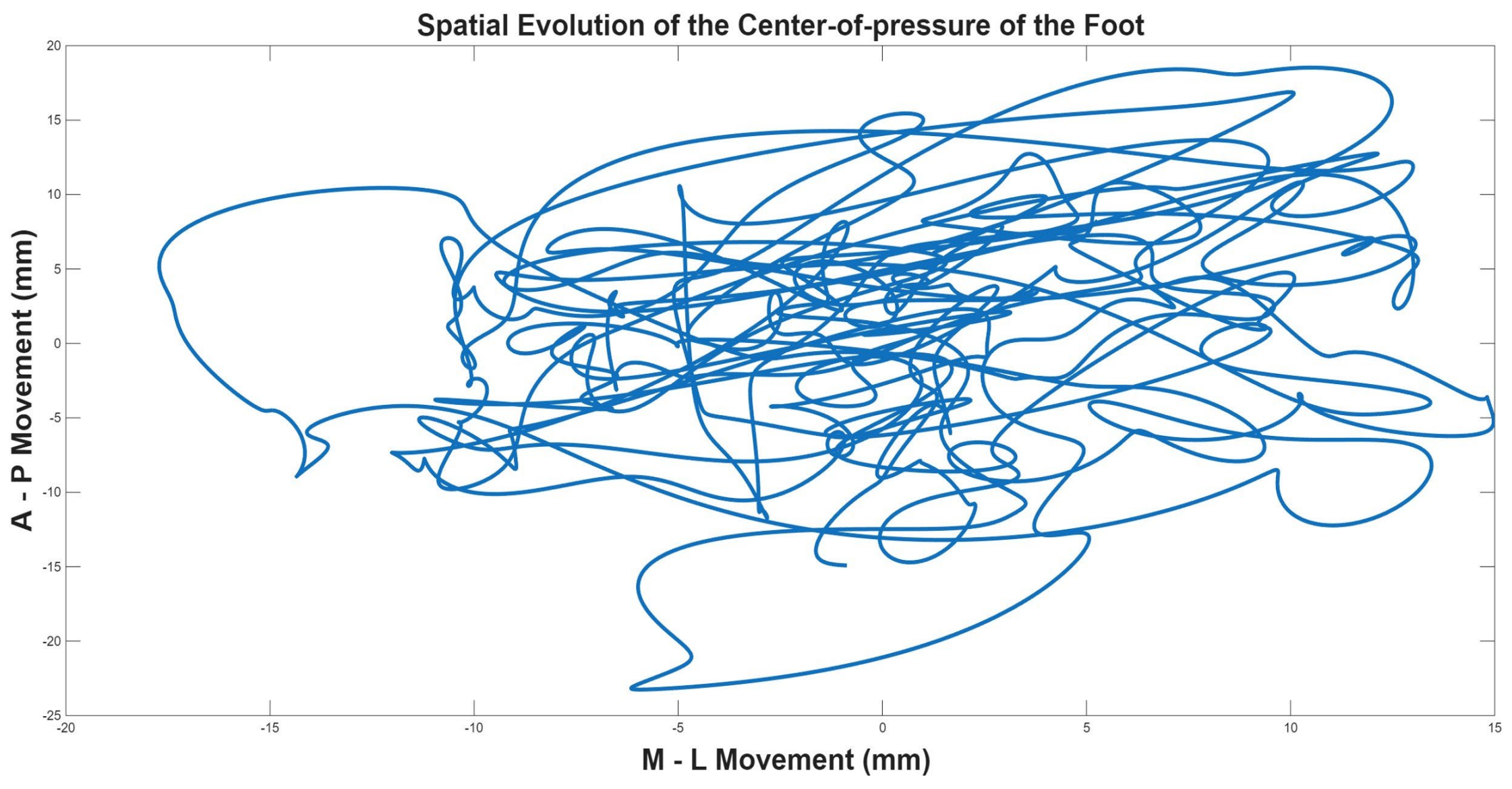

Fig. 1. A typical trajectory of the COP (sampled at 1000 Hz) during a single leg stance.

Data Collection

Force data were collected for subjects attempting to balance on each leg separately for 30-second sessions. Prior to data collection, all procedures were explained to the participant and written consent was obtained following local institutional review board policy.

- The data were sampled at 1000 Hz to see if a higher sample density than in our previous work leads to any alterations in the results.
- Also, given our knowledge of the frequency range of the machine noise, we wanted a fairly high Nyquist frequency to reveal a well-defined region for filtering and to avoid any aliasing effects.
- Machine noise primarily affected frequencies above 15 Hz. Our study concerns behavior below this.
- A low-pass finite impulse response (FIR) filter was applied (sharply) at 15 Hz and a high-pass infinite impulse response (IIR) filter was applied (sharply) at 0.50 Hz. Also, the signal was linearly detrended.

Acknowledgments

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Treatment of Data

Taking the jerk to be proportional to the first difference of the force measurements (which avoided noise amplification), we have the time series and autocorrelation (AC) estimates (below, Fig. 2 (a and b)) for the M-L jerk (for the sake of space, we’ll only discuss the M-L signal results). The AC estimates are for four sequential one-second nonoverlapping windows of the jerk signal (each enclosing several oscillations). One can get a sense of the temporal evolution of the autocorrelation function (ACF). This change in the statistics of the signal is indicative of a nonstationary time series.

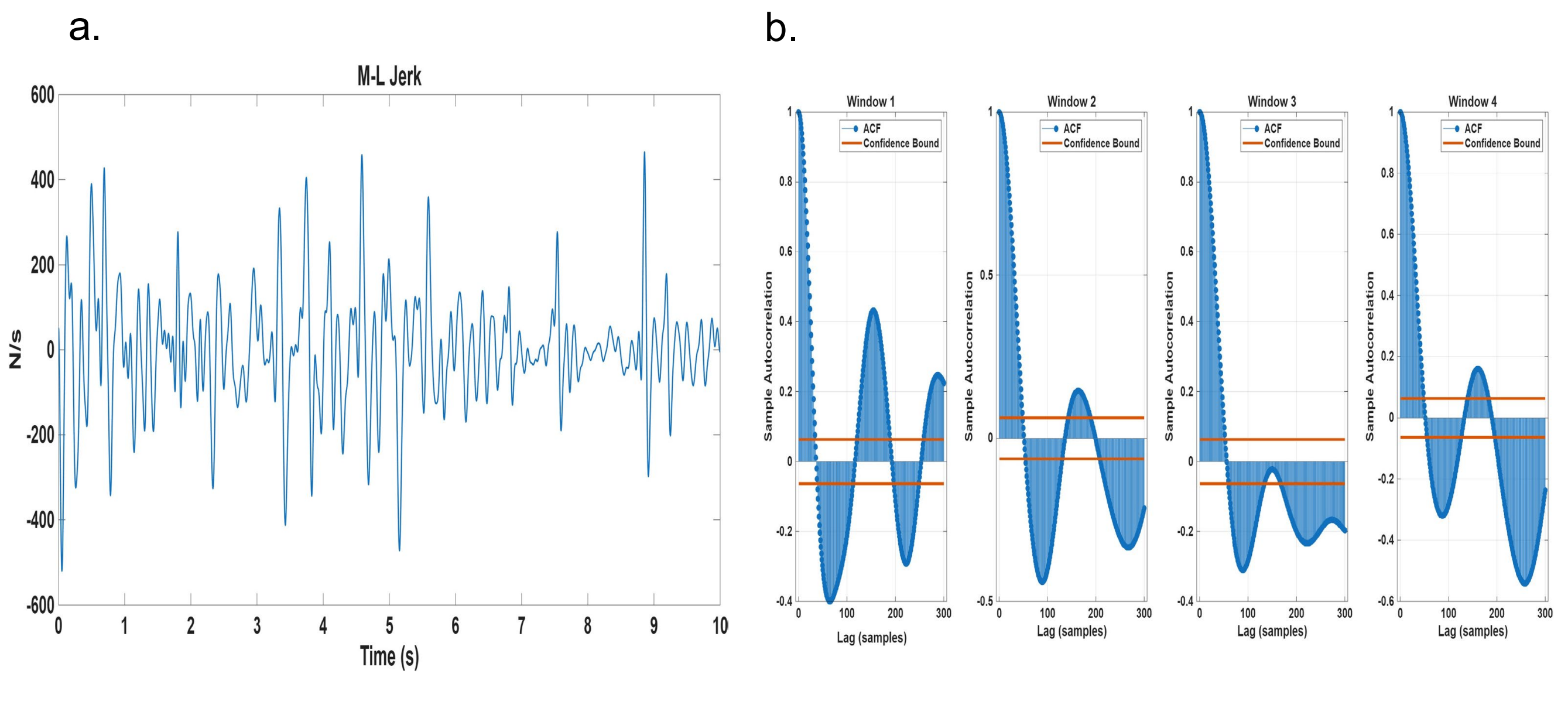

Fig. 2. This is the time series (a) and evolving autocorrelation profiles (with 95% confidence bounds) (b) for the M-L jerk.

Characterizing Local Statistics

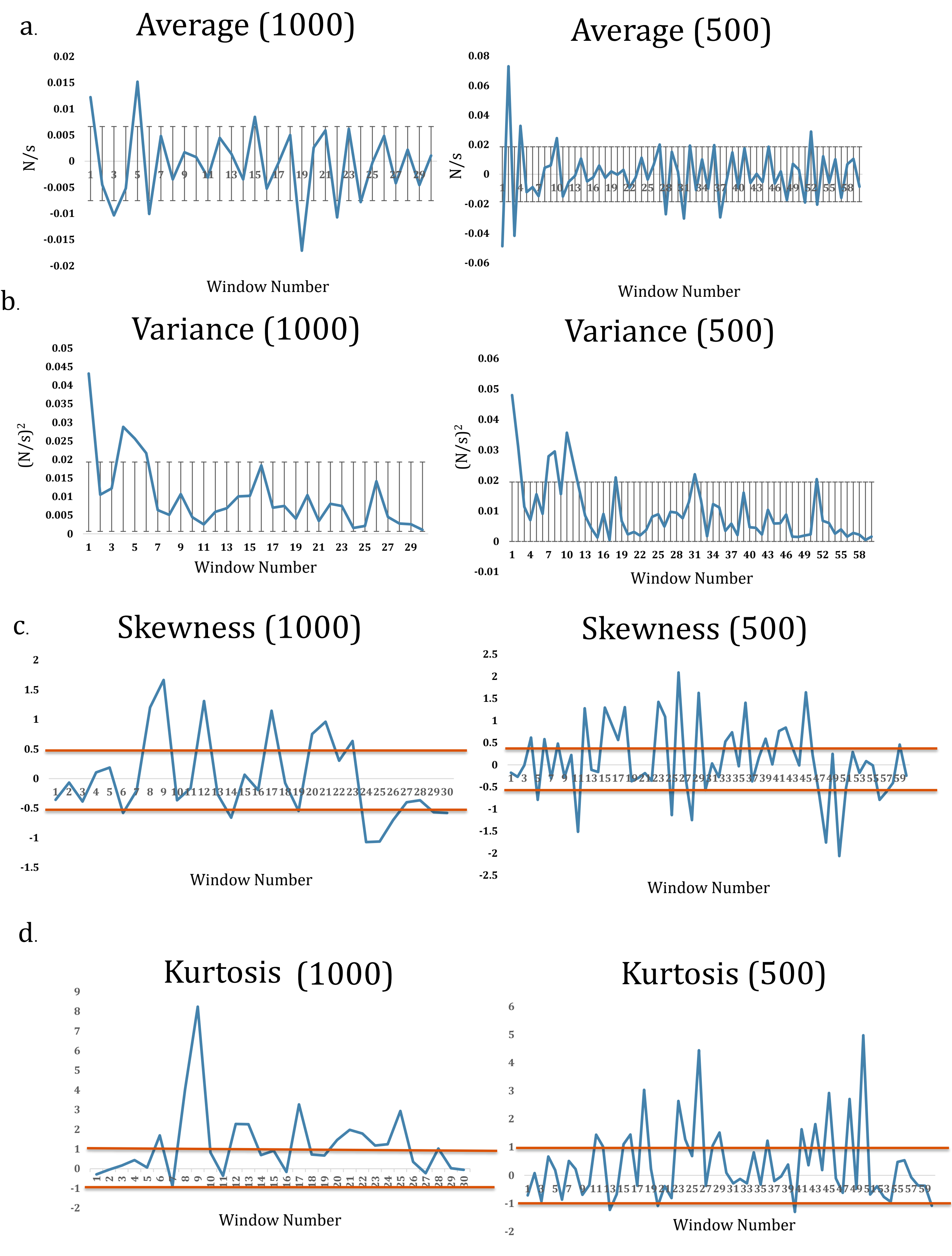

Fig. 3. Tracking local statistics in time. Significance is measured in each graph.

Discussing the local statistics: The time series was partitioned into a set of equal sized non-overlapping segments for which the average, variance, skewness, and kurtosis were measured. Windows of 500 and 1000 samples were used to assess the tendency for the statistics to change.

- The average and variance values were not significantly different from the standard deviation (indicated by the black bars in Fig. 3a and 3b). Overall trends of average and variance were similar between the two window sizes and do not appear to significantly evolve over time implying stationarity.
- Significance of skewness is indicated as exceeding +0.5 or -0.5 (indicated by the orange lines in Fig. 3c). Skewness measures the lack of symmetry in the distribution underlying the values in the window. Both windows show significant evolution in skewness thereby suggesting nonstationarity.
- Kurtosis measurements outside of the range of +1 or -1 indicate a lack of normality in a distribution (indicated by the orange lines in Fig. 3d). Our data suggest significant change in kurtosis which indicates nonstationarity.

Recurrence Plots

A recurrence plot is a tool used to visualize how the data revisits certain regions in a time series.

- This is done by taking one point as a reference and recording all other points that are within a certain distance, r, of this reference. This process is repeated by having each data point play the role of the reference.
- Reference points are paired with all points within a distance, r, and each point is indexed by its time of appearance in the series. These ordered pairs are plotted as blue dots, thus resulting in a recurrence plot such as seen below (left side of Fig. 4).
- Our data were compared to a known stochastic and stationary process, white noise.
- In addition, histograms counting the frequency of occurrence of each time difference between the points comprising the ordered pairs were examined (right side of Fig. 4).

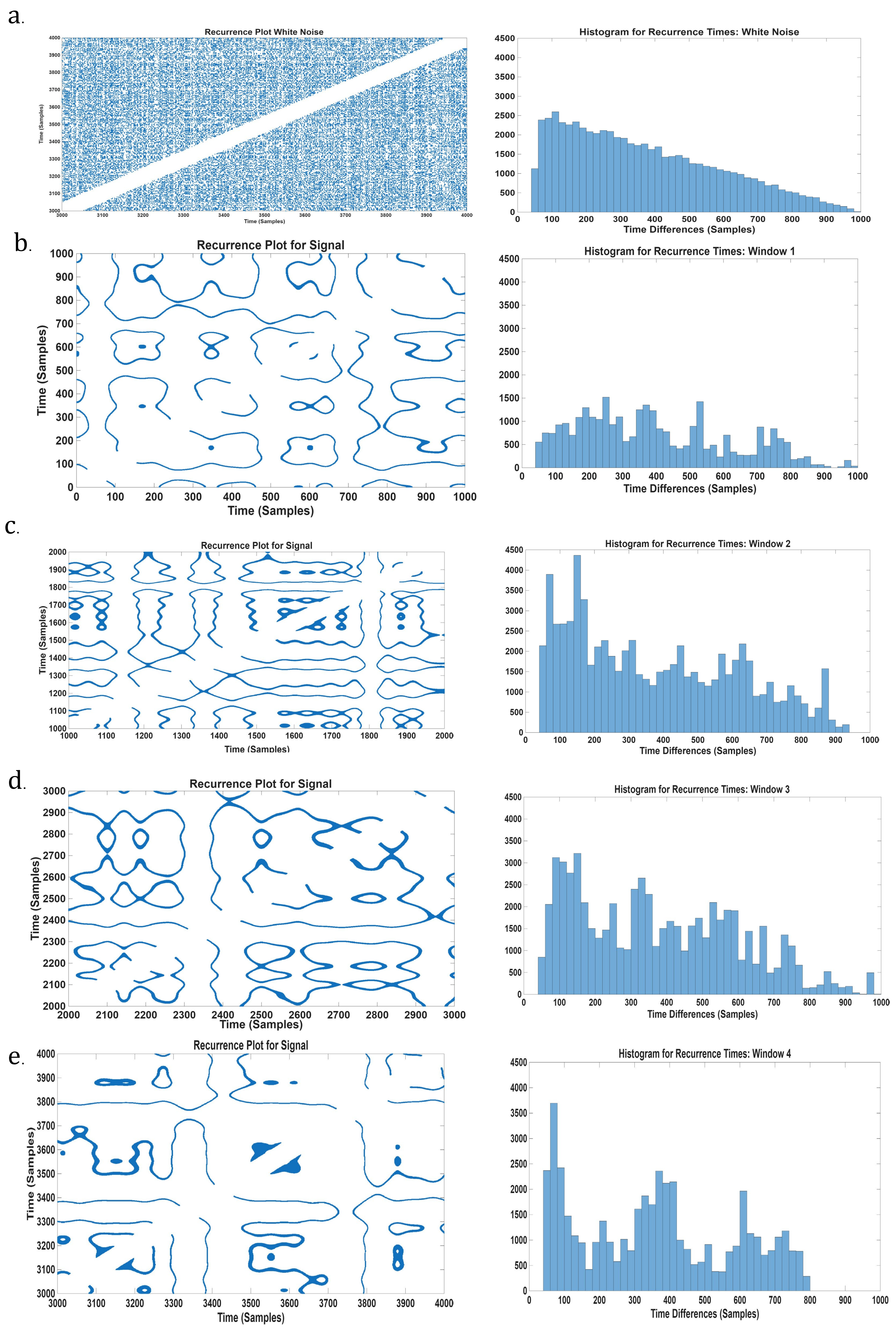

Fig. 4. Here we see recurrence plots and recurrence-time distributions across sequential windows of the signal (b-e) compared to a known signal, white noise (a).

Discussing the recurrence plots:

- The known stationary process, white noise, is the control. White noise shows uniformity in the distribution of time differences, and its frequency spectrum decays linearly as expected for a finite stationary time series.
- In our data, gross features in the recurrence plots appear to repeat, speaking to quasi-periodicity, while white spaces are regions of no recurrence. Differences in the shapes of the gross features suggest that fluctuations in the jerk occur over varying time scales.
- In the frequency spectra, our data do not demonstrate a linear decay.
- Moreover, these behaviors are changing window by window, speaking to nonstationarity.

Conclusion

Our characterization of the data shows that the jerk for a healthy adult attempting unipedal balance exhibits nonstationarity which could make identifying healthy behavior challenging.

References

[1] Semak, M., Schwartz, J., Heise, G., “Examining Human Unipedal Quiet Stance: Characterizing Control through Jerk.” *Computational and Mathematical Methods in Medicine.* Volume 2020, Article ID 5658321, 15 pages.

[2] Riley, M. A., Balasubramaniam, R., & Turvey, M. T. (1999). *Recurrence quantification analysis of postural fluctuations.* Gait & Posture, 9(1), 65–78.