# METHODOLOGICAL ISSUES IN QUANTIFYING COORDINATION-VARIABILITY

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The aim was to investigate the effects of stride definitions on vector-coding for quantifying coordination-variability between the shank and rearfoot angles for strides extracted from heel-strike (HS) versus toe-off (TO) events. Subjects with chronic ankle instability were randomly assigned to control and balance-training groups (n=31). Three peaks of coordination-variability consistently existed near midswing, midstance and just before HS during treadmill walking at 1.32m/s. Variability only reduced near HS after balance training for the HS to HS stride definition (pre 0.45±0.14; post 0.34±0.12; $P<0.05$). The inconsistent findings with stride definitions may be owing to rapid changes in variability near HS that are sensitive to error sources and identification of stride events. Greater accuracy in extracting data is required to enhance the use of coordination-variability to explain movement.

**KEYWORDS:** balance training; chronic ankle instability; rehabilitation; vector-coding.

**INTRODUCTION:** The use of variability to analyze data and explore biomechanical concepts has been gaining growing support (van Emmerik & van Wegen, 2002; Bartlett *et al.,* 2007). Theories and definitions, and corresponding “relevant” variables and “appropriate” analyses, are being explored in the literature. One avenue can be referred to as coordination-variability, that is, the stability of the functional link between the muscles and joints used to produce the desired performance or outcome (Mullineaux, 2007).

Several techniques exist in the literature, although, specifically for coordination-variability over the entire cycle only Continuous Relative Phase standard deviation (CRPsd), Root Mean Square Difference (RMSD) and vector-coding have been used previously. It is more complicated to calculate CRP than either RMSD or vector-coding, which has resulted in more papers addressing assumptions, methods and interpretation of CRP (e.g. Hamill et al., 2000). In comparing these methods, in changing the angle definition from the flexor to extensor side only vector-coding was unaffected (i.e. it is reliable) – this coupled with its ease of calculation led to the proposal that it is the most suitable technique for quantifying coordination-variability in kinematic data (Mullineaux, 2007). It has been suggested that angle definitions, methods of interpolating for time normalization, starting point in the gait cycle and smoothing problems with end data could all affect validity of the analysis (Mullineaux & Wheat, 2002). As these issues have not been addressed, the aim of this study was to investigate the effects of stride definition on vector-coding for quantifying coordination-variability.

**METHODS**: Thirty-one subjects with chronic ankle instability volunteered and provided written informed consent to participate, and were randomly assigned to balance-training or control groups. The balance-training group (6m, 10f, age: 22.2±4.5 years) completed training 3-times per week for 4 weeks. The program consisted of progressive dynamic activities designed to challenge subjects' ability to maintain single limb stance. The control group (6m, 9f, age: 19.5±1.2 years) was required to maintain their current level of activity over 4 weeks.

All subjects completed two gait analyses separated by 5 weeks to accommodate the intervention period. Six markers (M1-6) were placed on the subject in the anatomical standing position (Neutral) in similar locations to that of Pohl *et al.* (2006), which in this position the defined angles were zerod. M1 to M4 formed a square and rigid cluster that was placed on the lateral aspect of the shank. M1 (top of fibula) and M2 (mid fibula) on the long axis of the tibia defined vector A. The forward global axis and vector A defined plane 1. M3 and M4 were anterior and posterior to the shank, which defined vector B. The angle between plane 1 and vector B defined the internal-external rotation of the shank (ShankIE). On the foot, M5 (lateral calcaneus) and M6 (sustentaculum tali) formed vector C. The angle between vectors A and C defined eversion-inversion of the ankle (AnkleEI)(see Figure 1). Following acclimatization to the treadmill, during five 15 s trials walking at 1.32 m/s, similar to speeds used in previous studies, the 3D coordinates of the six markers were recorded at 240 Hz using 10 Vicon cameras and software (Oxford Metrics, Oxford, UK). To provide a separate clinical assessment of improvement the Foot and Ankle Disability Index Sport questionnaire (FADI Sport) was completed pre and post testing.

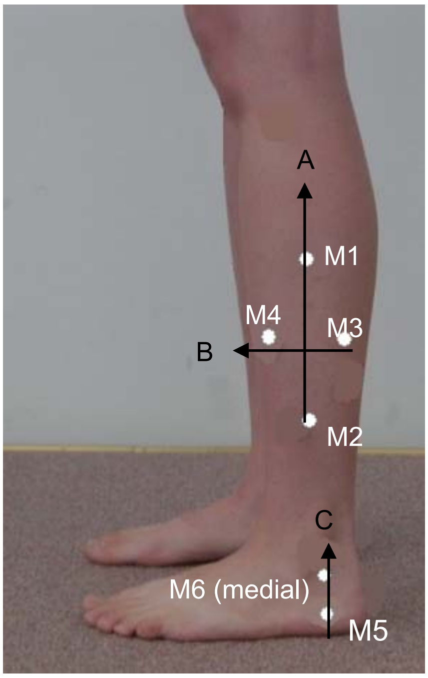

**Figure 1. Marker locations and vector definitions to define angles (see text for description).**

Data were analyzed using custom written code (MATLAB v2007b, MathWorks Inc., Natick, MA, USA). For each trial: data were smoothed using a fourth-order low pass filter with a 5 Hz cut-off frequency; angles calculated for ShankIE and AnkleEI; heel-strike (HS) and toe-off (TO) determined based on the algorithms of Zeni *et al.* (2008); three non-consecutive strides extracted; stride time normalized to 101 data points using a cubic spline interpolation, and; vector-coding calculated (Tepavac & Field-Fote, 2001). Next, systematic differences were reduced by subtracting the mean angle per trial from each trial. This offset-normalization alters zero, hence angles are described in terms of direction of motion for the ShankIE (increasing – internal; decreasing – external) and AnkleEI (increasing – eversion; decreasing – inversion). Data were obtained for three trials, and the data across these trials averaged.
Data were extracted based on two starting positions: HS and TO. For the ShankIE, AnkleEI and vector-coding values at HS, TO, maximum, and minimum or mean were compared using separate two-way mixed ANOVAs (Group v Time) using SPSS 15.0 for Windows (Chicago, IL, USA). The alpha level was set at 0.05 with no familywise error correction as the increased Type II error rate would likely mask new findings in this previously under-reported area. Descriptive statistics are presented as mean±SD.

**RESULTS:** All subjects displayed consistent patterns in angles and variability. A typical angle-angle plot pattern is illustrated in Figure 1A, although, diverse patterns existed between subjects. Four general phases (see Figure 1A) exist: 1-2 TO to midswing (shank internal rotation coupled with ankle inversion then eversion); 2-3 midswing to HS (shank external rotation with ankle inversion); 3-4 HS to midstance (shank internal rotation with eversion), and; 4-1 midstance to TO (shank internal rotation with ankle inversion).

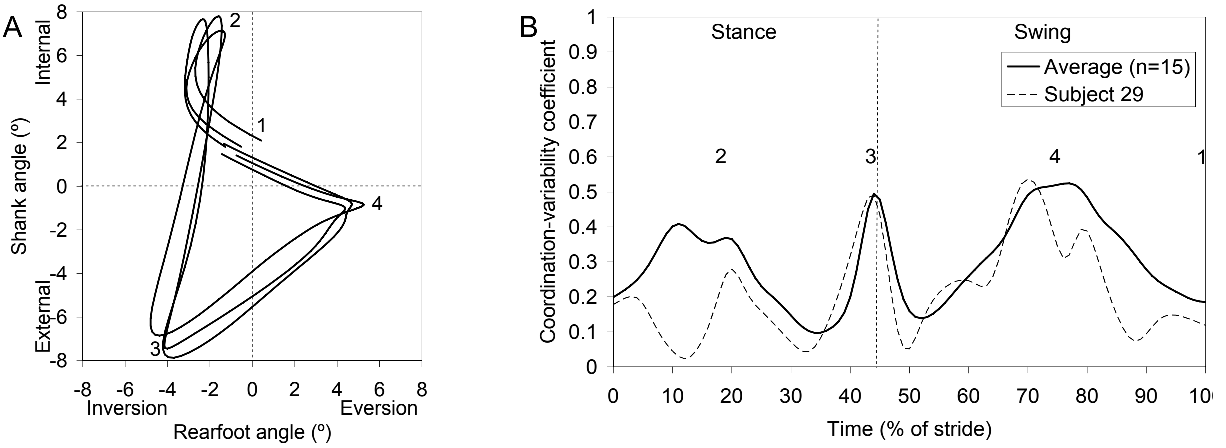

**Figure 1. Pre-control shank-ankle angle-angle: (A) plot for subject 29 walking on a treadmill, where zero is arbitrary but approximates to angles when in the anatomical standing position, and; (B) coordination-variability for 3 non-consecutive strides from TO to TO walking on the treadmill. Key moments: toe-off (1); midswing (2); heel-strike (3), and; midstance (4).**

With regard to variability, a common and consistent pattern emerged. The average pattern demonstrates three periods of increased coordination-variability (see Figure 1B). These three points, labelled 2, 3 and 4, approximately correspond to midswing, HS and midstance.

Of the three periods of increased variability, the largest occurred at mid-stance, followed by HS then by midswing. These events accompany periods of zero angular velocity. When the data were extracted from HS to HS, at HS the coordination-variability revealed a significant interaction with the control group remaining unchanged and the balance-training group decreasing (P<0.05; Table 1). In changing the extraction from TO to TO, the same pattern in variability occurred. However, with HS no longer at the end of the data, the variability was not statistically significantly different between groups. A significant interaction was also observed for the FADI Sport with an improvement in the balance-training group (pre 69.9±12.1; post 85.0±14.4%) versus no change in the control group (pre 66.5±9.8; post 66.3±11.8%; P<.05).

**Table 1. Angles and vector-coding descriptive statistics (means±SD) for stride definitions starting with heel-strike (HS) and toe-off (TO).**

| Instant | HS start | | | | TO start | | | |
|---|---|---|---|---|---|---|---|---|
| ShankIE(°) | Cpre | Cpost | BTpre | BTpost | Cpre | Cpost | BTpre | BTpost |
| HS | -12±5 | -13±4 | -11±4 | -12±4 | -12±5 | -13±4 | -11±4 | -12±4 |
| TO | 4±3 | 5±2 | 4±2 | 4±2 | 4±3 | 5±2 | 4±2 | 4±2 |
| Min | -12±5 | -13±4 | -11±4 | -12±4 | -12±5 | -13±4 | -11±4 | -12±4 |
| Max | 9±3 | 9±2 | 9±2 | 9±2 | 9±3 | 9±2 | 9±2 | 9±2 |
| AnkleEI (°) | | | | | | | | |
| HS | -2±1 | -2±1 | -2±1 | -1±1 | -2±1 | -2±1 | -2±1 | -2±1 |
| TO | -2±2 | -1±2 | -2±2 | -2±2 | -2±2 | -2±2 | -2±2 | -3±2 |
| Min | -5±2 | -4±1 | -6±1 | -6±1 | -5±2 | -5±2 | -6±1 | -6±1 |
| Max | 4±1 | 4±1 | 4±1 | 5±1 | 4±1 | 4±1 | 4±1 | 5±1 |
| VC (coefficient) | | | | | | | | |
| HS | .47±.20 | .50±.19 | .45±.14 | .34±.12 | .46±.13 | .47±.12 | .40±.10 | .42±.15 |
| TO | .18±.11 | .19±.10 | .26±.09 | .22±.07 | .19±.11 | .21±.09 | .25±.08 | .21±.09 |
| Max | .78±.10 | .78±.10 | .71±.11 | .74±.11 | .74±.13 | .77±.11 | .70±.11 | .72±.11 |
| Mean | .29±.07 | .28±.06 | .28±.06 | .28±.07 | .30±.08 | .30±.05 | .29±.06 | .29±.07 |

Variables are shank internal-external rotation (ShankIE; negative approximates to external), ankle eversion-inversion (AnkleEI; negative approximates to inversion) and vector-coding (VC; 0 no variability, 1 maximum variability). Instants are HS, TO, minimum (Min), maximum (Max) and average (Mean). Groups were control pre (Cpre) and post (Cpost), and balance training pre (BTpre) and post (BTpost). Statistically significant interaction is boxed (P<0.05).

**DISCUSSION**: The consistent pattern in coordination-variability is encouraging suggesting it may provide a useful tool to further our understanding of human motion. Large variability existed near the end of the swing phase, which has been reported previously in running where it is proposed to demonstrate "adaptability" to minimize the potential for injury (e.g. Heiderscheit *et al.,* 1999). In walking, the increase in variability found near HS may increase the likelihood of an "error", such as, the ankle "giving way" in subjects with chronic ankle instability. As it was found that balance-training decreased the variability at HS this may indicate a more stable relationship between the rearfoot and shank segments at this critical time period. The effect of training showed no differences in the angles, so possibly combinations of variables and multiple trials provided by coordination-variability may be more sensitive in distinguishing between groups as has been found previously with other spatial-temporal variables (van Wegen *et al.,* 2002).

Additional points at where increased variability was evident were near midstance and midswing. A number of events occur at these points including transition of the weight supporting leg from a braking to a propulsive phase at midstance. Mechanically, transitions are often instances where instability becomes more evident. At these two instances the rate of change in variability can be seen from Figure 1B to be slower than at HS. The ability to rapidly change variability may be functional, such as, to more quickly return to dynamic stabilization (Delahunt *et al.,* 2006). In the future, exploring instances of zero angular velocity particularly if it occurs in both angles may be beneficial, and calculating the rate of change of variability may provide greater insight into the role of variability. This might be relevant as despite the general pattern in angle-angle plots and variability (Figure 1), subjects did show consistent "individual" patterns. Individual deviations may be important, such as, indicating alternative or additional etiologies that may influence the results as variability is task dependent (Vaillancourt & Newell, 2002). For instance, the frequency of the variability for some subjects was low whereas for others it was high with rapid changes. The greater relative peaks with the high frequency may demonstrate more intentionality and functionality, if occurring at the correct instant, thus providing the required adaptability to correct for an unexpected event to prevent further injury.

Quantifying coordination-variability is sensitive to data treatment. First, in extracting consecutive strides and time-normalizing to 101 data points, when these are reattached to form consecutive strides "errors" for the HS-HS extraction were greater than for the TO-TO extraction. The higher frequency at HS from the greater angular velocity and larger impact forces likely contributes to this "error", which the spline-interpolation does not adequately cater for, resulting in artificially large coordination-variability values. Second, coordination-variability was found to contain a large frequency component, and in particular changed rapidly near HS. The method of defining HS and TO has a ±2 frame accuracy for treadmill walking (Zeni *et al.,* 2008), and is therefore not sufficiently accurate if coordination-variability is being calculated. Third, other factors that are often used to reduce variability on the premise it is noise may mask the "functional" noise or variability in the data. Rather than using an over-determined solution, using the least number of markers for the angle definition, and using the minimum of three trials for the calculation of coordination-variability may need investigating.

**CONCLUSION:** The overall pattern of coordination-variability was found to be similar between subjects over time. With balance training this variability reduced near HS, considered an important event in relation to injury (e.g. Heiderscheit *et al.,* 1999). However, as this finding was not consistent with different stride definitions further data analysis considerations are required to improve the reliability of coordination-variability prior to interpreting any interventions. The method of identifying key events for extraction of trials needs to be more accurate as at times vector-coding has a high frequency component which can change rapidly and is thus sensitive to errors in defining key events. Smoothing data in phases with padding may be beneficial, but the effects of time-normalization to create strides of equal length and of trial-normalization in vector-coding should both be appraised. Investigating other options, such as, marker placement, marker sets and trial size could all be important. Vector-coding results are as expected and correspond with the FADI Sport clinical improvements providing support for face-validity, however more robust validity assessments such as criterion validity are still required to confirm the appropriateness and meaningfulness of vector-coding as a measure of coordination-variability in biomechanics.

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