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Toward a synergetic model of postural coordination dynamics

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Abstract

In the present study the authors develop a double inverted-pendulum intrapersonal model for posture in the Sagittal plane. A novel synergetic approach is taken to successfully reproduce qualitative features of experimental data. The HKB model is investigated and modified into a more general type of "excitator" to create suitable dynamics for this application. Bifurcation analysis of HKB couplings revealed regimes where appropriate asymmetries exist in the fixed points. The findings suggest that this approach produces an innovative and viable solution for postural coordination dynamics.

1. Introduction

The coordination of the human body is a hugely complex task; it requires constraining a multitude of degrees of freedom (of some 10^3 muscles and 10^2 joints) to act as a single unit in accomplishing behavioural tasks. Double inverted-pendulum models in the sagittal plane have been shown to give a full representation of the repertoire of postural movements [3, 4]. Empirical evidence from Bardy et als experimental paradigm [2], in which humans move back and forth in order to track the displacement of a visual target, has revealed that the relative phase between the ankle and hip joint undergoes an abrupt phase transition in between attractors at approximately 20 and 180 degrees due to a symmetry breaking bifurcation as frequency increased above a critical level. The validity of a self-organised model of posture is further substantiated by evidence of critical fluctuations, critical slowing down and hysteresis between these two modes [2]. Considering this, the awkward complexity of existing physiological models [4] and the previous success of the Haken-Kelso-Bunz (HKB) model in coordination dynamics in human movement [6] an application of a synergetic approach is timely. We will focus on the experimental paradigm developed by Bardy et al [2] and attempt to reproduce the main qualitative features seen in the data.

2. The Model

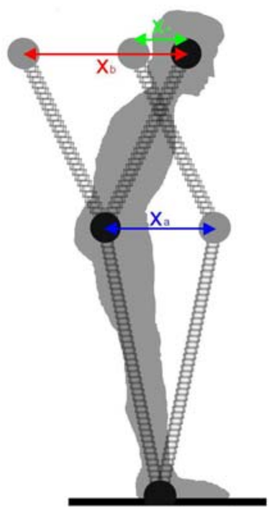

Figure 1: The value of x_a & x_b in the model represent the displacement of the lower and upper segments of the body. x_h ($x_h = x_a + x_b$) represents the displacement of the eye relative to the ankle (and hence to the ground). Peak to peak displacements are shown here.

Following the example of Kelso et al [6] a Synergetics approach will be taken. The dynamics in the experimental data can be fully described by the angle of the ankle and hip joints. To this end we introduce two variables; x_a represents the horizontal displacement of the hip joint relative to the ankle joint, x_b represents the horizontal displacement of the eye relative to the hip joint. A third variable x_h is a sum of the two aforementioned variables and represents the motion of the eye relative to the ankle joint (Figure 1).

Experimental results show a distinct change in the stability of relative phase as frequency (ω)is increased [2]. In line with previous research in coordination dynamics [6, 7, 8], we implement the equivalent of the former (specifically the relative phase, ϕ, between x_a & x_b) as our order parameter and the latter (ω) as our control parameter. The following main qualitative features are clearly seen in experimental data and we require that they also be reproduced by the model;

1. A change in the stability of the order parameter as the control parameter is increased.
2. Fixed points at 20 and 180 degrees.
3. Correct amplitude variations in x_a & x_b before and after the phase transition.

There are distinct similarities between postural dynamics and those seen in the finger tapping experiments that initially inspired the HKB model [6]. However, the symmetry breaking bifurcation seen in Kelso et als work [6] creates a transition with only the in-phase mode remaining stable at supercritical frequencies. In postural movement it is the anti-phase mode that remains stable. Therefore a reverse coupling [8] of the oscillators (opposed to the HKBs original form) is required to satisfy the first criteria.

The HKB model was created for a system of two symmetrical components (the index fingers of the left and right hand) [6] with fixed points at 0 and 180 degrees. In this application the upper and lower segments of the body and their coupling are clearly not symmetrical. The results of asymmetries are apparent in the fixed points (Criteria 2) and the amplitude variations (Criteria 3). An asymmetrical HKB model has been developed [9] which introduces a shift in both of the fixed points. However, to fulfil the second criteria the anti-phase fixed point must remain at 180 degrees.

A possible solution has arisen from bifurcation analysis on the coupling parameters (in combination with the asymmetrical HKB model [9]). A negative value of the coupling term β creates a phase locked solution (Figure 2) which, with a correct parameter choice, can produce a phase lead of 20 degrees in the anti-phase fixed point (in a reversed coupled HKB system), thus moving it to 200 degrees, with the in-phase fixed point remaining unchanged (at 0 degrees). Applying the asymmetrical HKB model (with appropriate parameter selection to shift both fixed point by -20 degrees) within this regime of negative β parameter will leave fixed points at 20 and 180 degrees thus satisfying the second criteria[1].

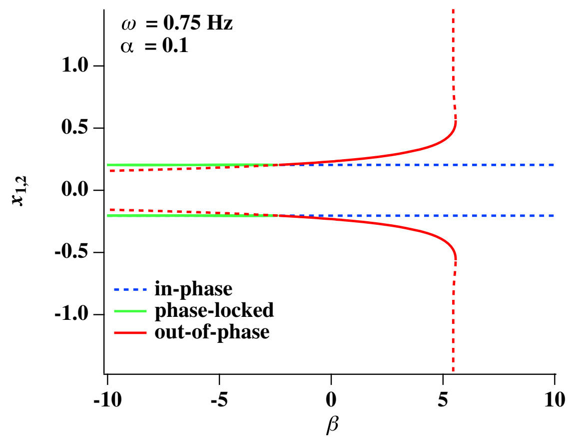

Figure 2: Bifurcation analysis on β, $\omega = 0.75$, $\alpha = 0.1$ (Other parameters $A = 1$, $B = 1$ & $\gamma = 0.7$). In phase (blue), anti-phase (red) and phase locked (green) fixed points (stable = solid line, unstable = dotted line) are shown. For a low value of β only the anti-phase (180 degrees) and phase locked (which can be set to 20 degrees with parameter choices).

Implementing the HKB model will produce values of x_a & x_b representing body positions which are impossible and do not fulfil the experimental task [2]. Experimental data reveal specific amplitude variations; in-phase (20 degree) motion is produced mainly from rotation of the ankle joint with a small contribution from the hip joint (larger hip rotations in this mode will move the centre of pressure outside of the base of stability); in anti-phase the amplitude of the hip rotation becomes much larger than the ankle rotations (motion of the head is produced by the difference in these amplitudes and is thus an essential requirement for the experimental paradigm we are attempting to model [2]). Variation in the relative amplitude of the two oscillators can be created if asymmetrical coupling parameters are applied. However, it is not possible to create pre- and post-transition amplitudes, as described above, by parameter selection alone.

[1] For the sake of brevity the following discussions will refer to the symmetrical HKB model rather than the asymmetrical form required

The summation of the two oscillators (x_a & x_b) varies from zero while in anti-phase to $2r$ while in-phase (where r is the amplitude of both HKB oscillators x_1 & x_2 [6]). Therefore a linear combination of x_1 & x_2 (such as $\lambda x_1 + \mu x_2$) can be implemented to created any required change in amplitude at the phase transition. Thus to fulfil criteria 3 a modification is applied to the original HKB such that:-

$$\begin{aligned} x_a &= x_1 \\ x_b &= \lambda x_1 + \mu x_2 \end{aligned}$$

The following substitution can be used to write the model as a system of 4 first-order differential equations;

$$\begin{aligned} x_c &= \dot{x_a} \\ x_d &= \frac{\dot{x_b} - \lambda \dot{x_a}}{\mu} = \frac{\dot{x_b} - \lambda x_c}{\mu} \end{aligned}$$

which gives;

$$\begin{aligned} \dot{x_a} &= x_c \\ \dot{x_b} &= \mu x_d + \lambda x_c \\ \dot{x_c} &= -(A x_a^2 + B x_c^2 - \gamma) x_c - \omega^2 x_a \\ &+ \left(\alpha + \frac{\beta}{\mu} \left(x_a \left(\lambda + \mu \right) - x_b \right)^2 \right) (x_c - x_d) \\ \dot{x_d} &= - \left(A \left(\frac{x_b - \lambda x_a}{\mu} \right)^2 + B x_d^2 - \gamma \right) x_d \\ &- \omega^2 (\frac{x_b - \lambda x_a}{\mu}) \\ &+ \left(\alpha + \frac{\beta}{\mu} \left(x_b - x_a \left(\lambda + \mu \right) \right)^2 \right) (x_d - x_c) \end{aligned}$$

Written in the form above one can see that a more general type of "excitator" [7] system has been created, though this result has arisen independently of associated literature. The first oscillator (x_a) is identical to the original HKB and an appropriate amplitude, for the motion of the lower segment of the body, can be created by parameter selection (Kelsos et als method for parameter fitting can be applied here [7]). The coupling parameters α and β can be selected to reproduce a phase transition at the correct frequency with β taking a negative value to create a phase lock of 20 degrees between oscillators. Following this λ & μ can then be selected to created correct amplitude variation of x_b (representing the top segment of the body). To create a reverse coupling (criteria 1) the inequality $\mu + \lambda < 0$ must be fulfilled. Selection of dummy parameters; $\lambda = 0.8$ & $\mu = -1.2$ create an amplitude variation (Figure 3) similar to that seen in experimentation (see Figure 4 compared to Figure 1 in [5] for a comparison).

The frequency of the postural experiments (0.1 0.75 Hz) [2] are much lower than used in the original HKB model and a sufficiently small value of A must be selected ($A << \omega$) in line with the slowly varying wave form approximation to substantiate analytical methods. Initial numerical simulations suggest that a system such as that outline above agrees well with experimental data (Figures 3 & 4).

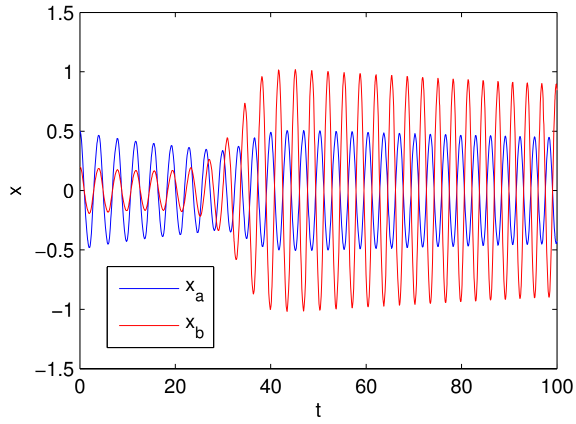

Figure 3: Numerical simulation of model. Parameter values; $A = 1, B = 1, \gamma = 0.7, \alpha = -0.3 \beta = 0.8, \lambda = 0.8 \& \mu = -1.2$. Simulation was run for 100 seconds with frequency increasing from 1.6 to 2.1 Hz.

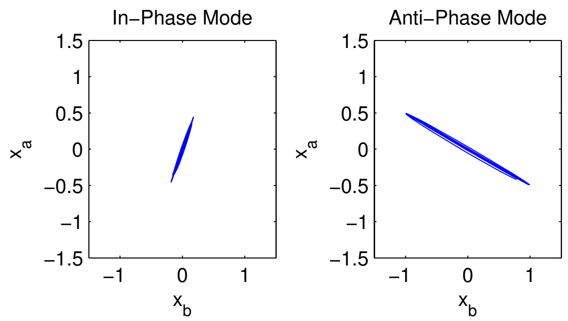

Figure 4: Phase portrait in x_a-x_b plane for simulation for in-phase ($\phi = 20$) mode (left) and anti-phase ($\phi = 180$) mode (right). (see figure 3 for futher details).

3 Conclusion

Our findings suggest that the Synergetic approach applied here yields dynamics which reproduces the main qualitative features of the experimental data [2]. The versatility of an "excitator" [7] opposed to the HKB model has been further substantiated, and arrived at independently from past literature. However, the analysis and simulations are shown here in the absence of noise, results that contain stochastic variations will be an important development. Furthermore, two distinct types of phase transition have been associated with the HKB model in past literature [1]; amplitude- and phase-modulated transition. Comparisons must be made between the model and experimental data to ensure the same mechanisms are apparent.

A specific amplitude is a requirement of the task in the experimental paradigm on which this work focuses [2]. This makes it difficult to distinguish between movements that are a natural product of the postural system and due to experimental constraints. There is a possibility of developing experimentation which requires rhythmical synchronisation but no specific amplitude so the emerging dynamics are less constrained.

Several important variations in potential function with parameter changes have been identified within this work (though they are only presented here in brief; Figure 2) further characterisation of the dynamics of the HKB model in all parameter regimes would aid the development of this model. The continuation of this work, to create a quantitative model of postural coordination dynamics, by data fitting, appears to be viable. However, the value of such a model will depend on its accuracy and number of parameters fitted compared to existing representations developed from physiology. An investigation into the intrinsic dynamics applied in these two different approaches may inform further model design and yield insights into the underlying mechanisms of human posture and which of these becomes modified in pathologies.

All past postural modelling incorporates the physiological features of the system, which leads to undesirably complicated models. This works offers the beginning of a new approach for this field; by focusing on the features that emerge in the dynamics it may be possible to isolate the essential mathematical features of the system and develop a new model for the coordination dynamics of human posture.

Acknowledgements

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