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A minimal limit-cycle model to profile movement patterns of individuals during agility drill performance: Effects of skill level

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ABSTRACT

Identification of control strategies during agility performance is significant in understanding movement behavior. This study aimed at providing a fundamental mathematical model for describing the motion of participants during an agility drill and to determine whether skill level constrained model components. Motion patterns of two groups of skilled and unskilled participants ($n = 8$ in each) during performance of a forward/backward agility drill modeled as limit-cycles. Participant movements were recorded by motion capture of a reflective marker attached to the sacrum of each individual. Graphical and regression analyses of movement kinematics in Hooke's plane, phase plane and velocity profile were performed to determine components of the models. Results showed that the models of both skilled and unskilled groups had terms from Duffing stiffness as well as Van der Pol damping oscillators. Data also indicated that the proposed models captured on average 97% of the variance for both skilled and unskilled groups. Findings from this study revealed the movement patterning associated with skilled and unskilled performance in a typical forward/backward agility drill which might be helpful for trainers and physiotherapists in enhancing agility.

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1. Introduction

Agility is an essential characteristic of physical activity, play and athletic performance in children and adults (Sheppard & Young, 2006). Agility is defined as the ability to decelerate, change direction and re-accelerate in minimum time (Vescovi, 2004; Wheeler, 2009). An individual athlete would therefore seek to coordinate and control actions under severe time constraint while performing the drill. Agility drills which are used to test how agile an individual is, primarily consist repetitive execution of movement patterns. In sport and physical activity, it has been suggested that trainers should organize agility trainings according to athletic skill levels (Holmberg, 2009). These suggestions are impractical since the control strategies of individuals during performance of an agility drill have never been fully explored or understood. In other words, it is unclear how individuals of different skill levels control body motion trajectory and velocity while seeking to reduce performance time. Currently, the only measure of athletic performance during an agility drill is the drill time or duration. However, although the drill time could provide a global measure of the individuals' behavior, it does not fully reveal the underlying mechanisms of motion control (Bootsma, Fernandez, & Mottet, 2004). To this effect, a new approach which can quantitatively capture the dynamics of movement through studying the motion pattern of athletes could be helpful in analysis of agility performance. In the first instance, a suitable mathematical model could provide a reliable portrayal of control strategies governing agility performance, especially in participants differentiated by experience and skill level. Agility drills are commonly made up of repetitive motion patterns which could be considered as rhythmic tasks, captured by the ubiquitous forward/backward running shuttle drill. Here, the dynamics of rhythmic movements were adopted to provide a mathematical description of human motion in an agility drill.

In terms of model development, many studies have considered rhythmic movements in humans as self-sustained oscillators modeled as limit-cycles (Beek & Beek, 1988; Cignetti, Schena, Mottet, & Rouard, 2010; Delignieres, Nourrit, Deschamps, Lauriot, & Caillou, 1999; Kay, Kelso, Saltzman, & Schöner, 1987; Mottet & Bootsma, 1999, 2001; Tlili, Babault, & Mottet, 2005). These studies are based on the assumption that the human central nervous system employs limit-cycle dynamics to generate rhythmic movements (Delignieres et al., 1999). Here, the objective is to propose a macroscopic model with a minimum number of variables capable of characterizing the dynamics of rhythmic movements (Delignieres et al., 1999; Tlili et al., 2005). Since macroscopic organization is the result of nonlinear interactions between microscopic components of the system, it could be argued that the proposed macroscopic model could capture the interaction of neural and biomechanical elements of the human movement system (Delignieres et al., 1999). Rhythmic movements can be described using second-order ordinary differential equations encompassing stiffness and damping properties of the movement (Delignieres et al., 1999; Tlili et al., 2005). The stiffness function shows the mass-spring properties of the movement, while the damping function describes the energy flow process (Tlili et al., 2005). Therefore, an important goal is to identify the stiffness and damping functions of the model (Beek & Beek, 1988). Three types of nonlinear oscillators are commonly adopted to describe stiffness and damping functions (Beek & Beek, 1988). In particular, for the stiffness function, the nonlinearity takes the shape of a Duffing oscillator ($x^3, x^5, x^7, \ldots$) and for the damping function, the nonlinear terms take the shape of Van der Pol ($x^2\dot{x}, x^4\dot{x}, x^6\dot{x}, \ldots$) and/or Rayleigh ($\dot{x}^3, \dot{x}^5, \dot{x}^7, \ldots$) oscillators. However, Terms from other series expansions, called π-mix series (even terms: $x^2\dot{x}^3, x^4\dot{x}^4, \ldots$ odd terms: $x^3\dot{x}^2, x^3\dot{x}^4, \ldots$) might also be adopted in the limit-cycle model of biological movements (Beek & Beek, 1988).

To identify these functions, Beek and Beek (1988) introduced the W-method which consists of two graphical and regression analyses steps. In the graphical analysis step, the Hooke's plane (acceleration vs. position), phase plane (velocity vs. position) and velocity time pattern (velocity vs. time) of the movement are visually examined to identify characteristics resembling those of the outlined oscillators. Recognition of resemblance results in a plausible limit-cycle model. In the regression analysis step, model coefficients are determined by applying a regression of all terms in the proposed model to the acceleration time series (for details on W-method, see Section 2). Previous studies have proposed limit-cycle models for rhythmic motion patterns such as arm movements (Beek & Beek, 1988), arm pendulum swinging (Beek, Schmidt, Morris, Sim, & Turvey, 1995), pointing tasks