DETECTION OF LONG-RANGE DEPENDENCE IN PEAK GROUND REACTION FORCES DURING RUNNING USING ARFIMA MODELING

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INTRODUCTION

The identification of the structure of a time series offers an insight into the control of biological processes. Long range or fractal correlations have been shown to exist in step or stride length and timing for both walking [2] and running [3]. Procedures such as the Detrended Fluctuation Analysis (DFA) [4] have been used to identify the presence of such long range dependence in biomechanical and physiological time series, however this analysis may result in the spurious identification of long term correlations [1]. There is no objective way to determine whether a linear regression line fits the data on the resulting log-log plot particularly well [5]. Furthermore short term correlations can mimic the power spectrum of a fractal series [1], since unambiguous detection of the latter from the spectrum often depends on the presence of very low frequencies that it may not be physiologically possible to measure.

Auto-Regressive Fractionally Integrated Moving Average (ARFIMA) models have been proposed as a complementary method to procedures such as the DFA to identify the presence of long range correlations [6]. ARFIMA (*p, d, q*) models are potentially composed of three components modelled by estimates of the parameters *p*, *d* and *q*. An autoregressive component determines the present value using a weighted sum of the previous *p* observations. A moving average component determines the present value based on random fluctuations for the *q* previous observations. The integrated component of the model determines whether values are modelled directly, or whether *d* differences between observations are modelled. In the ARFIMA model the *d* parameter can take on fractional values (between -0.5 and 0.5) that provide the model with long range dependencies. Standard errors associated with the parameter estimates allow for statistical tests of whether the *d* parameter is significantly different from zero. Use of criteria such as the Akaike Information Criterion allows the identification of the best model from a series of potential models with different components and numbers of parameters.

The purpose of this study was to use ARFIMA models to identify whether long range correlations existed in the peak impact and active vertical ground reaction forces during running in ten healthy recreational runners, and to compare the fractal exponents obtained with this analysis to those obtained using the DFA.

METHODS

Ten healthy experienced runners mean (±SD) age 24.6 ± 3.5 years, mass 63.9 ± 6.3 kg, were recruited. All experimental procedures were approved by the Institutional Review Board at The Pennsylvania State University, and all subjects provided written informed consent.

Each subject performed an eight minute running trial at their preferred running speed on a Gaitway instrumented treadmill. Two Kistler force plates placed one behind the other under the treadmill belt were used to record the vertical ground reaction forces (VGRF) throughout the eight minute trial at a sampling frequency of 250 Hz. Post-processing was conducted in Matlab 2009b (The Mathworks, MA, USA). The VGRF data were filtered in forward and reverse directions with a second-order Butterworth filter with a cut-off frequency of 30 Hz. A 30 N threshold was used for the identification of the start and end of each foot fall. The four variables extracted from each foot step are shown in Figure 1: a time series vector for each variable and each subject was created.

A DFA analysis implemented in Matlab was used to calculate the alpha value (or scaling exponent) for each time series. Subsequently, ARFIMA and ARMA models were fitted to each time series for each subject using the “fracdiff” package in R 2.12.1 (www.r-project.org./) according to the procedure proposed by Wagenmakers et al. [1].

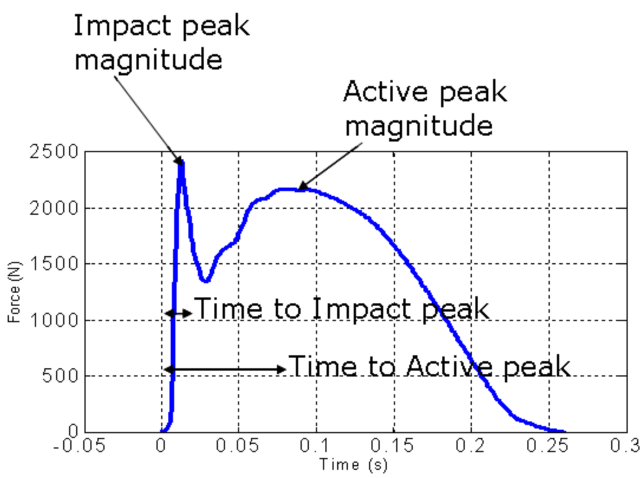

Figure 1: The four variables quantified for each running step.

RESULTS

The preferred running speed was 3.52 ± 0.97 m/s. Over the eight minute trials the subjects experienced 1,663 ± 79 footfalls. Alpha values for all parameters were significantly different from 0.5 ($p<0.05$, Figure 2), indicating the presence of long term correlations. However, the lower bound of the confidence intervals for the alpha value for the time of the impact peak and the time of the active peak did approach 0.5, for example the lower bound of the confidence interval for the time of the active peak was 0.54 (Figure 2).

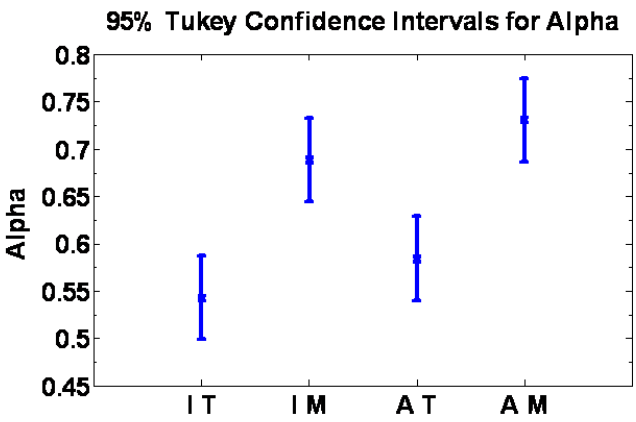

Figure 2: 95% Confidence Intervals for alpha values determined by the DFA for the time to impact peak (IT), magnitude of impact peak (IM), time to active peak (AT) and magnitude of active peak (AM).

The results of this analysis would suggest that the time series of the magnitude of the impact and active peaks exhibit the presence of long range correlations. However, the ARMA / ARFIMA procedure only consistently selected an ARFIMA model for all active peak magnitude time series, and for these models the d parameter was consistently different from zero. For the other three variables, the ARMA / ARFIMA procedure resulted in the selection of an ARMA model, or the ARFIMA model selected estimated a d parameter that was not significantly different from zero.

For the DFA analysis alpha values between 0 and 1 correspond to the Hurst exponent (also known as the scaling exponent) [1]. The Hurst exponent (H) can be calculated from the fractional d parameter of the selected ARFIMA model using the following equation [6]:
$H = (2 \times d + 1) / 2$.

There was good agreement between the Hurst exponents calculated using the two procedures for the magnitude of the active peak such that the values were typically within 0.03 of each other. The DFA procedure has previously been shown to provide unbiased estimates of the Hurst exponent over a large range of values [6]. The results of both analyses taken together provide strong evidence for the presence of long range correlations in the magnitude of the active peak during steady state running at the preferred running speed. However, the evidence for the presence of long range correlations in the timing of the two peaks and the magnitude of the impact peak is much weaker. While serial dependence seems to exist, short term dependence models may more appropriate for the processes associated with these variables.

The impact peak occurs within the first 10% of the stance period and is the result of the foot hitting the ground. The active peak occurs at approximately mid-stance and is the result of the muscular actions during foot contact. The magnitude of these peak ground reaction forces typically varies between 1.5 and 5 times body weight depending on running velocity and style [7]. The magnitude of the impact peak varies with running velocity and body configuration prior to foot contact [e.g.7]. Nigg [7] suggested the nature of the control mechanism for two peaks were different, the results of the present study would support this hypothesis. Although the magnitude of the impact peak can be less than the magnitude of the active peak, impact forces are most often considered to cause running injuries due to the high loading rate associated with this peak [e.g. 7]. It appears that the impact peak magnitude and the timing of the impact peak have at most only short range dependencies. The implications of this finding for injury rates are not presently clear, but it would be potentially informative to examine whether the behaviour of these time series is different for different running styles and performance levels, and for runners with an injury.

CONCLUSIONS

The ARMA / ARFIMA procedure agrees well with the results of the DFA analysis only for the time series of the magnitude of the active peak. While the DFA analysis suggests the presence of long range correlations in the magnitude of the impact peak and the timing of the two peaks, this conclusion is not supported by the ARMA / ARFIMA procedure. This suggests that these latter three time series contain only short term dependencies that mimic the presence of long range correlations. Future work should re-examine the scaling behaviour of other variables associated with steady state running and investigate the implications of the different scaling behaviour of the active and impact peaks.

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