An Analysis Of The Development Of Motor Coordination Of Infants Through Transfer Function Models

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Abstract: Problems associated with motor development in infants have received much attention in the recent years. Early infant spontaneous activity is thought to be an important determinant of later motor ability. Hence, early detection of any irregularities in spontaneous motor patterns such as kicking is important if we are to identify and correct problems that may develop later. Various studies have employed linear cross correlation to examine relationships between joints during spontaneous kicking in young infants. However, the angular displacement curves produced during spontaneous kicking lead to non-linear circular time series. In this paper the couplings between joints and limbs are examined using circular cross correlation function to provide an accurate assessment of the joint relationships. Then, the Box-Jenkins type transfer function approach is used to develop dynamic models to describe intralimb and interlimb coordination of infant kicking in fullterm infants at 12 weeks of age.

Keywords: *Motor coordination; Time-series analysis; Transfer Function Models; Angular Cross Correlation function*

1 INTRODUCTION

In recent years, motor development in infancy has been examined by studying the synchronous behaviour of joints, particularly in the legs (e.g., Geerdink, Hopkins, Heriza, 1988a; Jensen, Ulrich, Thelen, Schneider & Zernicke, 1994; Piek, 1996, 1998; Thelen, 1985) . Kicking in the first six months of life is a common behaviour, usually described as a spontaneous movement, where the behaviour does not appear to be initiated by an external stimuli, and is often rhythmical in nature (Piek, 1995). Early infant kicking is believed to be a precursor for later coordinated leg movements such as walking (Thelen, 1985).

The relationship between joints could be represented by two relationships, cross correlations and phase lag. This paper extends the previous work of Piek and colleagues by describing a procedure which integrates these two measures. The different joint relationships are described using linear transfer function models (Box & Jenkins, 1976) which are capable of representing many of the dynamic relationships found in real-life situations. Of particular interest to the current study is the ability of these models to capture a sufficient amount of the dependence structure which will then allow future behavior of the time series to be predicted. This will provide comparison models for other infant populations such as preterm and at-risk infants. The applications of such methods to behavioural phenomena have received some attention, but they are still relatively new.

The angular displacement curves produced during spontaneous kicking produce nonlinear, circular time-series.Hence, in the current study, statistical techniques for circular data were employed to analyse and model the spontaneous kicking patterns using angular-angular cross correlation functions rather than linear cross correlation functions. These techniques combine standard methods with recently developed techniques of circular data analysis in the time domain. The methods for analysing time series of circular (or angular) data have undergone considerable development over recent years (Fisher and Lee, 1983). The current paper employed the techniques for circular data analysis described by Fisher and Lee (1983) and Jammalamadaka and Sarma (1988)in order to determine angular-angular cross-correlation functions. These were then compared with the standard linear cross-correlation functions.

2. METHOD

2.1 Introduction

The data used in the modelling procedure was taken from three fullterm, 12 week old male infants who had normal birth histories. These infants were all born at 40 weeks gestational age, and had birth weights of 3540g (Infant A), 3385g (Infant B) and 3232g (Infant C).
Three second samples (five samples/infant) were taken for analysis (i.e., 75 data points/sample)and the angles were calculated between two contiguous segments, resulting in the joint angle displacement curves for the right hip, knee and the ankle joints.

2.2 Model fitting for circular data

In order to eliminate the autocorrelation effect and obtain valuable identification information from the cross correlations of each pair of joints, filtering or prewhitening of data was used. Following Fisher and Lee(1994), the circular autocorrelataion function used was

$$\hat{\rho}_T(k) = \frac{\det(\sum_{t=1}^{T-k} X_t X'_{t+k})}{\{\det(\sum_{t=1}^{T-k} X_t X'_t)\det(\sum_{t=k+1}^{T} X_t X'_t)\}^{\frac{1}{2}}} \qquad (1)$$

where $X_t = (\cos\theta_t, \sin\theta_t)'$; . θ_t is the angle of displacement.
Assuming that the conditional distributions of $\Theta_t|\theta_t$ are von Mises distributions with mean direction μ and concentration parameter κ (i.e., VM(μ , κ)), a suitable model was fitted. In many respects, the von Mises distribution is the 'natural' analogue on the circle of the Normal distribution on the real line. In practice, it does appear to be a reasonable model for symmetric unimodal samples of circular data. The concentration parameter κ describes how much variation there appears to be around the overall trend of the series. Depending on whether the series is dispersed ($\kappa < 2$) or concentrated ($\kappa \geq 2$) the series can be modelled by a circular ARMA(p,q)(CARMA(p,q)) or a linked ARMA(p,q)(LARMA(p,q)) model.. One difficulty in using the von Mises distribution in practice is the value of κ can not be easily evaluated. The difficulties are caused by the presence of modified Bessel functions, and an iterative procedure is needed.

However, as sample data tended to cluster in an arc, the estimate of κ is always greater than 2. Therefore, using $\tan^{-1} x$ as a link function the angular data can be linearized and the standard Box-Jenkins methodology can be used for the analysis of the transformed series.
The circular cross correlation coefficient proposed by Fisher and Lee (1983) is defined by

$$\gamma(k) = \frac{\sum_{1\le i<j\le n} \sin(\theta_i - \theta_j)\sin(\phi_{i+k} - \phi_{j+k})}{\{\sum_{1\le i<j\le n} \sin^2(\theta_i - \theta_j) \sum_{1\le i<j\le n} \sin^2(\phi_{i+k} - \phi_{j+k})\}^{\frac{1}{2}}} \qquad (2)$$

For computational purposes, this can be rewritten as ,

$$\gamma(k) = \frac{\det(\sum_{t=1}^{T-k} X_t Y'_{t+k})}{\{\det(\sum_{t=1}^{T-k} X_t X'_t)\det(\sum_{t=k+1}^{T} Y_t Y'_t)\}^{\frac{1}{2}}} \qquad (3)$$

where $X_t = (\cos\theta_t, \sin\theta_t)'$ and $Y_t = (\cos\phi_t, \sin\phi_t)'$.
In the current study, equation (3) was used to determine the circular cross-correlation functions (CCF) between each pair of joint angles assuming the circular time series are stationary.

2.3 Transfer Function Noise(TFN) models

Box and Jenkins (1976) gives a comprehensive description on transfer function modelling for input-output data. In their approach first the input and the output series are prewhitened using ARMA(p,q) type filters and transfer function models of the form

$$y_t = v(B)x_t + n_t \tag{4}$$

are fitted. The v(B) in equation (4) is known as the impulse response function and the n_t is a noise series. An equivalent representation of the model is given by

$$y_t = \frac{\omega(B)}{\delta(B)}x_{t-b} + \frac{\theta_1(B)}{\phi_1(B)}a_t \tag{5}$$

where $\{a_t\}$ is white noise sequence and $\omega(B),\ \ \delta(B)\ \ \theta_1(B), and\ \ \phi_1(B)$ are polynomials in the backward shift operator B.

The transfer function model building process described above involves three stages - identification, estimation and diagnostic checking.

Summary of transfer function modelling

(1) Prewhitening: $\frac{\phi(B)}{\theta(B)}x_t = \alpha_t$

where, x_t is the input, and α_t is white noise.

(2) Transform : y_t (output) so that $\beta_t = \frac{\phi(B)}{\theta(B)}y_t$.

(3) Obtain a model for $\beta_t : \beta_t = v(B)\alpha_t + e_t$.

(4) Identify $v(B)$ using cross correlations, and write the TFN model in the form $y_t^* = \frac{\omega(B)}{\delta(B)}x_{t-b} + n_t$.

(5) Obtain the noise series $n_t = y_t^* - y_t$ and fit a model $n_t = \frac{\phi_1(B)}{\theta_1(B)}a_t$, where $\phi_1(B),\theta_1(B)$ are polynomials in B and a_t is white noise.

(6) Perform diagnostic checking.

3. RESULTS AND DISCUSSION

Figure 1 gives a sample of angular displacement curves for the left and right leg of spontaneous kicking for each of the three infants, A, B, and C, respectively (one samples per infant). In order to be included, each sample required at least one kick for each leg where the angular displacement for either the hip or knee was a minimum of 10 degrees. The rate of kicking was quite variable between infants and between samples, although Infant A appeared to produce the most vigorous kicking and infant B appeared the least active.

Left **Right**

Infant A

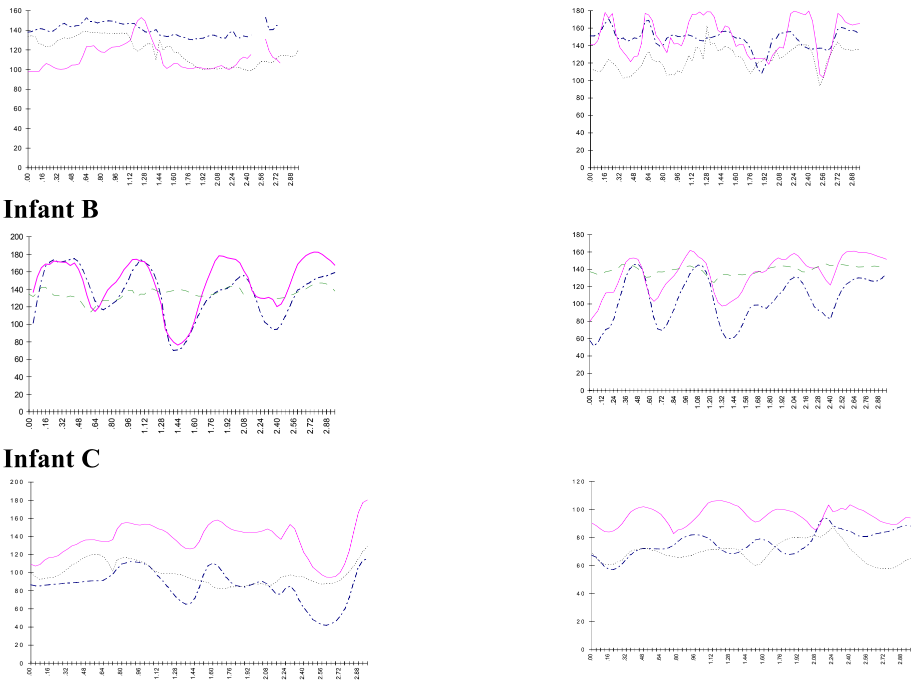

Figure 1. Left and Right leg kicking patterns for infants A,B and C

3.1 Intralimb Comparisons

Table 1 presents the angular-angular and linear cross-correlation functions for each sample, comparing the hip, knee and ankle joints for A) the left, and B) the right limb separately. Due to the multiple correlations produced, a conservative alpha level of .01 was set for significant correlations. This table also presents the orders of the parameters produced by the modelling procedure.

3.2 Cross-Correlation Functions

Firstly, it can be seen that the correlations for circular and linear calculations are very similar. Only one (sample 5 for the right hip/knee in Infant C) out of a total of 90 correlations differed by more than .05, suggesting that both angular/angular and linear cross-correlation functions are suitable for these types of time series curves.

Strong joint couplings were evident for all three joint comparisons. This is typical of previous findings for 12 week old infants (e.g., Jensen et al., 1995; Thelen, 1985). For the hip/knee, all angular/angular correlations were significant for both the right (Avg = .58) and left leg (Avg = .63). In addition, there was very little evidence of any phase lag between the two joints. For the left leg the two joints were synchronous (all lags were 0), whereas for the right leg, a phase lag was evident in only 4 out of the 15 samples. Likewise, for the knee/ankle comparisons, 13 out of the 15 correlations for both the right (Avg = .51) and left (Avg = .50) leg were significant, although a phase lag was more evident between these two joints. Five of the 15 samples for the left leg demonstrated a lag of 40 ms between the knee and ankle, whereas 3 of the 15 samples for the right leg showed phase lags of varying magnitude. Overall, however, these two joints were in synchrony during kicking.
Finally, the hip/ankle correlations were also significant in most cases (23 out of the 30 comparisons), although these were not as strong as the other joint correlations (right: $\underline{X}$ = .37; Left: $\underline{X}$ = .35). Also, there was a phase lag between the ankle and hip joints for more than 50% of the samples, with 8 of the 15 comparisons demonstrating phase lags for both the left and right leg. It is worth noting that 13 of these 16 lags were negative, demonstrating that the ankle leads the hip during the kicking action (i.e., a distal to proximal direction).

3.3 Transfer Function/Noise Models

The order columns in Table 1 define the general structure of the transfer function models produced for each sample. The predicted shape of the output (i.e., the impulse responses) are determined by the cross correlation functions and can be described by the order parameters, b, p, and q. The parameter ‘b’ demonstrates the level of synchrony (measured by phase lag) between the joint pairs. For example, for the left hip/knee, ‘b’ equals 0 in all 15 samples.
Parameter order was consistent across infants and joint comparisons, indicating the similarity in the behavior of these joint pairs across infants. There were, however, differences between the right and left legs. These findings are expected given that leg asymmetries have been found in earlier work. In particular, Piek and Gasson found that the right leg was more strongly coupled and more synchronous than the left. It can be seen in Table 1 that the right leg demonstrates a more consistent or regular pattern than the left leg. In all but 4 of the 45 samples, the q, p parameters are 1,1. When there is a phase lag of 1, the transfer function/noise model (of 1,1,1) would take the form:

$$y_t = \frac{\omega_0 - \omega_1 B}{1 - \delta_1 B} x_{t-1} + N_t \,.$$

This ‘b,1,1’ pattern in the tranfer function is also the most common found for the hip/ankle joints of the left leg. However, a different pattern emerges for the two joints that encompass the knee. The q,p order of 2,1 is found for all the knee/ankle samples and all but 3 of the hip/knee samples for the left leg. The transfer function/noise model of this order given 0 phase lag (i.e., 0,2,1) takes the form:

$$y_t = \frac{\omega_0 - \omega_1 B - \omega_2 B^2}{1 - \delta_1 B} x_t + N_t \,,$$

If there is no relationship between the two joints then, a model cannot be built. This is represented by the term ‘nil’ in the order column. This was rare for the intralimb comparisons (only four times out of the 90 samples), and only occurred for the hip/ankle comparisons which were not as tightly coupled as the other two joint pairs. Even when there was not a significant cross correlation between the two joints, a relationship was still evident between the two joints in the majority of cases which could be modelled.
The interlimb comparisons did not show any strong coupling and are not reported in this manuscript due to space limitations.

4 CONCLUSIONS

In the current study, the relationship between two non-linear time series were successfully modelled in the time domain. These transfer function models represent the dynamic patterns of movement that occur between joints of the same limb and also between the same joints for two different limbs. In conventional dynamic model building, the input signal is treated as noise free. In the current application, both the input and output signals are subject to stochastic noise. However, the effect of input noise on the modelling procedure was observed to be negligible in this case.

Evidence has been provided that the relationship between the joints changes over age (Jensen et al., 1995; Thelen, 1985), particularly for the interlimb joint comparisons. Furthermore, differences in the development of the joint angle relationships have been found between fullterm and preterm infants (Geerdink et al., 1996). We are currently utilizing the procedure outlined in this paper to model the data from both fullterm and preterm infants at different ages in order to quantify the developmental patterns of intralimb and interlimb coupling that occur during spontaneous kicking. Such models will contribute to our understanding of both normal and abnormal motor development.

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Left leg(Right leg)	INFANT A				INFANT B				INFANT C			
	Cross-Correlations		Phase Lag	Order	Cross-correlations		Phase Lag	Order	Cross-correlations		Phase Lag	Order
	Angular	Linear		b,p,q	Angular	Linear		b,p,q	Angular	Linear		b,p,q
Hip/ankle	.25(.14)	.25(0.14)	-1(0)	1,1,1(nil)	.22(.34*)	.21(.35*)	-2(-1)	Nil(1,2,1)	.39*(.32*)	.39*(.32*)	0(2)	0,1,1(2,1,1)
	.32*(.30*)	.32*(.30*)	0(-4)	0,1,1(4,1,1)	.47*(.34*)	.47*(.34*)	-2(-1)	2,1,1(1,1,1)	.5*(.48*)	.51*(.48*)	0(-1)	0,1,1(1,1,1)
	.62*(.62*)	.63*(.62*)	0(0)	0,1,1(0,1,1)	.42*(.35*)	.43*(.35*)	-1(-1)	1,1,1(1,1,1)	.36*(.51*)	.35*(.52*)	7(0)	7,1,1(0,1,1)
	.24(.41*)	.24(.41*)	0(0)	0,1,1(0,0,1)	.16(.35*)	.16(.35*)	-4(0)	Nil(0,0,1)	.3*(.29*)	.31*(.29*)	-3(-1)	3,1,1(1,1,1)
	.39*(.41*)	.40*(.38*)	-2(3)	2,1,1(3,1,1)	.39*(.14*)	.34*(.14*)	2(0)	2,1,1nil)	.57*(.50*)	.57*(.47*)	0(0)	0,1,1(0,1,1)
Hip/knee	.34*(.45*)	.35*(.45*)	0(0)	0,2,1(0,1,1)	.79*(.80*)	.8*(.81*)	0(0)	0,2,1(0,1,1)	.91*(.46*)	.92*(.47*)	0(-2)	0,2,1(2,1,1)
	.73*(.46*)	.74*(.47*)	0(0)	0,2,1(0,1,1)	.47*(.37*)	.48*(.37*)	0(-3)	0,2,1(3,1,1)	.57*(.46*)	.58*(.47*)	0(1)	0,2,1(1,1,1)
	.84*(.80*)	.85*(.81*)	0(0)	0,1,2(0,1,1)	.83*(.53*)	.84*(.53*)	0(0)	0,2,1(0,1,1)	.51*(.80*)	.51*(.81*)	0(0)	0,2,1(0,1,1)
	.32*(.68*)	.32*(.69*)	0(0)	0,1,2(0,1,1)	.58*(.73*)	.59*(.74*)	0(0)	0,1,2(0,1,1)	.64*(.48*)	.64*(.49*)	0(0)	0,2,1(0,1,1)
	.82*(.67*)	.83*(.68*)	0(0)	0,2,1(0,1,1)	.54*(.64*)	.54*(.65*)	0(0)	0,2,1(0,1,1)	.56*(.32*)	.57*(.24)	0(1)	0,2,1(1,1,1)
Knee/ankle	.28(.55*)	.28(.55*)	-1(0)	1,2,1(0,1,1)	.37*(.37*)	.35*(.38*)	0(0)	0,2,1(0,1,1)	.52*(.44*)	.52*(.45*)	0(0)	0,2,1(0,1,1)
	.19(.34*)	.21(.34*)	1(-7)	1,2,1(7,1,1)	.50*(.69*)	.50*(.70*)	1(0)	1,2,1(0,1,1)	.82*(.17)	.83*(.17)	0(2)	0,2,1(2,1,1)
	.52*(.66*)	.53*(.66*)	0(0)	0,2,1(0,1,1)	.50*(.65*)	.50*(.66*)	0(0)	0,2,1(0,1,1)	.71*(.77*)	.72*(.78*)	0(0)	0,2,1(0,1,1)
	.61*(.61*)	.62*(.61*)	0(0)	0,2,1(0,1,1)	.37*(.72*)	.37*(.72*)	1(0)	1,2,1(0,1,1)	.61*(.34*)	.62*(.34*)	0(8)	0,2,1(8,1,1)
	.40*(.42*)	.40*(.40*)	-1(3)	1,2,1(3,1,1)	.71*(.59*)	.72*(.60*)	0(0)	0,2,1(0,1,1)	.94*(.51*)	.95*(.51*)	0(0)	0,2,1(0,1,1)

$P^* < .01$

Table 1. Angular-angular and linear cross-correlation functions and order parameters for each intralimb joint pair compariso