NEW DEVELOPMENTS IN VECTOR CODING METHODS FOR ASSESSING COORDINATION VARIABILITY

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The purpose of this study is to propose modifications to current methods for the assessment of coordination variability through vector coding techniques. Commonly, vector coding starts from calculating the vector difference between adjacent data points on an angle-angle plot. This initial stage is analogue to estimating angular velocities from displacement, but with the limitation of differentiating the three axial components in isolation. Instead, the calculation of angular velocities from 3D data should take into account movement in other planes of motion. This study suggests the use of angular velocities in vector coding in place of the difference calculations and demonstrates how using this method can be integrated with recent developments which involve the use of ellipses for calculating coordination variability of angle-angle diagrams.

KEYWORDS: running, gait, joint coupling, kinematics.

INTRODUCTION: Vector Coding measures of coordination were first suggested by Sparrow et al. (1987) and involve the creation of vectors between adjacent data points on angle-angle plots (also known as relative motion plots or cyclograms). The vectors represent the dynamics of the system and vector coding has since provided the basis of several techniques for analysing coordination (Heiderscheit 2002) and coordination variability (Tepavac & Field-Fote, 2001; Heiderscheit et al., 2002; Stock et al., under review). All of these techniques share a common basis that their input comes from calculating the differences between adjacent data points in an angle signal (Δθ). The calculation of Δθ is similar to the numerator component of a finite difference velocity calculation (Equation 1). However, biomechanical conventions state that the angular dynamics calculated from one planar component of the 3D angle do not account for movement in other planes of motion.

$$\dot{\theta} = \frac{\theta_{i+1} - \theta_{i-1}}{2 \cdot \Delta t} \qquad (1)$$

Approximate derivative of θ calculated using the finite difference method.

$$\begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} \dot{\theta}_x + s_y \cdot \dot{\theta}_z \\ c_x \cdot \dot{\theta}_y - s_x \cdot c_y \cdot \dot{\theta}_z \\ s_x \cdot \dot{\theta}_y + c_x \cdot c_y \cdot \dot{\theta}_z \end{bmatrix} \qquad (2)$$

3D angular velocity (Winter 2009)
$s_i = \sin \theta_i$ for i=x,y,z and $c_i = \cos \theta_i$ for i=x,y,z, where x, y, and z are the three direction of the proximal segment reference frame.

Thus, although there are conditions when the finite difference method can approximate ω very well, the closeness of the match can vary. For example, $\dot{\theta}_x$ is only a good approximation of ω_x when $s_y \cdot \dot{\theta}_z \approx 0$. Consequently, by representing the dynamics of angular movement using $\Delta\theta$, possible errors are introduced. We are therefore proposing a modification of current vector coding methods. This move would align coordination calculations with biomechanical conventions for the calculation of 3D segment and joint dynamics.

The purpose of this study is therefore to demonstrate the use of 3D angular velocities in calculating coordination variability, and to show how this approach may make the output more robust to possible noise from the signals.

METHODS: Motion capture data of treadmill running were collected independently from two separate labs on two different participant groups (Lab 1: 10 males and 10 females running at 3.33 m/s, Lab 2: 2 males and 8 females running at 3.50 m/s). All participants provided informed consent to participate and the study was approved by the respective University (University of Bath and Loughborough University) ethics committees. Tracking markers were filtered with an 8 Hz cut-off, low pass, 2nd order, bi-directional Butterworth filter and used to calculate 3D joint angles and angular velocities. These data were exported to MATLAB (v2015b, The MathWorks Inc., Natick, MA) where a custom script separated data into temporally registered stride cycles (101 data points) by identification of foot strike using the algorithm validated by Maiwald et al. (2009). The sagittal hip-knee coupling was selected for this analysis.

We compared how coordination variability differs when using the 3D angular velocity input compared to the traditionally used difference input ($\Delta\theta$). We chose to use a new analysis technique to calculate coordination variability, as it has been demonstrated that methods that involve circular statistics may be influenced by a statistical artefact (Stock et al. in press). More specifically, when coupling vectors are shorter, traditional coordination variability measures are at risk of overestimating variability. A bivariate approach where the area of an ellipse is calculated around coupling vector end points (Figure 1) has been demonstrated to overcome this issue (Stock et al., under review).

To calculate ellipse area coordination variability using the traditional $\Delta\theta$ input (Difference Ellipse Method – DEM), ellipses were created around $\Delta\theta_{Hip}$ and $\Delta\theta_{Knee}$ coordinates at each time percentage using the equations provided by Duarte et al. (2002) with the size scaling adjusted according to the chi-squared value suggested by Mullineaux (2017). The greater the area of the ellipse the more variability there is in coordination (Figure 1A). In order to achieve the equivalent ellipse area coordination variability measure from a 3D angular velocity input (Velocity Ellipse Method (VEM), the same method was applied except that sagittal hip angular velocity (ω_{Hip}) and sagittal knee angular velocity (ω_{Knee}) were used as inputs.
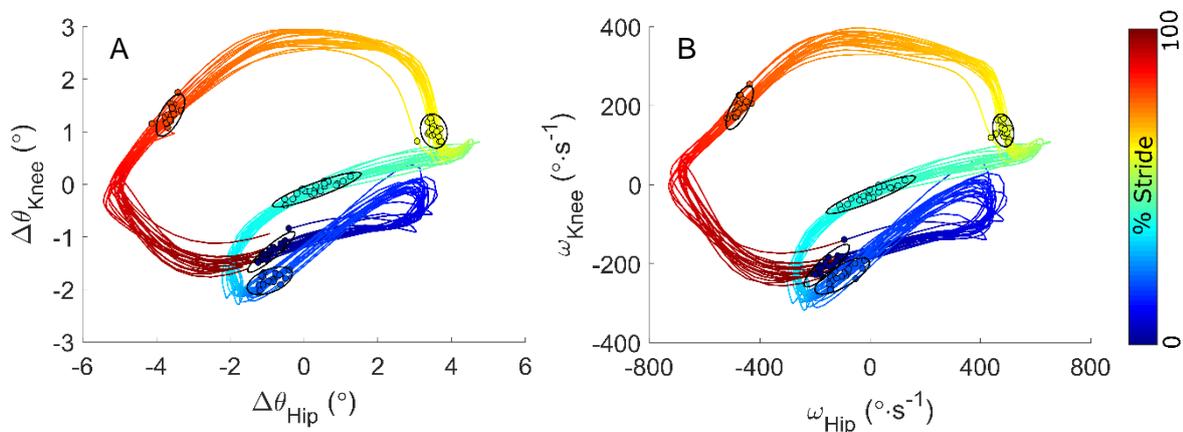

Figure 1. Two methods of calculating coordination variability are demonstrated for the same data from one participant for the sagittal hip–knee coupling of 20 gait cycles. Coordination variability at each instant is represented by the area of an ellipse calculated around coupling vector end points, the origins of which have been normalised to start at the origin. In A the coupling vector end points were created from $\Delta\theta$ (Difference Ellipse Method (DEM)) and in B they are derived from joint angular velocities (Velocity Ellipse Method (VEM)). Ellipses have been visually demonstrated for 5 different time points at 1%, 21%, 41%, 61%, and 81% of the cycle, where the data points from each of the 20 cycles used in the ellipse calculation for that single time percentage have been highlighted.

To compare the similarity of the ellipse areas from the DEM and VEM (A_{VEM} and A_{DEM}) a normalised cross-correlation was performed for each participant. The normalised cross-correlation required both signals to have the same length so the A_{VEM} signal was interpolated so that 100 data points were extracted, omitting the initial and final 0.5% of the cycle in the

same fashion as the DEM. The maximum value from the cross-correlation was extracted and then the mean and SD was calculated across all participants.

RESULTS: Qualitatively, the A_{VEM} and A_{DEM} signals were visually similar for all 30 participants from the two labs. This can be seen in Figure 2A for one individual. The normalised cross correlation supported this finding, with an average of 0.99 (± 0.01) showing that A_{VEM} had a high correlation with the A_{DEM}. However, on visual inspection of the graphs, 25 of the 30 (17/20 in the first lab and 8/10 in second lab) A_{DEM} outputs had brief but obvious spikes (e.g. Figure 2A, black trace at 80% of the stride cycle). In Figure 2B we show that a small amount of noise in just one cycle of the knee difference signal appeared to have caused the spike. The magnitude of this noise was less than half a degree and therefore was undetectable to the eye when inspecting the angle trace from which it was calculated (Figure 2B). The same noise did not appear in any of the measures calculated from angular velocities.
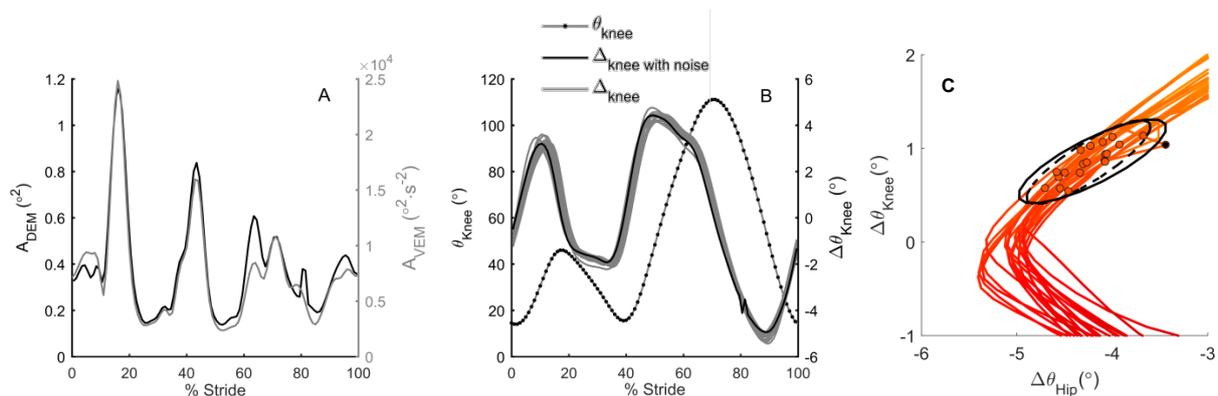

Figure 2. A) Comparison of VEM and DEM methods for calculating sagittal hip-knee coordination variability applied to the same data from an individual participant. B) Grey traces show multiple repetitions of $\Delta\theta_{Knee}$. One repetition is highlighted in black, chosen because a small amount of noise was apparent in the signal. This noise is believed to have caused the non-smooth peak in the black A_{DEM} signal in Figure 2A at 80% of the stride. The noise is not obvious in the corresponding θ_{Knee} trace from which the $\Delta\theta_{Knee}$ noise was calculated (grey and black dotted). C) To demonstrate how the noise affected the A_{DEM}, ellipses at 80% of the cycle were created with (solid) and without (dashed) including the noisy (black filled) data point. The inclusion of the noisy data shows a greater ellipse area for that time point than should have been calculated.

DISCUSSION: The purpose of this study was to propose a new method of calculating coordination variability that utilises 3D angular velocities as inputs, and to compare this approach to traditional difference techniques in vector coding. The newly proposed VEM was based upon mathematical concepts which are accepted methods in biomechanics and this is the primary justification for suggesting the change in method. Visual comparisons between the two different techniques showed that the patterns of the signal were very similar and these conclusions were supported by a high normalised cross correlation of 0.99.

Although similar, we observed that the VEM appeared to be less sensitive to noise than the DEM. This claim would require further quantitative testing but possible causes could be: a lower signal-to-noise ratio when calculating the difference between points than from a velocity calculation, or an error in the DEM data as a result of not considering movement in other planes of motion. Interestingly the noise was present in data collected from both labs. Further work will be required to quantitatively identify the noise and to understand what causes it.

Traditional vector coding may have developed to use the difference between adjacent points as input signals because 2D data were the only measures available when coordination analysis started being applied to movement science; 3D motion capture systems and 3D kinematics were less common than they are today. Regardless of these arguments, we

advise the use of 3D angular dynamics in combination with a bi-variate approach (Stock et al., 2018), when coordination variability is the output under investigation. This approach, as shown in the VEM method, is more consistent with 3D biomechanics fundamentals and proves more robust to possible artefacts in the signal.

CONCLUSION: This study proposed a development to the calculation of coordination variability from angle-angle diagrams. The proposed change is based on complying with biomechanical standards on how to represent 3D dynamics and on providing a measure that is less susceptible to noise. The use of velocity inputs together with a recently proposed ellipse method may result in a more robust measure of coordination variability for future use in research and clinics.

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