QUANTIFYING VARIABILITY IN COORDINATION DURING RUNNING

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It has been suggested that within-participant variability in coordination may have a functional role to play in human movement. The purpose of this study was to compare the variability in coordination for one participant, quantified utilising two previously used techniques. Hip and knee flexion-extension angles during the stance phase were calculated and interpolated to 100 data points, for 10 trials of running at 3.8 m.s^{-1}. The standard deviation in continuous relative phase and coefficient of correspondence from vector coding were calculated at each data point. The two techniques gave similar indications of coordination variability in early stance, but were contradictory towards the end of stance. The results of this investigation suggest that authors conducting independent studies, using different analysis techniques, may draw conflicting conclusions about the variability in coordination.

KEY WORDS: continuous relative phase, coordination, variability, vector coding.

INTRODUCTION: Variability is inherent within and between all biological systems (Newell and Corcos, 1993). With the large number of degrees of freedom in the human body (10^2 joints, 10^3 muscles, 10^3 cell types and 10^4 neurons: Kelso, 1995), generating identical movement patterns on different attempts at performing the same task would seem impossible. In the past this variability has been viewed as system noise or error that must be eliminated. Recently, however, it has been suggested that variability has a functional role to play in human movement. In ecological motor control it has been proposed that variability is vital for changes in the coordination between body segments to take place (Kelso, 1995). Tepavac and Field-Fote (2001) also stated that the variability over multiple trials may offer insights into the control mechanisms underlying the coordination of the behaviour. Both Hamill *et al.* (1999) and Heiderscheit *et al.* (1999) also suggested that variability in lower extremity coordination may play a functional role in attenuating the large impact shocks present during the stance phase of running. A non-variable pattern would result in the same anatomical surfaces receiving the shock repeatedly. With increased variability the forces would be imparted to various structures, potentially reducing the risk of injury from repetitive strain (Heiderscheit *et al.*, 1999). Indeed, trial-to-trial variability within participants has recently been employed as a clinical measure (Heiderscheit, 2000). Hamill *et al.* (2000) outlined a number of techniques for quantifying the variability in coordination. These techniques can be classified as either discrete or continuous measures. Discrete measures, such as discrete relative phase, cross-correlations and return maps, are useful because no further manipulation to the data is required after joint angles have been calculated (Hamill *et al.*, 2000). These discrete measures do, however, only give an evaluation of coordination by providing a single value per trial. An advantage of continuous techniques is that coordination, and the variability in coordination, can be evaluated through the provision of values over the entire trial. Examples of the continuous techniques used to assess coordination variability during running include continuous relative phase (Hamill *et al.*, 1999; Heiderscheit *et al.*, 1999) and vector coding (Tepavac and Field-Fote, 2001). The purpose of this study was to compare variability in coordination, during over-ground running, quantified using both continuous relative phase and vector coding.

METHODS: One healthy male (mass = 78 kg; height = 1.83 m; age = 22 years) volunteered to participate in the study, and written informed consent was obtained before data collection began. All procedures were in agreement with the department's ethics guidelines. Pre-moulded, Velcro backed thermoplastic shells equipped with four 25 mm retro-reflective markers, were attached to the participant's shank and thigh using the 'optimal' technique described by Manal *et al.* (2000). Briefly, the shells were attached to the segments in distal-lateral locations by fastening the Velcro to an under-wrapped elasticised band. Four further retro-reflective markers were attached to the participant's pelvis at relevant anatomical landmarks. An eight camera, video based motion analysis system (Motion Analysis Corporation, Santa Rosa, CA, USA) collecting at 120 Hz, was used to obtain the three-dimensional coordinates of each marker, whilst the participant ran across the laboratory at 3.8 $m.s^{-1}$ (±5%). The raw kinematics data were filtered using a fourth order low-pass Butterworth filter with an 8 Hz cut-off frequency, selected through visual inspection of the fit. Ten 'good' trials were collected, in which the whole of the performer's left foot struck a Type 9281CA Kistler force platform (Winterthur, Switzerland) collecting at 1200 Hz, without any obvious alterations to their running gait. The vertical component of the ground reaction force data, above a 30 N threshold, was used to define the stance phase. Segment coordinate systems for the shank, thigh and pelvis were defined in a static trial using the technique described by Cappozzo *et al.* (1995), in which anatomical landmarks are identified using a 'pointer' technique. This procedure allowed the calculation of three-dimensional Joint Coordinate System angles (Grood and Suntay, 1983) at the knee and hip joints, during stance using MARey Software (Cavanagh *et al.*, 2001) written for MATLAB (Natick, MA, USA). The coordination between hip flexion-extension and knee flexion-extension was chosen for study, and both segment profiles were interpolated to 100 data points using a cubic spline procedure. Subsequently, the coefficient of correspondence from vector coding (see Tepavac and Field-Fote, 2001) and the standard deviation in continuous relative phase (see Hamill *et al.*, 1999), were calculated at each data point over the stance phase. The average coefficient of correspondence and standard deviation over each quarter of the stance phase were also calculated.

RESULTS: The raw data over the stance phase are presented in Figure 1, in the form of a hip-knee angle-angle plot. It is clear that within participant variability is present and that the amount of variability changes over the course of the stance phase.

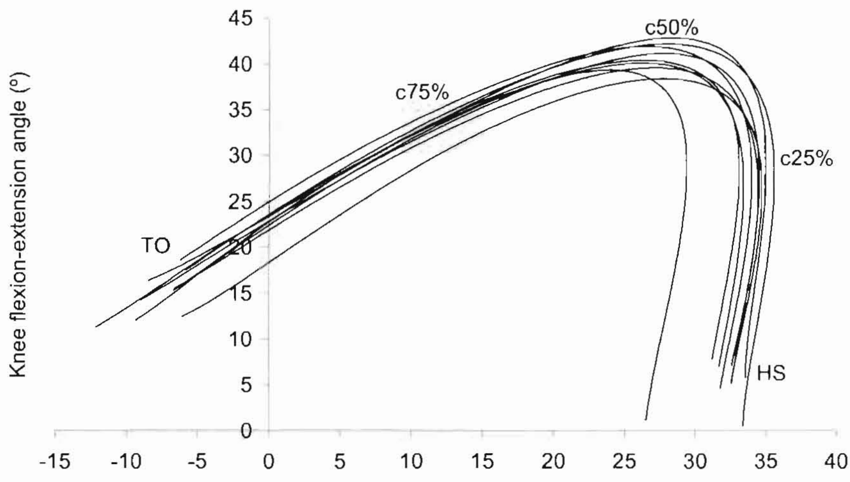

Figure 1. Angle-angle plot of knee flexion-extension against hip flexion-extension. An approximate indication of the beginning (heelstrike: HS), 25%, 50%, 75% and end (toe-off: TO) of the stance phase is provided.

The results of the variability analysis using both continuous relative phase and vector coding are given in Figure 2. When interpreting the data in Figure 2 it should be noted that a lower coefficient of correspondence indicates greater variability, whereas a lower continuous relative phase standard deviation indicates less variability. The general shape of the continuous relative phase standard deviation and coefficient of correspondence traces suggests only some similarities in the patterns of variability. From both techniques variability is apparent at the beginning of the stance phase, then the coordination becomes more consistent up until approximately 15-20%, before increasing until approximately 35% of the stance phase. However, there are distinct differences between the meaning of the traces. The highest coefficient of correspondence, indicating the least amount of variability occurred at approximately 10% of stance, whereas the smallest standard deviation in continuous relative phase occurred at approximately 50%. Also the two measures appear to contradict each other after approximately 45% of stance.

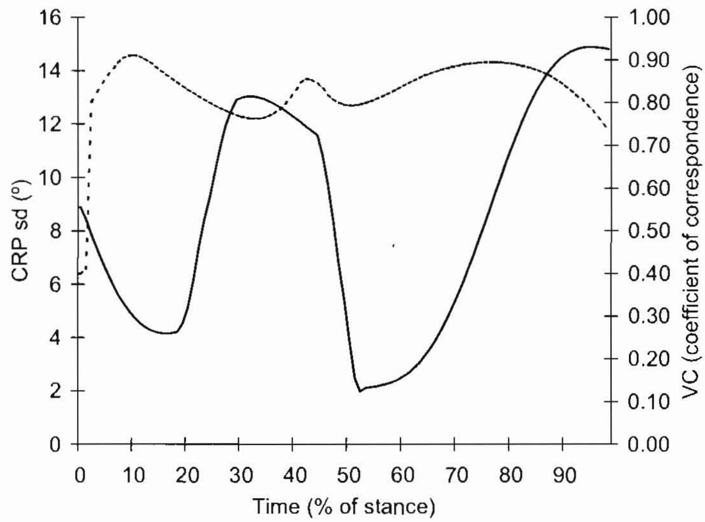

Figure 2 . Continuous relative phase standard deviation (CRP sd: solid line) and vector coding coefficient of correspondence (VC: dashed line) over the stance phase during running.

The average coefficient of correspondence from vector coding and standard deviation in continuous relative phase over the four quarters of the stance phase are given in Table 1.

Table 1. Average standard deviation in continuous relative phase and coefficient of correspondence from vector coding over the four quarters of the stance phase.

Quarter	Continuous relative phase sd (°)	Vector coding (Coefficient of correspondence)
1	5.9	0.83
2	11.5	0.80
3	3.7	0.84
4	13.0	0.85

DISCUSSION: It is clear from the data presented that there was within-participant variability in coordination between the hip and knee over the ten trials collected. This can be seen qualitatively in Figure 1, from which it is also apparent that the amount of variability changes over the course of the stance phase. The results from the continuous relative phase and vector coding analyses were similar at the beginning of stance, but were contradictory towards the end of the stance phase. In an attempt to give a more quantitative indication of any differences between the variability calculated using the two techniques, the average continuous relative phase standard deviation and coefficient of correspondence over four quarters of the stance phase are presented in Table 1. This analysis was also included because a similar technique has been used previously by both Heiderscheit *et al.* (1999) and Hamill *et al.* (1999). The results confirm the previous qualitative observations. The continuous relative phase standard deviation indicates that the greatest amount of variability occurred in the fourth quarter of the stance phase. Conversely, the coefficient of correspondence suggests that this quarter contained the least variability. These values would lead authors using the two techniques independently to draw contradictory conclusions about coordination variability over different phases of stance during running. The differences between the techniques presented here may be due to the need to normalise the angular displacement and velocity data before the continuous relative phase between body segments can be calculated; no such normalisation is required with vector coding. Also, it has been shown previously that continuous relative phase variability is affected by the procedure with which the angular velocities are normalised during its calculation (Hamill *et al.*, 2000). However, continuous relative phase calculation has the advantage of presenting temporal as well as spatial information (Hamill *et al.*, 2000) as, in addition to angle data, angular velocity is included. This may make measures of continuous relative phase more sensitive to variability in coordination.

CONCLUSION: This study highlighted differences between two techniques previously used to quantify the variability in coordination between two body segments. These differences may lead authors to draw contradictory conclusions about coordination variability from two independent studies using different techniques. It is suggested that no direct inter-study comparisons of coordination variability can be made if these two different techniques have been used.

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