AN IMPROVED SURROGATE METHOD FOR DETECTING THE PRESENCE OF CHAOS IN GAIT

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INTRODUCTION

Surrogate analysis is essential to prevent the misdiagnoses of a purely random signal as deterministic chaos [1]. Several surrogate algorithms have been presented that attempt to destroy the chaotic features of a time series while maintaining the essential linear features. If the original time series is statistically different from the surrogate then, the fluctuations in the time series have a deterministic structure. Alternatively, a failure to find significant differences between the surrogate time series and the original time series indicates that the fluctuations are merely random noise. Recently, the surrogate algorithm of Theiler et al. [3] has been applied to support the notion that fluctuations in human gait have a deterministic pattern [1]. However, inspection of the generated surrogate indicates that much of the essential geometric features of the gait time series are destroyed (Figure 1A and C). In this case, it is questionable if this surrogate can be used to effectively discern the difference between chaotic fluctuations and random noise in a gait time series. Recently, Small and Tse [2] have overcome this difficulty with a pseudoperiodic surrogate (PPS) algorithm that preserves the inherent periodic components of the time series while destroying the subtle nonlinear structure. Although this algorithm appears promising, it has not been tested in human gait patterns. Here we show that the PPS algorithm provides a more robust verification of the presence of chaos in gait by preserving the essential features of the time series.

METHODS

Six subjects walked at a self-selected pace on a treadmill for two minutes while the sagittal knee angles were captured with a 3D optical capture system. Surrogates of the respective time series were generated based on the PPS [2] and Theiler's algorithms [3]. Theiler's algorithm reorganizes the phases of the complex conjugate pairs in the frequency domain such that surrogate contains linearly filtered independent and identically distributed noise. The PPS algorithm generates a surrogate that follows the same vector field as the original time series, but is contaminated with dynamic noise. The PPS algorithm requires that the user define the embedding dimension, the time lag, and the noise radius. The embedding dimension and time lag were calculated with the Tools from Dynamics Software (Applied Chaos, LLC). Noise radius (?) was chosen such that the fine intercycle dynamics were removed, but the intracycle dynamics were preserved. If ? is too small, then the surrogate and the original time series are identical. If ? is too large, then the surrogate is a series of uncorrelated random noise. We selected ? to be the value that maximizes the expected number of short segments (length 2) to be the same between the surrogate and the original time series [2]. The largest Lyapunov exponents of the respective time series were calculated to test the null hypothesis that the surrogate and the original time series had the same dynamics.

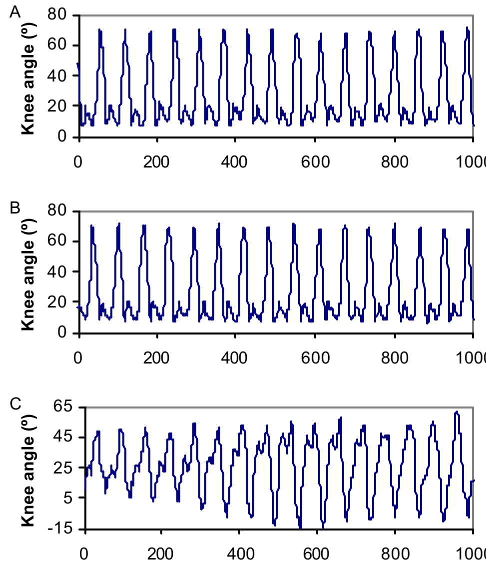

Figure 1: Exemplar original knee angle time series (A), PPS (B), and Theiler's surrogate(C).

RESULTS AND DISCUSSION

Significant differences ($p<0.05$) were found between the original and the respective surrogate time series. Both surrogate tests indicated that fluctuations in the knee time series had a deterministic structure that was significantly different from random noise. However, inspection of Figures 1A and C verifies that Theiler's algorithm alters the original geometric structure of the time series. Hence, it is trivial to find a significant difference between the surrogate generated by Theiler's algorithm and the original time series. It appears that Theiler's algorithm is of limited use for verifying the presence of chaos in gait patterns with an underling periodic structure. Inspection of Figure 1A and B indicates that the PPS algorithm maintains the essential geometric structure of the gait time series. In fact, the surrogate and the original gait time series appear virtually indistinguishable. These results support the notion that the PPS algorithm is more suitable for detecting the presence of subtle chaotic fluctuations that appear in gait. The PPS algorithm should be adopted in future investigations to rigorously verify that fluctuations in gait patterns are in fact chaotic and not random noise superimposed on top of the time series.

ACKNOWLEDGMENTS

This work is supported by the Nebraska Research Initiative.

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