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A Minimal Limit-cycle Model to profile movement patterns of Athletes during Agility Drill performance: Effects of Skill level

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Abstract

The aim of this study was to provide a fundamental mathematical model for the motion of participants in a forward/backward agility drill and to determine whether skill level effects constrained model components. Coordination patterns of two groups of skilled and unskilled participants (n=8 in each) in a forward/backward agility drill were considered as self-sustained oscillators modeled as limit-cycles. Participant movement was recorded by motion capture of a reflective marker attached to the sacrum of each individual. Graphical analysis of movement kinematics in Hook's plane, phase planes and velocity profiles was performed to determine linear and nonlinear components of the models. Follow up regression analysis determined the contribution of each component. Results showed that the models of both skilled and unskilled groups, although differing, had terms from Duffing stiffness as well as Van der Pol and Rayleigh damping oscillators. Data also indicated that the proposed models captured on average 92% and 94% of the variance for skilled and unskilled groups, respectively. Findings from this study could reveal the movement patterning associated with skilled and unskilled performance in a typical forward/backward agility drill which might be helpful for sport practitioners in training agility.

Introduction

Agility is an essential characteristic of athletic performance in various field and indoor sports (Sheppard and Young 2006). Agility drills primarily consist of repetitive execution of movement patterns involving deceleration, change of direction and re-acceleration phases. It has been argued that a skilled athlete can perform an agility drill in a short period of time while exhibiting good control of motion (Vescovi 2004; Wheeler 2009). It has also been suggested that trainers should organize agility training according to athletic skill levels (Holmberg 2009). These suggestions are inconclusive since assigning appropriate training, based on skill level, does not always follow a systematic or well established set of rules (Holmberg 2009). The control strategies of athletes during performance of an agility drill have never been fully explored or understood. Primarily, it is unclear how individuals of different skill levels control body motion trajectory and velocity to optimize movement stability while aiming to reduce performance time. In the first instance, a suitable mathematical model could provide a reliable portrayal of control mechanisms governing performance in an agility drill, 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 (e.g., Kay, Kelso et al. 1987; Beek and Beek 1988; Delignieres, Nourrit et al. 1999; Mottet and Bootsma 1999; Mottet and Bootsma 2001; Tlili, Babault et al. 2005; Cignetti, Schena et al. 2010). These studies are based on the assumption that the human central nervous system employs limit-cycle dynamics to generate rhythmic movements (Delignieres, Nourrit 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, Nourrit et al. 1999; Tlili, Babault 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, Nourrit et al. 1999). Rhythmic movements can be described using second-order ordinary differential equations encompassing stiffness and damping properties of the movement (Delignieres, Nourrit et al. 1999; Tlili, Babault et al. 2005). The stiffness function shows the mass-spring properties of the movement, while the damping function indicates the energy flow of the system in maintaining stability (Tlili, Babault et al. 2005). The nature of biological movements is such that only three types of nonlinear oscillators could be adopted to describe stiffness and damping functions (Beek and Beek 1988). In particular, for 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. Therefore, an importantgoal is to identify the stiffness and damping functions of the model (Beek and Beek 1988).

To identify these functions, (Beek and Beek 1988) and (Mottet and Bootsma 1999) introduced the W-method which consists of two graphical and regression analyses steps. In the graphical analysis step, the Hook'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 three 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 the Methods section). Other studies have also proposed limit-cycle models for rhythmic coordination patternss such as arm movements (Beek and Beek 1988), arm pendulum swinging (Beek, Schmidt et al. 1995), pointing tasks (Mottet and Bootsma 1999; Mottet and Bootsma 2001), basketball-bouncing (Tlili, Babault et al. 2005) and also skiing (Delignieres, Nourrit et al. 1999; Cignetti, Schena et al. 2010).

Based on these ideas, the motion pattern of an athlete performing a repetitive agility drill could be considered as a self-sustained oscillator modeled by a limit-cycle. That is, to control stability of movement in an agility drill, athletes should manage flow of energy during three key phases of acceleration, deceleration and change of direction. The mechanism governing control of these energy flows could be described through stiffness and damping functions. It is therefore possible to represent the control strategies adopted by an athlete during performance of an agility drill by limit cycles with appropriate stiffness and damping terms. However, this control strategy is also likely to be affected by individual skill level. The implications being that the limit-cycle model might be different for athletes with different skill level.

The aim of this study was to provide mathematical models to investigate control mechanisms of the performance of groups of skilled and unskilled participants during performance of a forward/backward agility drill and to determine how model components might vary between the two groups. To this aim, the movement coordination patterns of athletes during performance of this specific agility drill were considered as self-sustained oscillators modeled as limit-cycles.

Methods

Participants

This study involved two groups of male participants, each with 8 members. The distinction between the two groups was defined by performance evaluation on a standard agility test (Illinois agility test), habitual levels of physical activity and previous experience of agility training. The first group consisted of sport science students with regular agility training as part of their physical education program, aged 23.2±1.8 yrs (mean±s) with average mass and height of 70.6±5.1 kg and 1.76±0.25m, respectively. They were also members of the varsity soccer team. In addition, they had received 4.6±1.2 hour/week agility training for the past two years. Members of the first group were considered skilled participants because of their experience in regular agility training. The second group consisted of college students with no regular agility training experiences and little previous experience of sporting activities. They were aged 23.2±3.4 yrs and had an average mass and height of 68.1±11.6 kg, 1.73±0.06 m, respectively. These individuals were considered unskilled due to lack of any agility training. In addition, the results of performance on a standard agility test showed that skilled group performed the drill in a significantly shorter period of duration ($P<0.05$). Demographics of the two groups were similar (P-values were 1.00, 0.34 and 0.8 for age, height and mass, respectively) and thus were considered not to influence the results. All participants declared themselves free from any musculoskeletal injuries at the time of experiments, and all provided written informed consent before participation in the study. The ethics committee of Amirkabir University of Technology approved the experimental procedure.

Marker placement

This study was a part of broader program of work on agility skill, and five passive reflective markers (14 mm diameter) were attached to the skin of each participant’s right hand side of the body on the bony landmarks at the head of 2nd metatarsal bone (foot), lateral malleolus (ankle), lateral epicondyle of femur (knee), greater trochanter (hip) and S1 vertebrae. However, for the purpose of this study, the S1 marker was used to represent the whole body motion during the drill execution. All marker placements were carried out by the same experienced operator responsible for using the Vicon® motion analysis system (Oxford Metrics, Oxford, UK).

Task

All participants repeated a 10-cycle forward/backward shuttle agility test (Figure 1). One complete cycle was defined as a forward run from cone 1 to 2 followed by backpedalling to cone 1. This test was designed because forward and backward running are common movement patterns in many team sports. A certified trainer approved and supervised the testing session. Participants performed a supervised 10-minute pre-test warm-up before performing the drill. Athletes were not allowed to change direction before reaching the target, otherwise the cycle would be viewed as incomplete and the task had to be repeated. All participants had enough time to become familiar with the test before participating in the actual test. All agility tests took place on the same indoor surface floor. The tests were all carried out on the same day. Individual participants were asked to perform the tests twice and the best performances were adopted for the consequent analyses.

Data recording

The three-dimensional coordinate data of the markers were recorded using five Vicon® VCAM motion capture calibrated cameras (Oxford Metrics, Oxford, UK) at the sampling frequency of 200 samples/second. Camera placements and the experimental setup are shown in Figure 1.

Reconstruction and labeling were performed using Vicon® Workstation software (Oxford Metrics, Oxford, UK).

Data Analysis

Kinematic data obtained from S1 marker in the Anterior-posterior direction of motion were used to derive the limit-cycle model. Position data were first filtered using a fourth-order low-pass Butterworth filter with 10 Hz cutoff frequency. The first and second derivatives of the filtered position time series were calculated using a three-point difference method. The individual cycles were identified and separated by applying a peak-picking algorithm on position data. For all participants, kinematic data (i.e. position, velocity and acceleration) for individual cycles were time-normalized to 100 data points. In addition, to eliminate possible effects of movement amplitude on the ensuing comparisons, kinematic data for each individual cycle was range-normalized (Cignetti, Schena et al. 2010). Amplitude of all kinematic data after normalizations was consequently made to reside between -1 and 1. These normalizations ensured that the data associated with different participants were comparable (Mottet and Bootsma 1999; Cignetti, Schena et al. 2010). Furthermore, for each individual, the ensemble averages of kinematic data were calculated by averaging each data point over 8 cycles (the first and last cycles were omitted due to inconsistencies). Finally, kinematic data weresummarized in group means by averaging the ensemble kinematic data of individuals. These averages were deemed to produce the best representation of the underlying dynamical system by eliminating system noise (Mottet and Bootsma 1999; Cignetti, Schena et al. 2010).

Modeling approach

To propose a dynamical model for the motion of participants in this agility drill, the W-method introduced (Beek and Beek 1988) and adapted in previous work(Mottet and Bootsma 1999) was implemented. This method is based on two assumptions which are widely accepted in the literature. First, it is assumed that the human central nervous system implements limit-cycle dynamics to generate rhythmic movements (Tlili, Babault et al. 2005), and second, that micro-scale fluctuations are the result of random noise in the system (Delignieres, Nourrit et al. 1999; Mottet and Bootsma 1999; Mottet and Bootsma 2001; Cignetti, Schena et al. 2010).

Based on these assumptions, the motion of an athlete during an agility drill could be expressed as a second-order differential equation with fixed origin, mass and main frequency in the form of expression 1:

$$\ddot{x} + F(x, \dot{x}) = 0 \tag{1}$$

where x is the spatial deviation from the origin and F is a function which summarizes all linear and nonlinear stiffness and damping terms with differentiations taking place with respect to time. The first step in the W-method is a qualitative assessment of graphical representations to gain insight into the linear and/or nonlinear components (Beek and Beek 1988; Mottet and Bootsma 1999; Mottet and Bootsma 2001; Cignetti, Schena et al. 2010). There are three representations which are mostly adopted for graphical assessments (Mottet and Bootsma 1999). The first is the Hook's plane (i.e. acceleration vs. position) representing the stiffness term in the model. A purely linear system is represented by a straight line in the Hook's plane. Therefore, any nonlinearity results in deviations from a straight line. Hook's plane could also provide an estimate of the percentage variance associated with the contribution of nonlinear components

(NL) to the model. This model outcome is achieved by calculating $NL=1-R^2$, where R^2 is the coefficient of determination of the acceleration vs. position linear regression (Mottet and Bootsma 1999). The second representation is the phase plane (i.e. velocity vs. position) which provides an impression of the nonlinear damping components in the model. A purely linear system is represented by a circle in the phase plane. Therefore, any deviation from circular shapes in the phase plane implies that nonlinear damping terms should be considered in the model. The third representation is the velocity time pattern (i.e. velocity vs. time) which could help in identifying damping components of the model.

However, it has been reported that identifying nonlinear damping using such graphical methods is not as straight-forward as nonlinear stiffness (Delignieres, Nourrit et al. 1999). Therefore, an additional graphical method introduced by (Beek and Beek 1988) and later utilized by (Delignieres, Nourrit et al. 1999) was implemented in this study. Here, the contribution of nonlinear damping terms was isolated by applying a regression of all linear and nonlinear stiffness along with linear damping terms, to acceleration data. Regression residual (RES) should, thus, primarily represent characteristics of nonlinear damping components. It is, therefore, possible to recognize damping components by: a) identifing the Van der Pol limit cycle by plotting RES/velocity vs. position, expecting a parabola, and then b), identifying the Rayleigh limit cycle by plotting RES vs. velocity, expecting an N shape (Beek and Beek 1988; Delignieres, Nourrit et al. 1999). The second and final stage of the W-method was to determine the coefficients in the estimated model, achieved through application of a multiple linear regression of all components to the acceleration data.

Results

Graphical analysis and model proposition

Figure 2 represents the Hook's plane (top), phase plane (middle) and velocity time patterns (down) for skilled (left) and unskilled (right) participants. The figure indicates tangible deviations from a straight line, thus pointing to the existence of nonlinearity in the motion patterns of both groups of athletes. This observation implies that nonlinear terms should be included in the associated limit-cycle models. The contribution of this nonlinearity was quantified using the NL measure. NL was, thus, determined to be 0.16±0.04 and 0.13±0.12 for the skilled and unskilled groups, respectively.

Furthermore, it is possible from the Hook's plane representation to identify the nonlinear stiffness term. As depicted in Figure 2, for the unskilled group, local stiffness decreases at close proximities to the change of direction points, with the ensuing shape resembling that of an N. This finding showed that a cubic stiffness (i.e. Duffing) term with negative sign $(-x^3)$ should be included in the model. For the skilled group on the other hand, local stiffness tended to increase near change of direction (i.e. reversal) points in Hook's plane, implying the existence of a cubic Duffing term with positive sign $(+x^3)$ in the model. In addition, the asymmetry between half-cycles in the Hook's plane for both groups indicated that nonlinear damping terms should also be considered in the model.

As discussed in the Methods section, the phase planes and velocity time patterns are useful to identify nonlinear damping components of the model. However, visual inspection of these two figures did not help in recognition of nonlinear damping terms. We, thus, employed the method of residuals (RES) explained in the Methods section. Figure 3 shows the plots of RES/$\dot{x}$ vs. x

(shown on top) and RES vs. $\dot{x}$ (down) for two groups of skilled (left column) and unskilled (right).

For the unskilled group, the plot of RES/$\dot{x}$ vs. x exhibited parabolic features pointing towards a general Van der Pol equation ($x^2\dot{x}$). For the skilled group on the other hand, the plot of RES/$\dot{x}$ vs. x contained adouble minima, indicating the presence of a quadratic Van der Pol term ($x^2\dot{x} + x^4\dot{x}$). Further consideration of the plot of RES vs. $\dot{x}$ for the unskilled group, shed light on the presence of two N shapes suggesting that a quintic term ($\dot{x}^3 + \dot{x}^5$) should be added to cater for the Rayleigh damping. For the skilled group on the other hand, an N shape was identified suggesting the need for inclusion of a Rayleigh damping term ($\dot{x}^3$).

Finally, considering all linear and nonlinear stiffness and damping terms, the limit-cycle models for skilled and unskilled groups could be presented by expressions (2) and (3), respectively:

$$\ddot{x} + c_{10}x + c_{01}\dot{x} + c_{30}x^3 + c_{03}\dot{x}^3 + c_{21}x^2\dot{x} + c_{41}x^4\dot{x} = 0 \quad (2)$$

$$\ddot{x} + c_{10}x + c_{01}\dot{x} + c_{30}x^3 + c_{03}\dot{x}^3 + c_{05}\dot{x}^5 + c_{21}x^2\dot{x} = 0 \quad (3)$$

where c_{ij} are coefficients of $x^i\dot{x}^j$ according to W-method (Beek and Beek 1988). In the proposed models, c_{10} should have a positive sign while c_{01} should have a negative sign to produce a limit-cycle. In addition, at least the sign of one of the Rayleigh (c_{03}, c_{05}) and Van der Pol terms (c_{21}, c_{41}) should be opposite to the sign of linear damping term. Finally, as pointed out previously, the sign of the nonlinear stiffness term (c_{30}) should be positive for skilled and negative for unskilled groups.

Regression analysis

The results of a regression analysis on the data for skilled and unskilled groups are presented in Tables 1 and 2. The coefficients of determination (R^2) were on average 0.92±0.06 and 0.95±0.04 for the skilled and unskilled groups respectively. In the skilled group, all participants' coefficient values obeyed the proposed model. In addition, the sign of all coefficients were in accordance with mathematical requirements discussed earlier. That is, $c_{01}$was negative and $c_{30}$was positive as expected. Furthermore, the sign of nonlinear damping terms (c_{03}, $c_{21}$and c_{41}) was opposite to the linear damping term (c_{01}). In the unskilled group, however, not all participant data obeyed the proposed model tenets. That is, while performance data from five participants obeyed the estimated model (S1, S3, S4, S7 and S8), three participants (S2, S5 and S6) revealed different limit-cycle models from the estimated model. However, the sign of all coefficients was in accordance with the expected sign conventions discussed earlier.

Discussion

The aim of this study was to provide fundamental mathematical models to investigate control mechanisms in performance of a forward/backward agility drill in participants of differing skill levels. To this effect, the motion pattern of the marker placed on S1 in two groups of skilled and unskilled participants during performance of a forward/backward agility drill revealed rhythmic self-sustained oscillating characteristics. Such distinctive features could be characterized using limit-cycle models, which were consequently adopted to characterize motion patterns in this study. The ensuing limit-cycle models of agility drill performance exhibited nonlinearities exemplified by Duffing Stiffness terms along with both Van der Pol and Rayleigh damping terms. The limit-cycle models for skilled and unskilled groups, however, differed in the contributions of individual terms. These models portrayed on average 92% and 94% of the performance variance for skilled and unskilled individuals, respectively.

It has been shown that the signs of cubic stiffness terms are responsible for controlling the movement near reversal points during task performance (Mottet and Bootsma 1999; Mottet and Bootsma 2001; Cignetti, Schena et al. 2010). The sign of the cubic stiffness term (x^3) in this study was found to be different for skilled and unskilled participants (Tables 1 and 2) suggesting that the two groups implemented different control strategies near change of direction points.

The negative sign of the cubic stiffness term for unskilled participants implied that they exhibited tendencies to behave like a softening spring close to reversal points (i.e. local stiffness decreases near reversal points; Figure 2). In other words, the negative sign indicated a slowing down of movement near reversal points to prevent local spatial variability from increasing (Mottet and Bootsma 1999; Mottet and Bootsma 2001) and postural stability to be maintained (Delignieres, Nourrit et al. 1999). A softening spring has invariably been encountered in the limit-cycle models for many precision aiming tasks (Mottet and Bootsma 1999), implying that an agility drill can be similarly categorised The positive cubic stiffness term associated with the performance of skilled participants on the other hand, implied that they behaved like a hardening spring close to direction change points where local stiffness values increased. Increases of local stiffness values could lead to an increase in variability to facilitate switching between forward and backward motion patterns, a viable performance strategy for reducing contact time.

In addition, it has been argued that the damping terms show the energy flow of the system (Tlili, Babault et al. 2005) to sustain task stability (Delignieres, Nourrit et al. 1999; Tlili, Babault et al.

2005). However, the Rayleigh and Van der Pol damping oscillators act differently in sustaining the stability of the motion pattern. That is, in a Rayleigh oscillator ($\dot{x}^3, \dot{x}^5, \ldots$) stability emerges from velocity information, while in a Van der Pol oscillator ($x^2\dot{x}, x^4\dot{x}, \ldots$), emergence of stability is the result of both velocity and position information (Tlili, Babault et al. 2005). In our study, skilled and unskilled participants displayed terms from both Rayleigh and Van der Pol oscillators, with the orders of these terms differing between the two groups. In particular, for unskilled participants, the Rayleigh component had an additional quintic term ($\dot{x}^5$), while for skilled participants, the Van der Pol component had an additional quadratic term ($x^4\dot{x}$). From one point of view, the inclusion of a quadratic Van der pol term in the performance model of skilled participants could suggest that this group of participants relied more on position rather than velocity information. On the other hand, for unskilled participants, the inclusion of a quintic Rayleigh term might imply that these participants relied more on velocity rather than position information.

From another point of view, adding a quintic term to the equation of Rayleigh oscillator results in state space being more skewed to the second and fourth quadrants which means that peak velocity occurs earlier in the half-cycles. Furthermore, adding a quadratic Van der Pol to the associated equation results in state space being more skewed towards the first and third quadrants. This in turn, means that peak velocities occur later in the half-cycles. In an agility drill, better performance is associated with longer acceleration time. The results of this study on damping terms of the models confirmed this argument. That is, skilled participants who displayed better performance in our study, also showed additional Van der Pol nonlinear damping terms indicative of longer acceleration periods.

In summary, the method adopted in the present study, which included both graphical and regression analyses, was capable of capturing the organizational dynamics of motion control in an agility drill both from qualitative (i.e. sign constraints) and quantitative (i.e. regression accuracy) perspectives. This study provided evidence that skilled and unskilled participants used different strategies to control movements in a forward/backward agility drill. This difference was observed during both forcing (damping terms) and braking (stiffness terms) phases of the drill. The limit-cycle model of skilled athletes revealed a picture of behavioral characteristics (i.e. stiffness and damping) associated with functional performance in forward/backward agility drill. The model could thus direct practitioners towards suitable training programs to improve agility of athletes.

It is worth noting a number of small limitations associated with this study. First, the performance of three unskilled participants did not follow the corresponding model. The small number of participants involved in this study limits explanations of such inconsistencies. The result might also differ in performance of other agility drills which require different movement patterns. Data reported here were unique to performance of forward/backward agility drills. Finally, inclusion of higher-order terms could result in more precise models for the performance of the two groups. However, this would contradict the minimality criterion for the models.

Conclusion

Here we provided mathematical models to characterise control mechanisms during performance in a forward/backward agility drill. Results demonstrated that the proposed models were capable of explaining the dynamics of control mechanisms, both from qualitative (i.e. sign constraints) and quantitative (i.e. regression accuracy) points of view. Data indicated that skilled and unskilled participants adopted different strategies to control the movement, observed during both forcing (damping terms) and braking (stiffness terms) phases of the drill. The limit-cycle models revealed behavioral characteristics specifically associated with skilled and unskilled performance in forward/backward agility drill. Findings of this study could be applied by exercise scientists and conditioning specialists to assign appropriate training regimes to individualized athletic performance enhancement programs.

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References:

Beek, P. J. and W. J. Beek (1988). "Tools for constructing dynamical models of rhythmic movement." Human Movement Science **7**(2-4): 301-342.

Beek, P. J., R. C. Schmidt, et al. (1995). "Linear and nonlinear stiffness and friction in biological rhythmic movements." Biological Cybernetics **73**: 499-507.

Cignetti, F., F. Schena, et al. (2010). "A limit-cycle model of leg movements in cross-country skiing and its adjustments with fatigue." Human Movement Science **29**(4): 590-604.

Delignieres, D., D. Nourrit, et al. (1999). "E€ ects of practice and task constraints on sti€ ness and friction functions in biological movements." Human Movement Science **18**: 769-793.

Holmberg, P. (2009). "Agility Training for Experienced Athletes: A Dynamical Systems Approach." Strength and Conditioning Journal **31**(5): 73-78.

Kay, B. A., J. A. Kelso, et al. (1987). "Space-time behavior of single and bimanual rhythmical movements: data and limit cycle model." Journal of Experimental Psychology Human Perception and Performance **13**(2): 178-192.

Mottet, D. and R. J. Bootsma (1999). "The dynamics of goal-directed rhythmical aiming." Biological Cybernetics **80**: 235-245.

Mottet, D. and R. J. Bootsma (2001). "The dynamics of rhythmical aiming in 2D task space: relation between geometry and kinematics under examination." Human Movement Science **20**(3): 213-241.

Sheppard, J. M. and W. B. Young (2006). "Agility literature review: classifications, training and testing." Journal of Sports Sciences **24**(9): 919-932.

Tlili, M., N. Babault, et al. (2005). "A minimal limit-cycle model of hand kinematics in basket-ball-bouncing." Neuroscience Letters **382**(3): 201-205.

Vescovi, J. D. (2004). "Agility." NSCA hot topic series.

Wheeler, K. (2009). Agility skill execution in rugby union, University of Sunshine Coast. .

Tables:

Table 1: The stiffness and damping coefficients calculated for skilled participants.

	linear		**Duffing**	**Rayleigh**	**VanderPol**		**R^2**
	c_{10}	c_{01}	c_{30}	c_{03}	c_{21}	c_{41}	
S1	0.1	-0.07	0.6	0.14	0.14	0.7	0.92
S2	0.08	-0.2	0.48	0.34	-0.35	0.95	0.96
S3	0.12	-0.91	0.34	0.98	0.97	0.52	0.94
S4	0.38	-0.58	0.03	0.7	0.46	0.21	0.84
S5	0.03	-0.52	0.63	0.65	0.34	0.26	0.96
S6	0.1	-0.71	0.53	1.05	-0.27	1.38	0.96
S7	0.15	-2.2	0.52	2.86	2.24	0.12	0.97
S8	0.31	-0.45	0.18	0.53	0.6	-0.01	0.82
mean	**0.16**	**-0.71**	**0.41**	**0.91**	**0.52**	**0.52**	**0.92**
SD	**0.12**	**0.66**	**0.21**	**0.85**	**0.82**	**0.47**	**0.06**

Table 2: The stiffness and damping coefficients calculated for unskilled participants.

	linear		**Duffing**		**Rayleigh**		**VanderPol**	**R^2**
	c_{10}	c_{01}	c_{30}	c_{50}	c_{03}	c_{05}	c_{21}	
S1	0.86	-1.22	-0.28	-	2.19	-0.88	1.35	1
S2	0.87	-0.17	-1.06	0.41	-	-	0.33	0.94
S3	0.5	-1.11	-0.07	-	2.42	-1.2	1.1	0.89
S4	0.42	-0.46	-0.09	-	0.75	-0.22	0.54	0.91
S5	0.69	-0.14	-1.04	0.69	-	-	0.12	0.94
S6	0.36	-0.11	-	-	0.45	-0.34	-	0.95
S7	0.59	-1.82	-0.06	-	3.02	-0.9	1.92	0.98
S8	0.57	-0.71	-0.21	-	1.22	-0.47	0.79	0.98
mean	**0.61**	**-0.72**	**-0.40**	**0.55**	**1.68**	**-0.67**	**0.88**	**0.95**
SD	**0.19**	**0.62**	**0.45**	**0.20**	**1.02**	**0.38**	**0.63**	**0.04**

Figure captions:

Figure 1: Test setup used for this study. The markers are shown as white circles at foot, ankle, knee, hip and S1. For the purpose of this study however, only the S1 marker was used.

Figure 2: Normalized average cycle of Hook's plane (top), phase plane (middle) and velocity time pattern (down) for skilled (left) and unskilled (right) group.$\ddot{x}$, $\dot{x}$ and x denote acceleration, velocity and position, respectively and t is the time. The circles in the Hook's and phase planes show the starting position.

Figure 3: Scouting for Van der Pol and Ryleigh oscillators by plotting residuals (RES). (Top) plot of RES/$\dot{x}$ vs. x for scouting Van der Pol term, (down) plot of RES vs. $\dot{x}$ for scouting the Rayleigh term. For more details about the method, see the text.

Figures:

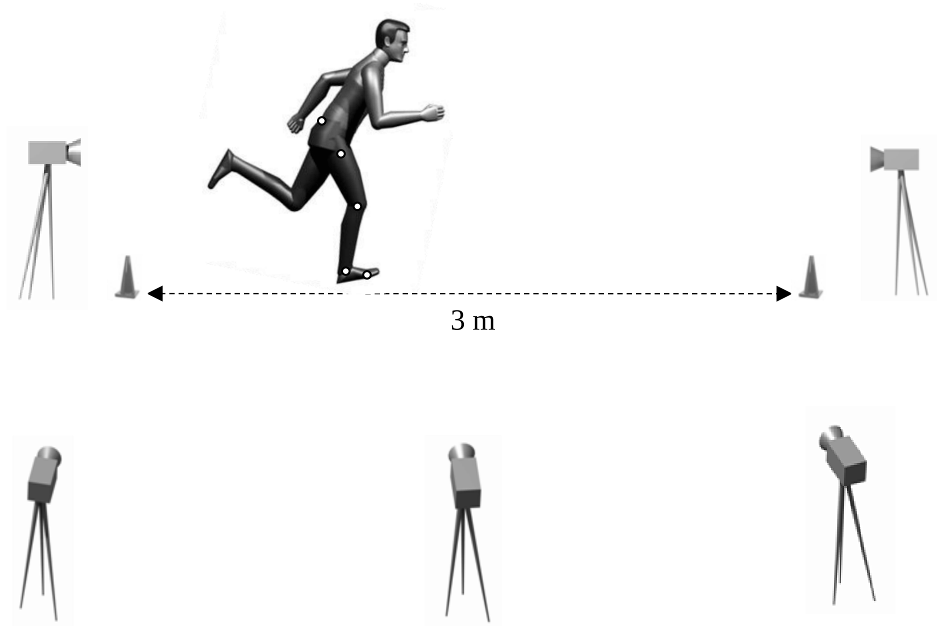

Figure 1

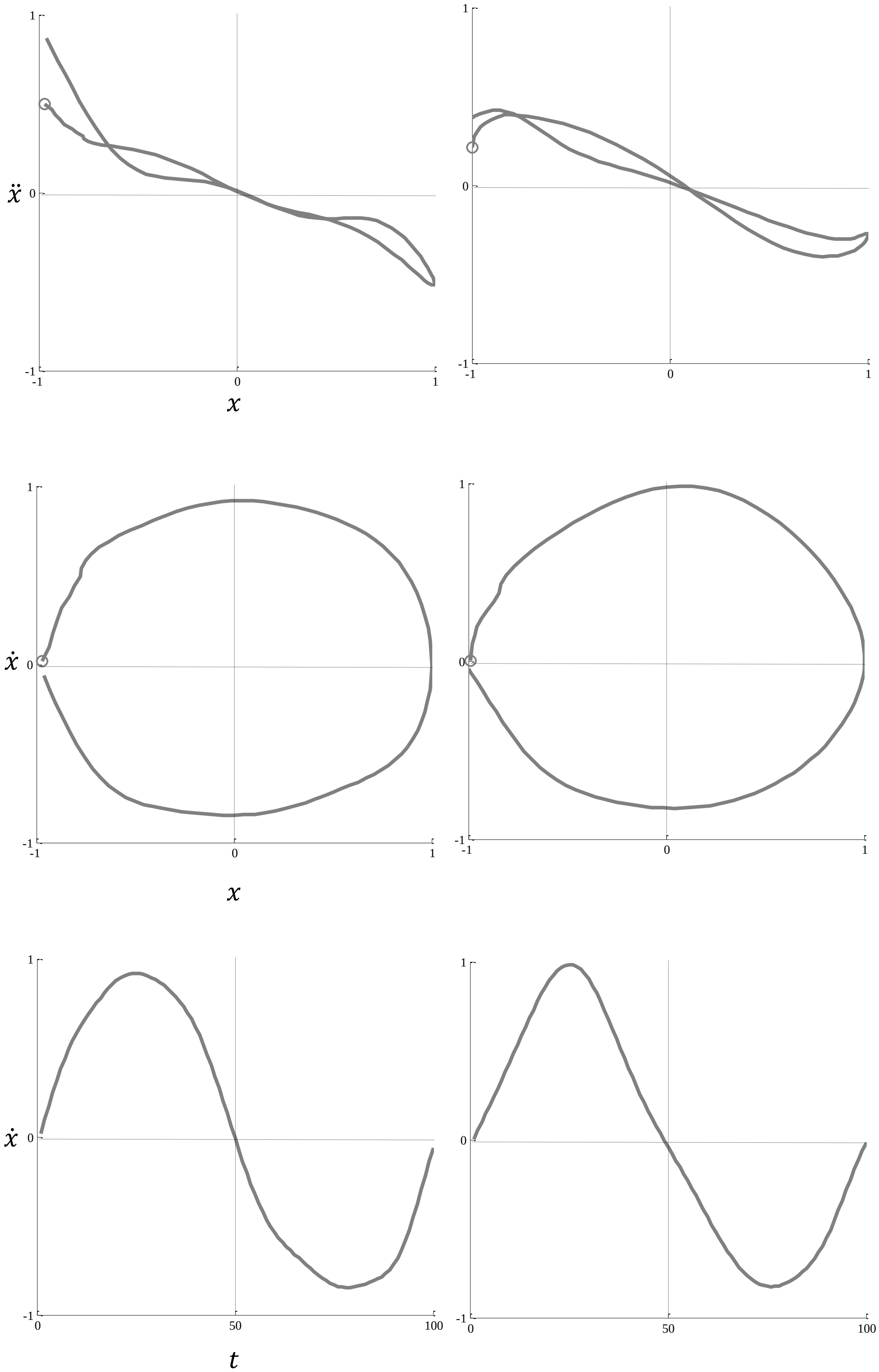

Figure 2

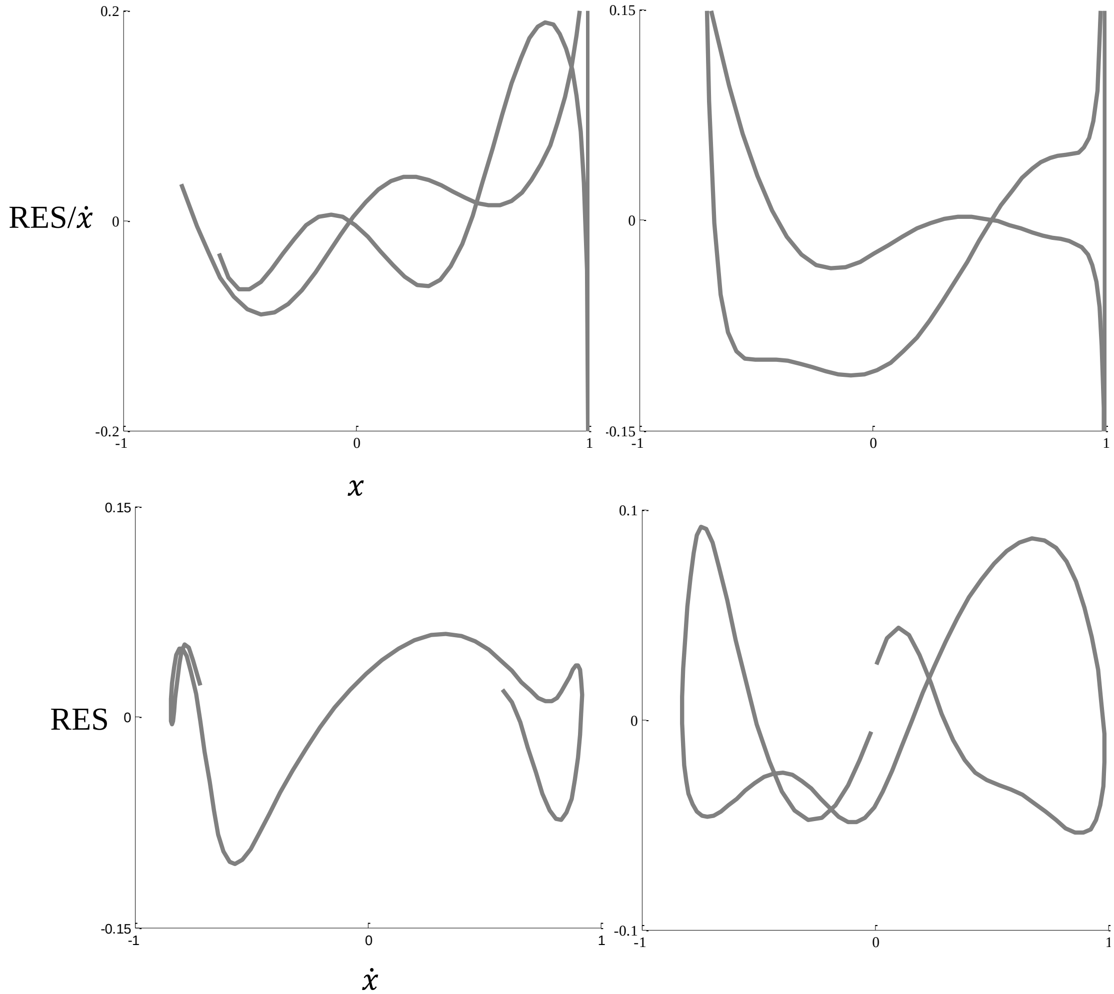
RES/$\dot{x}$
0.2
0
-0.2
-1
0
1
0.15
0
-0.15
-1
0
1
x
RES
0.15
0
-0.15
-1
0
1
0.1
0
-0.1
-1
0
1
$\dot{x}$

Figure 3