QUANTIFYING COORDINATION IN KINEMATIC DATA: A RUNNING EXAMPLE

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To compare methods of quantifying coordination, one healthy male participant was filmed in three dimensions at 120 Hz whilst running at 3.8 m.s^{-1}. The knee and hip angles and angular velocities of the left stride, normalised to 100 data points, were analysed using continuous relative phase (CRP) and cross correlations (CC). The phase planes were normalised to -1 and +1, and the component phase angles (I) for each segment calculated with the range $0^\circ \leq I \leq 180^\circ$. CC indicated a strong linear relationship between the knee and hip with a lag of 19% of the stride time in the hip data (r = 0.85). The relationship was linear and non-linear at different phases, which may warrant a separate analysis of phases of running to identify coordination. CRP of one trial did not provide any meaningful indication of coordination, but the variability of CRP over several trials may provide an alternative indication of stability of coordination.

KEY WORDS: continuous relative phase, coordination, cross correlations, variability.

INTRODUCTION: Kinematic data provide the researcher with a simplified representation of human movement. These data are used to analyse technique via methods including reporting of values at single instances or key moments, time series of a single variable and quantification of variable-variable plots. As human movement is complex, the analysis of variable-variable plots may provide the most comprehensive information. Typically these variable-variable analyses are used to explore either variability or coordination. In analysing variability, i.e. the degree of departure from the central score, greater measures have been viewed as indicative of poor technique (Davids *et al.*, 1997). Alternatively, greater variability has also been viewed as functional in producing the desired outcome (Arutyunyan *et al.*, 1968). In analysing coordination, i.e. the functional link between the muscles and joints used to produce the desired performance or outcome, then some measure is required. As variability has been considered functional, this can be used as a measure of coordination. The methods used for quantifying variable-variable data for either variability or coordination studies are similar. They are different, however, principally in that either several or one trial are required to quantify variability and coordination, respectively, and the use and interpretation of the results vary. Focusing on methods that exist to quantify coordination, these may include continuous relative phase (CRP; Hamill *et al.*, 2000) and cross correlations (CC; Amblard *et al.*, 1994; Mullineaux *et al.*, 2001). Although these methods are beneficial in that they provide a quantification of coordination, there are a number of limitations in their use. For instance, Hamill *et al.* (2000) highlights a variety of methods for normalising the data in CRP, but Kurz and Stergiou (2002) suggest that, as the arc tangent can account for differences in amplitudes between segments, no normalisation is required. In addition, the polynomial smoothing for interpolation used by Hamill *et al.* (1999) may introduce errors into end data. To highlight further benefits and limitations of these statistical techniques, the aim of this study was to compare CRP and CC as methods for quantifying coordination.

METHODS: In agreement with the department's ethics guidelines, one healthy male (mass = 78 kg; height = 1.83 m; age 22 years) volunteered and provided written informed consent to participate in this study. Ten trials of the participant running at 3.8 m.s^{-1} were recorded at 120 Hz using eight Falcon cameras and Realtime 2.80 software (Motion Analysis Corporation, Santa Rosa, CA, USA). The three-dimensional coordinates of three sets of four-marker clusters on the pelvis, thigh and shank for each trial were recorded (Manal *et al.*, 2000). Custom written code using MATLAB (MathWorks Inc., Natick, MA, USA) was used to analyse the data. The coordinate data were smoothed using an 8 Hz fourth-order low pass filter, and knee (positive flexion values – full extension is 180°) and hip (positive flexion angles between the pelvis and thigh – full extension is 0°) angles and angular velocities were calculated. To allow for comparisons between the statistical methods, a cubic spline interpolation was used to normalise each stride to 100 data points from toe off to toe off of the left foot. To quantify coordination between the hip and knee, the statistical methods used were CRP and CC. To calculate CRP, firstly the phase-plane portrait of both the knee and hip were normalised to -1 and +1 of the angle range over the trial (hence 0 on the x-axis reflects the angle at half the range) and to +1 or -1 of the maximum absolute angular velocity over the trial (hence 0 on the y-axis reflects $0^{\circ}.s^{-1}$) – see Hamill *et al.* (1999). The component phase angles (I) of each segment, that is the arctangent of the angular velocity over the angle for each of the 100 data points, were calculated with the range $0^{\circ} \leq I \leq 180^{\circ}$. The difference between the knee and hip phase angles provided the CRP. Cross correlations between the knee and hip angles were calculated using SPSS for Windows v 10.0 (SPSS Inc., Chicago, IL, USA). The linearity assumption of the CC function was tested by visual inspection of the fit.

RESULTS: The coordination of the knee and hip during one running stride, from toe-off to toe-off, demonstrates a typical angle-angle plot (see solid line in Figure 1). To quantify the coordination, a cross correlation revealed a strong relationship between the knee, with no time lag, and the hip, with a time lag of 19% of the stride time (r = 0. 85). The linear coordination between these two variables with the time lag in the hip data is clear at certain periods (see dashed line; Figure 1), but more complicated at other times.

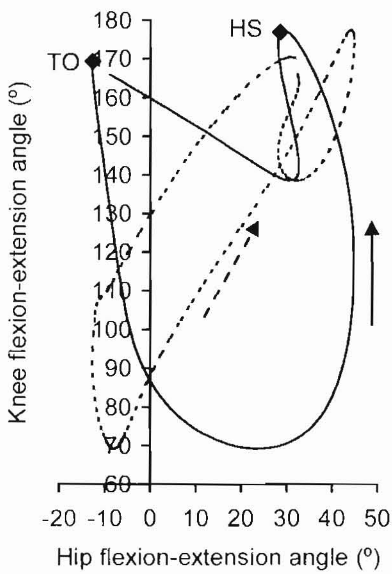

Figure 1. Angle-angle plot with no time-lag (solid line) and 19% time-lag only in the hip angle (dashed line). Toe off (TO), heel strike (HS) and directions (arrows) indicated.

Figure 2 illustrates the normalised phase-plane portraits for the knee (solid line) and hip (dashed line) for the same stride. Qualitatively the knee shows a more uniform pattern than the hip, although the overall patterns are similar. To quantify the coordination, the differences between the knee and hip phase angles provided the CRP illustrated in Figure 3. The inconsistent pattern, with no periods of 0° or 180° indicating the knee and hip to be in or out of phase respectively (Hamill *et al.*, 2000), suggests no apparent coordination between the knee and hip during running.

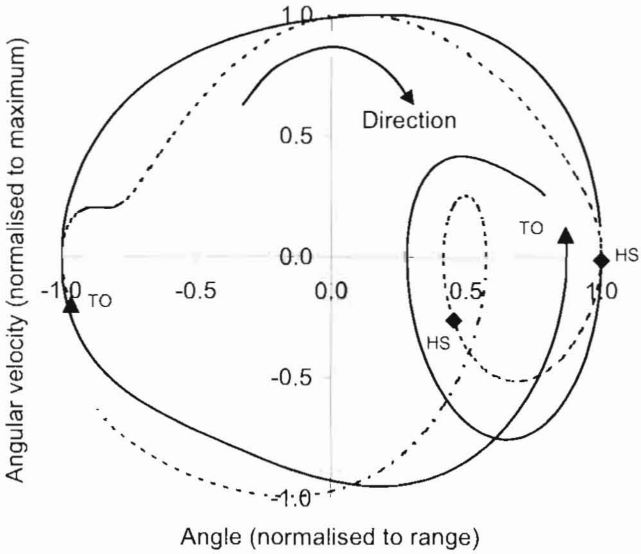

Figure 2. Phase plane portraits for the knee (solid line; triangles) and hip (dashed line; diamonds). Toe offs (TO), heel strikes (HS) and directions (arrow) indicated.

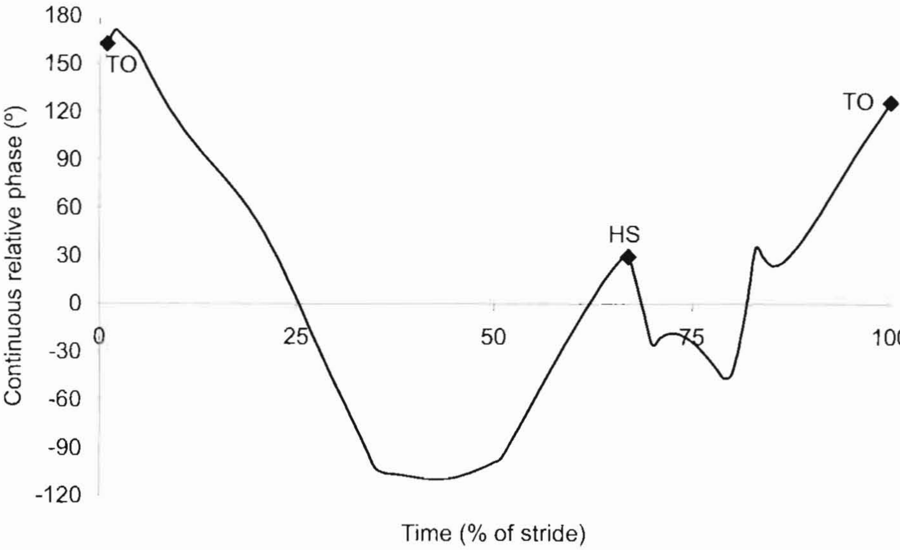

Figure 3. Continuous relative phase between the hip and knee. Toe offs (TO) and heel strike (HS) indicated.

DISCUSSION: Quantifying the coordination between the knee and hip during running using CC and CRP provides different results. The CC indicated that if a time delay of 19% of the stride time is introduced into the movement of the hip angle, then a strong linear relationship exists between the hip and knee angles (r = 0.85). Inspection of Figure 1 (dashed line) provides two additional findings about the coordination between the knee and the hip with the time lag. Firstly, the majority of the linear relationship is proportional at approximately two to one between the knee and hip, at either positive or negative ratios depending on the period during the cycle. Secondly, however, there are clear periods of a non-linear relationship between the hip and knee. Potentially, either a linear transformation needs to be applied to the data prior to running the analysis, or the stride could be separated into phases and each of these analysed separately as has been performed previously by Hamill *et al.* (1999). The CRP provided less informative results about the coordination of hip and knee over one running trial than CC. Although the phase plane portraits in Figure 2 show some similarities between the hip and knee, the inconsistent CRP in Figure 3 suggests that there is no linear coordination between these two segments. The assumptions underpinning the use of CRP and methods employed may account for this finding – the knee and hip should possess a one to one ratio and be sinusoidal. Normalising the phase plane portraits improves the one to one ratio, but there is a poor sinusoidal pattern in the hip and knee data. Potentially, a transformation technique may improve the sinusoidal pattern, but the greater data processing may not be warranted as it could make the interpretation too complicated. Although not provided, the CRP patterns change radically with the methods used, particularly through the segment angle definitions and component phase angle calculations employed. In addition, the method of interpolating the data to 100 points, smoothing and choice of starting point in the gait cycle should be standardised for comparison with previous studies. For instance, Hamill *et al.* (1999) reported greater variability at foot strike, but this may be an artefact of the measurement beginning at foot-strike and the associated smoothing problems with end data. Although, the analysis of one trial in CRP, as calculated within these methods, provided little or no information about coordination between the hip and knee during running, the variability in the CRP over several trials may provide alternative information about the coordination between segments.

CONCLUSION: Quantifying the coordination between the hip and knee during one running stride can be achieved using CC, but CRP does not provide any clear indication of coordination. To improve the analysis using CC, further consideration should be made of linearising the data and whether to analyse different phases of the cycle separately. The use of CRP to analyse coordination may be more appropriate when there is more than one trial and periods of small and large variability can be used to infer any coordination strategies used. In using CRP, care should be taken in the data analysis to allow for comparisons with previous studies by, for example, calculating CRP in the same way and minimising the influence of end data effects.

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