Acta of Bioengineering and Biomechanics
Vol. 16, No. 3, 2014

Original paper
DOI: 10.5277/abb140307

Quantification of stability in an agility drill using linear and nonlinear measures of variability

SINA MEHDIZADEH[1], AHMED REZA ARSHI[1]*, KEITH DAVIDS[2]

[1] Biomechanics and Sports Engineering Group, Faculty of Biomedical Engineering,
Amirkabir University of Technology, Tehran, Iran.
[2] Centre for Sports Engineering Research, Sheffield Hallam University UK
and School of Exercise and Nutrition Sciences,
Queensland University of Technology Australia.

This study implemented linear and nonlinear methods of measuring variability to determine differences in stability of two groups of skilled (n = 10) and unskilled (n = 10) participants performing 3m forward/backward shuttle agility drill. We also determined whether stability measures differed between the forward and backward segments of the drill. Finally, we sought to investigate whether local dynamic stability, measured using largest finite-time Lyapunov exponents, changed from distal to proximal lower extremity segments. Three-dimensional coordinates of five lower extremity markers data were recorded. Results revealed that the Lyapunov exponents were lower ($P < 0.05$) for skilled participants at all joint markers indicative of higher levels of local dynamic stability. Additionally, stability of motion did not differ between forward and backward segments of the drill ($P > 0.05$), signifying that almost the same control strategy was used in forward and backward directions by all participants, regardless of skill level. Furthermore, local dynamic stability increased from distal to proximal joints ($P < 0.05$) indicating that stability of proximal segments are prioritized by the neuromuscular control system. Finally, skilled participants displayed greater foot placement standard deviation values ($P < 0.05$), indicative of adaptation to task constraints. The results of this study provide new methods for sport scientists, coaches to characterize stability in agility drill performance.

Key words: *foot placement variability, largest finite-time Lyapunov exponent, local dynamic stability, standard deviation*

1. Introduction

Stability is an important component of agility in sport performance (Ross and Guskiewicz [19]; Wheeler [24]; Young and Farrow [25]) and it has been argued that a skilled athlete exhibiting competence in an agility drill may depend on stability (Vescovi [23]). However, there are a number of limitations in current understanding of the concept of stability in agility skill. The lack of a proper definition of stability, and an acceptable method for quantifying it in an agility drill, are most obvious. In addition, the effect of skill level on stability during an agility drill has not been considered. These issues are addressed in this paper.

In studies of human locomotion, stability is often related to falls risk (Bruijn [2]; Hamacher et al. [10]) and defined as the ability of a movement system to preserve its functional state (i.e., movement) in the presence of kinematic perturbations (England and Granata [6]). A strategy of the neuromuscular system to maintain stability (mostly in static conditions) is to try to keep the center of mass (COM) within the limits of the base of support (BOS). In performance of dynamic movements, it has been suggested that correc-

---

* Corresponding author: Ahmed Reza Arshi, Biomechanics and Sports Engineering Group, Faculty of Biomedical Engineering, Amirkabir University of Technology, Tehran, Iran, Hafez Ave., Tehran, Iran. Tel: +98-21-64542377, Fax: +98-21-66468186, e-mail: arshi@aut.ac.ir

Received: July 27th, 2013
Accepted for publication: November 19th, 2013

tive measures, such as appropriate foot placements, are required to keep the COM over the BOS (Hamacher et al. [10]). In other words, it has been argued that a proper anterior-posterior and medial-lateral foot placement at each step ensures stability in a movement (Balasubramanian et al. [1]). If, on the other hand, the foot contacts the ground in an inappropriate position, subsequent steps should correct this error by re-adjusting foot position. Attempts to adjust foot placement in consecutive steps in order to maintain stability can result in foot placement kinematic variability. Measurements of foot placement kinematic variability might, therefore, provide insights into attempts to maintain movement system stability during performance in dynamic tasks such as agility drills.

Both linear and nonlinear methods of measuring kinematic variability have been implemented in order to quantify stability of human movement. The linear method uses standard deviation of kinematic variability as an indication of stability (Hausdorff et al. [11]; Maki [17]). Research studies that implement the linear method argue that greater kinematic variability is associated with greater instability and greater risk of falling (Hausdorff et al. [11]; Maki [17]). Quantification of stability using linear methods as a measure of stability, however, has been questioned in the recent literature (Dingwell and Marin [5]; England and Granata [6]). That is, recent studies argued that the linear method only reports data on the magnitude of variability and does not indicate how the neuromuscular control system responds to perturbations (Dingwell and Marin [5]; England and Granata [6]). In other words, it has been proposed that the neuromuscular control system of human movement tries to maintain stability of movement by attenuating system perturbations from stride to stride (England and Granata [6]). Therefore, measuring the rate of attenuation of perturbations or the rate of decreasing of variability could be a more appropriate method of quantifying stability (Dingwell and Marin [5]; England and Granata [6]). Following this line of reasoning, it has been proposed that if a person could adapt to perturbations in one step, he/she might overcome perturbations in the following steps and will avoid falling (Bruijn [2]). In this approach, stability is quantified using nonlinear measures such as the largest finite-time Lyapunov Exponent (LyE). The LyE measures the exponential rate of divergence of neighboring trajectories of the state space constructed by kinematic data obtained from a movement system (Dingwell and Marin [5]; Rosenstein et al. [18]). This measure of stability is considered a local dynamic stability since LyE quantifies the ability to respond to small local perturbations during a movement (Dingwell and Marin [5]).

Based on the theoretical framework explained above, if an athlete were able to respond to local perturbations while performing an agility drill, he/she would probably preserve his/her state of motion (executing the drill) and avoid falling. Therefore, a proper response to perturbations and maintaining the state of motion could be considered as an indication of stability in an agility drill. However, it has been shown that due to decreased foot contact time (more ballistic motion), running is an action which is locally less stable than walking (Jordan et al. [12]). Since an agility drill is composed of running with maximal speed in different directions, it is expected that maintaining stability becomes more challenging for unskilled athletes. In other words, it seems that experienced athletes who tend to have better agility performance, should be more capable of adapting to stride-to-stride perturbations and thus demonstrate a more stable motion in an agility drill. Furthermore, different running patterns (e.g., forward or backward) in an agility drill may require different control strategies to maintain system stability. Therefore, levels of stability might be different in different motion patterns.

The objectives of the present study were, therefore, three-fold. The primary objective was to implement both linear (standard deviation) and nonlinear (LyE) methods of measuring foot placement variability to determine differences in stability between performance of an agility drill by groups of skilled and unskilled participants. Since running forward and then backward is a common movement pattern in many sports, a repetitive forward to backward shuttle run has been implemented for the purpose of this study. We hypothesized that skilled participants would show higher levels of dynamic stability in both the forward and backward parts of drill. The second objective was to determine whether stability measures differed between forward and backward segments of the drill. The third objective was to determine whether local dynamic stability (measured using LyE) changed from distal to proximal joints in the lower extremity. Three-dimensional kinematic data were recorded for stability analysis of lower body joints' motion in anterior/posterior (AP), medial/lateral (ML) and vertical (VT) components of motion, in the forward and backward segments of the drill.

2. Methods

Participants

This study involved two groups of male participants, each with 10 members. The distinction between the two groups was defined by evaluation with a standard agility test (Illinois agility test), levels of physical activity and experience of agility training. That is, to validate the skill level of the athletes, all participants performed a standard Illinois agility test on a separate day before the main testing session. In addition, to define participants' physical activity levels and their agility training experience, a questionnaire was administered to them in which they were asked to declare the amount of agility trainings they complete expressed in hour/week. The general inclusion criteria for participants included having no musculoskeletal injury at the time of the test in addition to wishing to participate in the study. Additionally, it was required for skilled participants to complete the standard Illinois agility test with an "above average" score according to the Davis et al. [4] classification. Unskilled participants were included in the study if they had performed the Illinois test with a "poor" score according to Davis et al. [4] classification. Participants were excluded from the study if they did not meet any of the above mentioned selection criteria. Data associated with anthropometric, Illinois agility test results and amount of training hours per week are presented in Table 1. The first group consisted of sport science students with regular agility training as part of their physical education program. They were also members of the varsity soccer team. Members of the first group were skilled participants because of the results of the standard agility test and their experience in regular agility training (Table 1). The second group consisted of college students with no regular agility training experiences (based on the results of questionnaire) and little previous experience of sporting activities. These individuals were considered unskilled due to the results of the standard agility test and their lack of any agility trainings (Table 1). Demographics of the two groups were similar (P-values were 0.74, 0.21 and 0.45 for age, height and mass, respectively) and thus would not influence the results. None of the participants suffered from any musculoskeletal injuries at the time of experiments. All participants provided written informed consent before participation in the study. The ethics committee of Amirkabir University of Technology approved the experimental procedure.

Marker placement

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. The marker set used in this study was based on that used in the studies of Kadaba et al. [13] and England and Granata [6], with some modifications to suit this study. The spatial-temporal motions of the markers in three dimensions were consequently recorded for further analysis. 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/back ward shuttle agility test (Fig. 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 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

Table 1. Mean (SD) of anthropometric, Illinois agility test and training hours of the two skilled and unskilled groups

	Age (years)	Mass (kg)	Height (m)	Illinois agility test (s)	Training hours per week
Skilled	22.8(1.8)	71.6(5.0)	1.77(0.04)	15.30(0.54)	4.6(1.2)
Unskilled	23.2(3.4)	68.1(11.6)	1.73(0.06).	27.40(2.32)	0

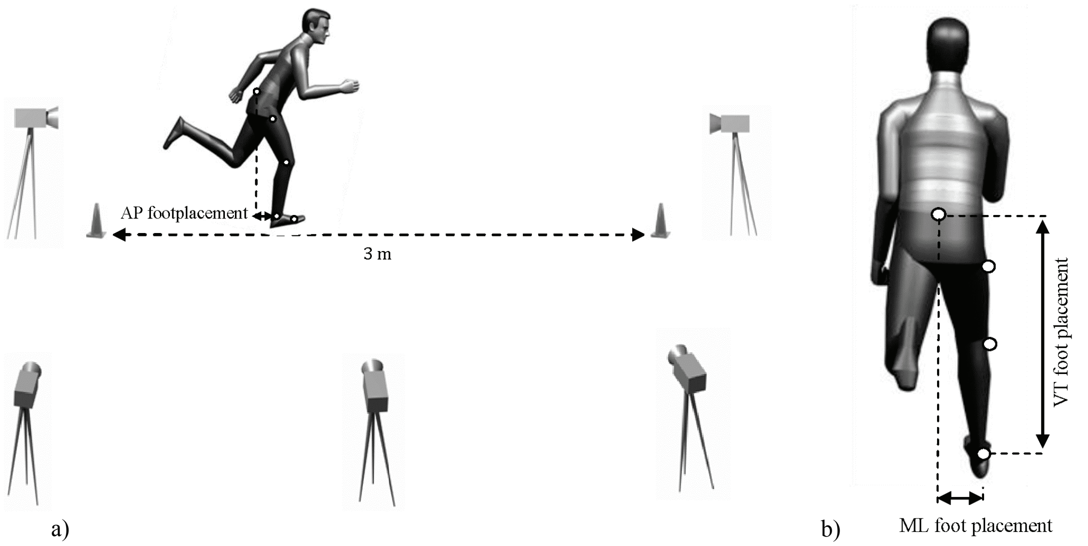

Fig. 1. (a) Test setup used for this study. The markers are shown as white circles at foot, ankle, knee, hip and S1; (b) schematic frontal plane view of an athlete performing the drill. AP, ML and VT foot placements are shown in the figure

perform the tests twice and the best performances were adopted for the stability analysis.

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 Fig. 1. Reconstruction and labeling were performed using Vicon® Workstation software (Oxford Metrics, Oxford, UK).

Data analysis

Data associated with x (AP), y (ML) and z (VT) components of the attached markers' motion were analyzed. The necessity of a stationary characteristic for nonlinear analysis of the time series data resulted in the adoption of velocity profiles for further analyses (Dingwell and Marin [5]; Kantz and Schreiber [15]). Although the common approach at this stage of analysis is to filter the signals obtained from movement system, possible loss of information at critical points prohibited implementation of any filtering algorithms (Kantz and Schreiber [15]). Furthermore, time series associated with the forward and backward segments of the drill were separated. The separation point was identified as the instance that S1 markers' velocity in sagittal plane changed direction. The separated forward time series of each cycle were then combined together to construct the forward motion time series. This task was also performed for backward motion. A total number of 15 consecutive strides were analyzed for forward and backward segments of the **motion**.

Since skilled and unskilled participants performed the drill with different velocities, time series of the two groups had different number of data points and were time normalized. It has been proposed that changing the time series length more than 50% could significantly affect the obtained LyE values (England and Granata [6]). In this study, all time series were time-normalized to each individual stride comprising 150 data points that resulted in less than 50% change in time series length. An equal number of strides was analyzed for both groups.

As the linear measure of variability, standard deviation (SD) of foot placement was calculated as follows. An ankle marker was used to calculate foot placement SD because of the foot marker's occlusion during certain parts of motion (Fig. 1). AP and ML foot placement SD were determined as the between-stride SD values of the distance between the ankle and S1 markers at heel strikes. Additionally, in this study, VT foot placement SD was also calculated as the between-stride SD value of the distance between the ankle and S1 marker in VT direction at heel strikes. Although the relationship between VT and the other two foot placement variability measures have not, as yet, been established, VT could indicate the variability of vertical positioning of the pelvis relative to the foot at each stride.

To quantify local dynamic stability (as the nonlinear measure of variability) first, an appropriate state space was reconstructed using equation (1)

$$X(t) = [x(t), x(t+\tau), x(t+2\tau), ..., x(t+(d_E-1)\tau)]^T \quad (1)$$

where $X(t)$ is the re-constructed state vector, $x(t)$ is the original velocity time vector, τ is the time delay and d_E is the dimension of the state space, i.e. the embedding dimension (Kantz and Schreiber [15]; Takens [22]). Time delay τ is determined as the first local minimum of Average Mutual information (AMI) function (Fraser [7]). The AMI is a statistical measure from theory of information that shows how much information about a random variable can be obtained from the information of another random variable (Shelhamer [21]). In this method, mutual information between a time series $x(t)$ and its time shift $x(t + \tau)$ is calculated for different values of τ until the mutual information is minimized (Shelhamer [21]). A time delay of 10 samples was found to be appropriate for data associated with the three x, y and z directions, respectively.

In addition, a Global False Nearest Neighbors (GFNN) measure was used to determine embedding dimension d_E (Kennel et al. [16]). False Nearest Neighbors are points which are close together in dimension d_E but not in dimension $d_E + 1$ (Shelhamer [21]). According to this method, the dimension is gradually increased until the number of false nearest neighbors is reduced to zero. For the purpose of this study, an embedding dimension of $d_E = 4$ was calculated for data associated with AP, ML and VT directions, respectively.

In order to quantify local dynamic stability, the largest finite-time Lyapunov Exponent (LyE) was determined from kinematic data (Fig. 2). The LyE measures the exponential rate of divergence of neighboring trajectories in the state space (Rosenstein et al. [18]). Since LyE measures the rate of divergence of the trajectories, a greater LyE value is indicative of lower local dynamic stability of the system. The approach implemented in this study was introduced by Rosenstein et al. [18] which is suitable for finite time series. Here, the largest finite-time Lyapunov exponent (λ_1) could be determined using equation (2)

$$d(t) = C\exp(\lambda_1 t) \tag{2}$$

where $d(t)$ is the average distance between neighboring points at time t, and the initial separation of the neighboring points is represented by C. According to expression (2), for the j-th pairs of neighboring points in state space we have

$$d_j(t) \approx C_j \exp(\lambda_1(i\Delta t)). \tag{3}$$

Taking the logarithm from both sides of (3) results in

$$\ln[d_j(i)] \approx \ln[C_j] + \lambda_1(i\Delta t). \tag{4}$$

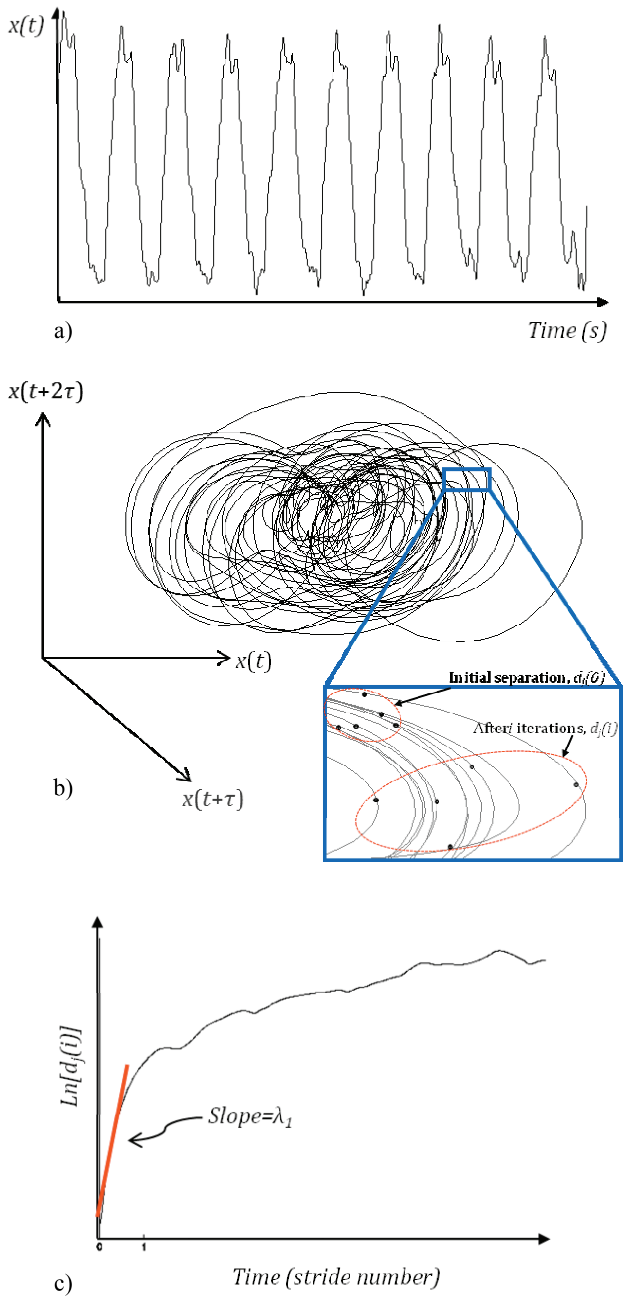

Fig. 2. State space reconstruction and local dynamic stability analysis of time series obtained from experiment; (a) original velocity time series $x(t)$, (b) 3D representation of state space reconstructed from time series $x(t)$ and its time copies $x(t + \tau)$, and $x(t+)$. Note that the dimension of state space might be greater than three but cannot be visually observed. The expanded view is a region of state space in which it is schematically shown that initial separation of j-th pairs of points, $d_j(0)$, diverge after i time steps shown by $d_j(i)$; (c) average logarithmic divergence of all pairs of neighboring points plotted over time (shown as stride number) to calculate LLyE. See text for further information

λ_1 is thus calculated through application of a linear fit to the following curve in the range $(i\Delta t)$) of 0 to 0.5 stride (Bruijn et al. [3])

$$y(i) = \left(\frac{1}{\Delta t}\right)\langle d_j(i)\rangle \tag{5}$$

where $\langle d_j(i)\rangle$ denotes the average over all pairs of j. In the present study, all LyEs were presented as the rate of divergence/stride.

Before analyzing the experimental data, the LyE algorithms were validated by feeding a Lorenz system with typical inputs to the algorithms and comparing the outcomes with the published results (Gates and Dingwell [8]; Graham et al. [9]; Rosenstein et al. [18]).

Statistical analysis

Separate two-way factorial analysis of variance (ANOVA) tests were applied to determine whether there was a significant difference in: (i) foot placement SD and LyE measures between the two groups; and (ii), between the measures in the forward and backward segments of the drill. Here, foot placement SD and LyE of ankle marker were considered as dependent variables and skill level (skilled vs. unskilled) and drill segment (forward vs. backward running) were independent variables. In addition, separate repeated-measures ANOVA tests were used to determine whether LyE changed significantly from distal to proximal joints of participants (Kang and Dingwell [14]). In these tests, LyE was again a dependent variable and joint type was an independent variable. Statistical significance levels were set at $p < 0.05$.

3. Results

Foot placement SD results

Data on foot placement SD in both groups are reported in Table 2. Results indicated a significant effect of skill level on AP, ML and VT foot placement SD (Table 2, $P < 0.05$) with skilled participants showing greater values of foot placement SD. On the other hand, the results indicated that drill segment (except in the AP direction, $P < 0.001$) did not affect foot placement SD ($P > 0.05$). In addition, there was no interaction effect ($P > 0.05$).

LyE results

For all AP, ML and VT directions, the main effect of skill level significantly changed λ_1 in all lower extremity joint markers ($P < 0.001$) except S1 ($P > 0.05$), with skilled participants displaying lower λ_1 values indicative of greater local dynamic stability. However, no significant effect of drill segment (forward vs. backward) was observed ($P > 0.05$). In addition, there were no significant interactions ($P > 0.05$). These results indicate that there were no differences in λ_1 between forward and backward parts of the drill for both groups (Table 2). In addition, ANOVA results showed that, except in the VT direction, λ_1 decreased significantly from distal to proximal joint markers in

Table 2. Mean (SD) and ANOVA results of foot placement SD and largest finite-time Lyapunov exponent (λ_1) for skilled and unskilled groups

Mean (SD) results						ANOVA results					
		Skilled		Unskilled		Skill level		Movement part		Interaction	
		Forward	Backward	Forward	Backward	*P*-value	η^2	*P*-value	η^2	*P*-value	η^2
Foot placement SD results											
Foot placement SD (m)	AP	0.22(0.05)	0.14(0.02)	0.16(0.05)	0.13(0.04)	0.01	0.18	<0.001	0.35	0.05	0.11
	ML	0.05(0.02)	0.05(0.03)	0.04(0.01)	0.03(0.01)	0.01	0.20	0.45	0.01	0.57	0.01
	VT	0.08(0.03)	0.07(0.01)	0.05(0.02)	0.04(0.01)	<0.001	0.33	0.07	0.10	0.80	0
Largest finite-time Lyapunov Exponents results											
Ankle	AP	3.06(0.30)	3.28(0.39)	5.33(0.79)	4.83(0.61)	<0.001	0.77	0.44	0.01	0.06	0.10
	ML	2.27(0.24)	2.20(0.23)	4.17(0.76)	4.28(0.31)	<0.001	0.86	0.88	0.00	0.54	0.01
	VT	2.45(0.24)	2.49(0.28)	3.89(0.83)	3.62(0.57)	<0.001	0.64	0.50	0.01	0.37	0.02
Knee	AP	2.69(0.31)	2.65(0.28)	4.98(0.84)	4.71(0.89)	<0.001	0.78	0.45	0.01	0.59	0.01
	ML	2.61(0.25)	2.57(0.34)	4.42(0.85)	4.16(0.30)	<0.001	0.78	0.36	0.02	0.49	0.01
	VT	2.65(0.28)	2.35(0.2)	4.36(0.72)	3.89(0.84)	<0.001	0.71	0.05	0.11	0.65	0.00
Hip	AP	2.39(0.47)	2.45(0.30)	3.63(0.46)	3.60(0.79)	<0.001	0.59	0.93	0.00	0.81	0.00
	ML	1.70(0.25)	1.93(0.34)	3.05(0.49)	3.10(0.56)	<0.001	0.72	0.32	0.03	0.52	0.01
	VT	2.47(0.38)	2.64(0.30)	3.92(0.40)	3.98(0.66)	<0.001	0.73	0.45	0.01	0.73	0.00
S1	AP	1.67(0.82)	1.98(0.89)	1.94(0.47)	1.55(0.18)	0.73	0.00	0.87	0.00	0.13	0.06
	ML	1.32(0.72)	1.69(0.70)	1.74(0.52)	1.45(0.13)	0.65	0.01	0.85	0.00	0.10	0.07
	VT	2.10(0.67)	2.25(0.63)	2.55(0.47)	2.19(0.37)	0.31	0.03	0.60	0.00	0.18	0.05

η^2 = effect size (partial eta-squared). AP = anterior-posterior. ML = medial-lateral. VT = vertical.

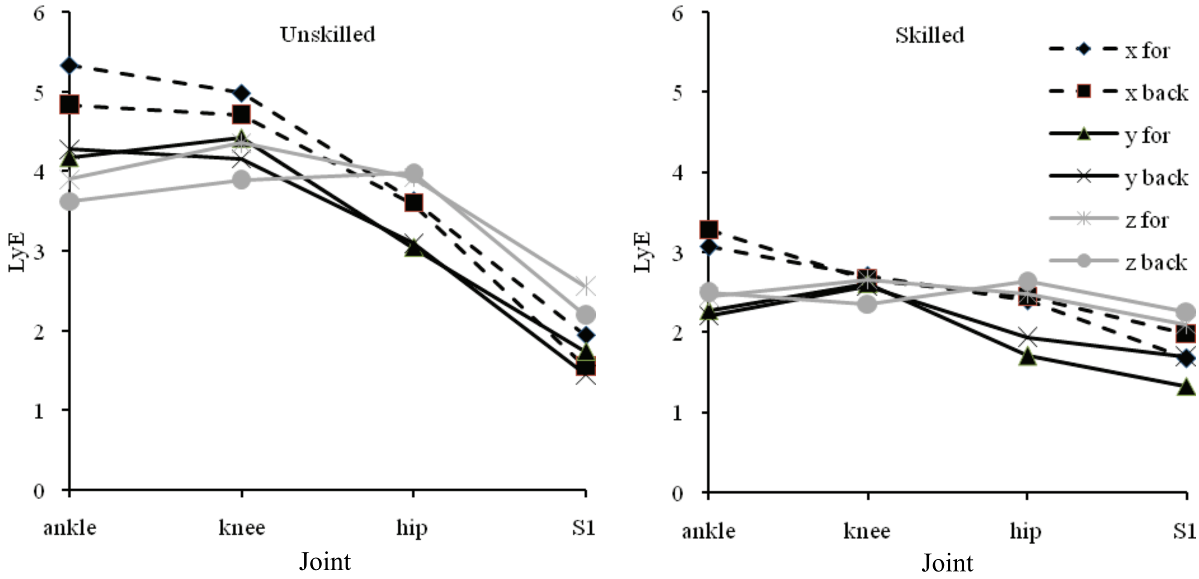

Fig. 3. Group means of λ_1 at each joint for both unskilled (left) and skilled (right) groups. Standard deviations are not shown for clarity of the figure

both groups' performance (Fig. 3 and Table 3), which is an indication of increasing local dynamic stability from distal to proximal.

Table 3. Results of repeated-measure ANOVA for comparison λ_1 among joints

	Forward			Backward		
	AP	ML	VT	AP	ML	VT
Skilled	$P < .001$	0.001	NS	0.003	0.009	NS
Unskilled	$P < .001$	$P < .001$	NS	$P < .001$	$P < .001$	NS

4. Discussion

The role of stability as a key component of agility skill has been emphasized previously (Vescovi [23]; Wheeler [24]). A quantitative evaluation of stability however, has rarely been provided in the extant literature. In addition, a detailed investigation of the effect of skill level on the stability of an athlete's body segments has yet to be made available. The primary objective of this study was therefore to implement both foot placement SD and LyE methods to determine differences in stability between performances exhibited by two groups of skilled and unskilled participants.

Foot placement SD and stability

Maintaining stability during performance in dynamic tasks (e.g., an agility drill), requires functionally adaptive behaviors, i.e. corrective foot placements, with ensuing corrections of BOS relative to COM (Hamacher et al. [10]). Attempts in correcting foot placements in an agility drill will consequently lead to foot placement variability. Table 2 provides evidence of greater AP, ML and VT foot placement SD measures for skilled participants. Greater stride to stride SD has previously been considered as an indication of greater instability and thus a predictor of falls (Maki [17]). More recent studies argue that variability cannot directly quantify stability (Dingwell and Marin [5]). It has also been proposed that changes in variability might be the result of adaptation to task or environmental constraints (Schulz [20]).

In the current article, a key task constraint was minimum time to completion of the drill, which resulted in the skilled participants exhibiting higher values of movement velocity than the other group. This is equivalent to higher stride velocities or shorter stride durations. The shorter duration of strides in a movement tends to limit the error correction abilities of a neuromuscular control system (England and Granata [6]). This in turn points to greater foot placement SD. Therefore, it could be argued that skilled participants trade lower magnitudes of movement variability (i.e., better error correction) to reduce the time taken to perform the drill.

LyE and stability

Table 2 reveals that skilled participants displayed significantly lower values of λ_1 in the AP, ML and VT directions. This was observed in all lower extremity joints except S1. The lower value of λ_1 at ankle joint pointed towards greater local dynamic stability of foot placement for skilled participants. The lower value of λ_1 at knee and hip joints also indicated that having greater local dynamic stability in all lower extremity joints is a characteristic of skilled agility performance. In other words, it could be suggested that skilled participants displayed a greater capacity to respond to inherent local perturbations at all lower extremity joints while performing the drill.

The falling values of λ_1 as shown in both Fig. 3 and Table 3, (except in VT direction), is an indication of an increase of local dynamic stability from distal to proximal joints. This observation is in accordance with findings from previous studies of gait, where it has been reported that increases of local dynamic stability from distal to proximal joints may be due to a shock absorption role of distal joints resulting in proximal joints being less affected by perturbations in the movement (Kang and Dingwell [14]). In other words, the stability of proximal segments is prioritized over distal segments by the neuromuscular control system (Kang and Dingwell [14]). In the VT direction, however, results suggested that, local dynamic stability was preserved through all lower extremity joints for both groups of participants. This is an indication that responding to local perturbations or shock absorption did not occur in the vertical component of joint motion. In addition, results showed there were no significant differences in foot placement SD (except in the AP direction) and the local dynamic stability between forward and backward segments of the drill for both groups. This finding suggests that for both groups, the neuromuscular control system's ability in making corrective adjustments and responding to local perturbations was similar for both the forward and backward segments.

The results reported in this study seem consistent with arguments that linear measures of variability could not quantify stability in human movement. It is, however, shown that stability could be directly quantified using methods such as LyE which measure the ability of a movement system to respond to inherent perturbations (Dingwell and Marin [5]). The outcomes show that skilled participants revealed greater magnitudes of variability, as well as higher local dynamic stability. It seems that observing higher values of foot placement variability in an agility drill may indicate the level of adaptation to task constraints and may not be an indication of greater levels of system instability.

There are some limitations associated with this study. First, our study considered only the foot placement variability of a single side of the participants' body. Studying foot placement characteristic of both sides of the body could provide more information on step width variability and its relationship to stability. Another issue is that to quantify local dynamic stability, the methodological approach adopted in this study was based on measurements of maximum finite-time Lyapunov Exponent that demonstrates the least stable component of Lyapunov spectrum. However, studying the whole spectrum of Lyapunov Exponents might reveal other aspects of an athlete's stability in an agility drill. The related point is that the LyE measures the ability to respond to inherent local perturbations during the movement (Dingwell and Marin [5]). The relationship between the local dynamic stability and ability to maintain stability when larger (i.e., global) perturbations (e.g., impact with another individual) are observed in an agility drill, however, requires further empirical evaluations. In addition, the current analysis was based on performance of a forward/backward agility drill. Future studies should concentrate on developing a methodology based on more generalized drills with more varying and complex movement trajectories. Finally, although the number of data points to calculate LyE was sufficient in this study (2250 data points), the small number of strides (15 strides) might affect the calculated LyE. Since agility drills are performed in short durations, future studies thus might focus on calculating LyE for movement systems with small number of repetitions.

5. Conclusion

The findings reported here suggest that sport scientists, coaches and trainers might consider other potential outcomes from performance of an agility drill, rather than simply time to perform the task. Greater magnitudes of foot placement variability (foot placement SD) for the skilled group for example, might indicate that when training agility, coaches should place less emphasis on the exact movement or process used by an athlete to achieve the performance goal. In addition, quantification of local dynamic stability (LyE) as a measure of stability in an agility drill might be an appropriate method for sport scientists to assess the agility performance of an athlete. Finally, results of LyE at different lower extremity joints position suggested that to improve stability in an agility drill, it might not be sufficient to improve stability of only a specific body segment and the stability of all lower extremity joints should be improved in training tasks.

Acknowledgment

The tests conducted for this study were supported by the Sports and Health Engineering Center and performed at the Biomechanics Lab, University of Social Welfare and Rehabilitation Sciences.

References

[1] BALASUBRAMANIAN C.K., NEPTUNE R.R., KAUTZ S.A., *Foot placement in a body reference frame during walking and its relationship to hemiparetic walking performance*, Clin. Biomech., 2010, 25(5), 483–490. DOI: 10.1016/j.clinbiomech.2010.02.003.

[2] BRUIJN S.M., *Is stability an unstable concept Quantifying dynamic stability of human locomotion*, (Doctoral Dissertation), Vrije Universiteit Amsterdam, 2010, Retrieved from http://dare.ubvu.vu.nl/

[3] BRUIJN S.M., VAN DIEEN J.H., MEIJER O.G., BEEK P.J., *Is slow walking more stable?* Js. Biomechs., 2009, 42, 1506–1512. DOI: 10.1016/j.jbiomech.2009.03.047.

[4] DAVIS B., BULL R., ROSCOE J.U., *Physical education and the study of sport*, 4th ed., Mosby, 2000.

[5] DINGWELL J.B., MARIN L.C., *Kinematic variability and local dynamic stability of upper body motions when walking at different speeds*, J. Biomech, 2006, 39(3), 444–452. DOI: 10.1016/j.jbiomech.2004.12.014.

[6] ENGLAND S.A., GRANATA K.P., *The influence of gait speed on local dynamic stability of walking*, Gait Posture, 2007, 25(2), 172–178.

[7] FRASER A.M., *Using mutual information to estimate metric entropy*, [in:] G. Mayer-Kress (ed.), *Entropies and Dimensions*, Springer, Berlin 1986, 82–87.

[8] GATES D.H., DINGWELL J.B., *Comparison of different state space definitions for local dynamic stability analyses*, J. Biomech., 2009, 42(9), 1345–1349. DOI: 10.1016/j.jbiomech.2009.03.015.

[9] GRAHAM R.B., SADLER E.M., STEVENSON J.M., *Does the personal lift-assist device affect the local dynamic stability of the spine during lifting?* J. Biomech., 2011, 44, 461–466. DOI: 10.1016/j.jbiomech.2010.09.034.

[10] HAMACHER D., SINGH N.B., VAN DIEEN J.H., HELLER M.O., TAYLOR W.R., *Kinematic measures for assessing gait stability in elderly individuals: a systematic review*, J. R. Soc. Interface, 2011, 8(65), 1682–1698. DOI: 10.1098/rsif.2011.0416.

[11] HAUSDORFF J.M., ZEMANY L., PENG C.K., GOLDBERGER A.L., *Maturation of gait dynamics: stride-to-stride variability and its temporal organization in children*, J. Appl. Physiol., 1999, 86(3), 1040–1047.

[12] JORDAN K., CHALLIS J.H., CUSUMANO J.P., NEWELL K.M., *Stability and the time-dependent structure of gait variability in walking and running*, Hum. Mov. Sci., 2009, 28(1), 113–128, DOI: 10.1016/j.humov.2008.09.001.

[13] KADABA M.P., RAMAKRISHNAN H.K., WOOTEN M.E.,. *Measurement of lower extremity kinematics during level walking*, J. Orthop. Res., 1990, 8(3), 383–392.

[14] KANG H.G., DINGWELL J.B., *Dynamic stability of superior vs. inferior segments during walking in young and older adults*, Gait Posture, 2009, 30(2), 260–263. DOI: 10.1016/j.gaitpost.2009.05.003.

[15] KANTZ H, SCHREIBER T., *Nonlinear Time Series Analysis*, Cambridge University Press, 2004.

[16] KENNEL M., BROWN R., ABARBANEL H., *Determining embedding dimension for phase-space reconstruction using a geometrical construction*, Physical Rev. A, 1992, 45(6), 3403–3411. DOI: 10.1103/PhysRevA.45.3403.

[17] MAKI B.E., *Gait changes in older adults: predictors of falls or indicators of fear*, J. Am. Geriatr. Soc., 1997, 45(3), 313–320.

[18] ROSENSTEIN M.T., COLLINS J.J., DE LUCA C.J., *A practical method for calculating largest Lyapunov exponents from small data sets*, Physica D, 1993, 65, 117–134.

[19] ROSS S.E., GUSKIEWICZ K.M., *Time to stabilization: a method for analyzing dynamic postural stability*, Athl. Ther. Today, 2003, 8, 37–39.

[20] SCHULZ B.W., *Healthy younger and older adults control foot placement to avoid small obstacles during gait primarily by modulating step width*, J. Neuro. Eng. Rehabil., 2012, 9(69).

[21] SHELHAMER M., *Nonlinear Dynamics In Physiology A State-Space Approach*, World Scientific, Singapore 2006.

[22] TAKENS F., *Detecting strange attractors in turbulence*, [in:] D. Rand, L.-S. Young (eds.), *Dynamical Systems and Turbulence*, Warwick 1980, Vol. 898, 366–381): Springer, Berlin–Heidelberg 1981.

[23] VESCOVI J.D., *Agility*, NCSA Hot Topic Series, 2004.

[24] WHEELER K., *Agility skill execution in rugby union*, Doctoral Dissertation, University of the Sunshine Coast, 2009, Retrieved from http://research.usc.edu.au/vital/access/manager/Index

[25] YOUNG W., FARROW D., *A Review of Agility: Practical Applications for Strength and Conditioning*, Str. Condg. Jl., 2006, 28(5), 24–29.