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Artificial neural networks for analyzing inter-limb coordination: The golf chip shot

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ABSTRACT

Motor control research relies on theories, such as coordination dynamics, adapted from physical sciences to explain the emergence of coordinated movement in biological systems. Historically, many studies of coordination have involved inter-limb coordination of relatively few degrees of freedom. This study looked at the high-dimensional inter-limb coordination used to perform the golf chip shot toward six different target distances. This study also introduces a visualization of high-dimensional coordination relevant within the coordination dynamics theoretical framework. A specific type of Artificial Neural Network (ANN), the Self-Organizing Map (SOM), was used for the analysis. In this study, the trajectory of consecutive best-matching nodes on the output map was used as a collective variable and subsequently fed into a second SOM which was used to create visualization of coordination stability. The SOM trajectories showed changes in coordination between movement patterns used for short chip shots and movement patterns used for long chip shots. The attractor diagrams showed non-linear phase transitions for three out of four players. The methods used in this study may offer a solution for researchers from a coordination dynamics perspective who intend to use data obtained from discrete high-dimensional movements.

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1. Introduction

Understanding how individuals coordinate the movements of many different body parts to produce a functional outcome is important for researchers, clinicians, movement analysts and educators. For any whole body movement, cellular units of the order of 10^{14}, in hundreds of varieties, must organize to operate nearly 800 muscles (Turvey, 1990). Such complexity makes the process of coordination a challenging program of study. Nicolai Bernstein recognized the challenge as that of overcoming the complexity by mastering the redundant *biomechanical* degrees of freedom to produce controlled movement Bernstein (1967). Turvey expressed the redundancy problem that expands on what Bernstein may have meant by mastering redundant degrees of freedom. As put by Turvey, "... every movement comprises a state space of many dimensions; the problem of coordination, therefore, is that of compressing such high-dimensional state spaces into state spaces of very few dimensions" Turvey (1990, pp. 938–939). The task of compressing redundant information into useful low-dimensional information represents a significant challenge to studies of coordination.

Intuitively, researchers have looked for answers to how coherent macroscopic behavior in human movement is achieved from apparent disorder at the microscopic level, in theories of complex physical systems (for example, chaos theory and dynamical systems theory). From physical systems the concept of self-organization states that a system's components can coalesce to produce organized behavior without the intervention of an outside agent. Under the framework of coordination dynamics, concepts have been developed to relate physical systems to neurobiological systems. According to coordination dynamics, the *collective variable* specifies the relationships among the interacting components of the system Bressler and Kelso (2001). Often the collective variable represents the relative phase between two oscillating components of the system. The *control parameter* is a variable that leads the system through a range of coordinative states, which are measured using the collective variable. Haken, Kelso, and Bunz (1985) conducted an experiment involving coordinated index finger movements of both hands. In the experiment, participants oscillated their fingers either in-phase or in anti-phase. If the participant began in an anti-phase state of coordination and the oscillation frequency (the control variable) was increased, a sudden switch to in-phase coordination occurred at a critical frequency. The sudden switch in coordination was marked by instability, measured by an increase in variability in the relative phase of the oscillating fingers (the collective variable). If, however, the participant began oscillating in in-phase coordination, no change in coordination was seen when oscillation frequency increased. The lack of change in coordination from in-phase to anti-phase implied that the in-phase patterning of movements was stable for all tested values of the control parameter, while anti-phase coordination was only stable at lower frequencies. Moreover, since in-phase coordination was stable for low and high frequencies, when the frequency decreased, no spontaneous shift back to anti-phase coordination from in-phase coordination occurred.

A visualization of a ball rolling on a landscape composed of one or many valleys – usually called *basins* – has been used to illustrate coordination stability Haken et al. (1985). A deep basin represents stable coordination and a shallow basin represents relatively unstable coordination. There can be many basins of attraction for a system, representing many possible coordination states. For the ball to move from one basin to another, the system must be perturbed. Accordingly, a stronger perturbation is required to unsettle a stable state of coordination compared to a less stable state. Once perturbed sufficiently the ball may settle in a different basin, representative of a different stable state of coordination.

The attractor basins have typically been used to depict the stability of coordination for cyclic bimanual movement tasks. However, the principles of discrete and cyclic movement generation may not be as closely related as once thought (Hogan & Sternad, 2007; Sternad & Schaal, 1999). Further, Rein, Davids, and Button (2010) have identified that there may be a task bias in experiments involving continuous cyclic movements of relatively few degrees of freedom. Although the task goal and the movement pattern may be coupled tightly in experiments of bimanual coordination, this may not necessarily be true for everyday tasks. Indeed, constraints imposed on laboratory bimanual movement tasks may limit the way in which new movements are patterned. Without the experimental constraints common in the bimanual coordination paradigm there may exist a larger set of possible