WITHIN-DAY REPEATABILITY OF COORDINATION VARIABILITY MEASURES ACROSS THE RUNNING GAIT CYCLE

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The purpose of this study was to identify the within-day repeatability of coordination variability calculated using a velocity ellipse area method. Twenty participants attended two data collection sessions within 6 hours. At each session, a marker based motion capture system measured kinematics whilst participants ran at 12 km/h on a treadmill. The minimum detectable change in coordination variability was calculated for four commonly researched joint/segment couplings. Of the couplings investigated, thigh flexion/extension – shank flexion/extension and hip flexion/extension – knee flexion/extension were most repeatable. But in the most repeatable coupling, an average change of 75% across the gait cycle would be required between sessions to detect a meaningful change. This indicated poor repeatability and possible causes are discussed.

KEYWORDS: vector coding, absolute reliability, MDC

INTRODUCTION: Variability in the way that humans execute movement is inevitable because small amounts of error are introduced at every level and stage of a movement (Bays & Wolpert 2007). Researchers have however provided supporting evidence that variation in motor behaviours are not always a result of error. In some situations, higher levels of variability in movement have been suggested to be functional. For example, expert performers can make continual functional adaptations to adapt to the interacting constraints they experience (Seifert et al. 2013) and in learning, movement variability can indicate exploration for the most successful movement pattern (Muller & Sternad 2004). Furthermore, it has been suggested that there is an optimal amount of variability that may be a sign of healthy movement with reduced risk of injury (Hamill et al. 2012). Human movement is achieved via a complex system of linked segments and movement at one segment or joint impacts on neighbouring segments and joints. Researchers have therefore looked to investigate the variability not just of movement, but of the coordination of movements. Angle-angle plots (also known as relative motion plots or cyclograms) are one of multiple methods for depicting movement coordination patterns and a number of different methods for calculating coordination variability have been based on these plots (Hamill et al. 2000, Tepavac & Field-Fote 2001, Stock et al. 2018, Mulloy et al. 2019). However, methods that use circular statistics are affected by a statistical artefact when the distance between points on the angle-angle plot is small (Stock et al. 2018). Repeatability (also known as absolute reliability) is the closeness of agreement between results of successive measurements carried out under the same conditions (Taylor & Kuyatt, 1994). To date, no publications have measured the repeatability of coordination variability calculated from angle-angle plots in running gait. Repeatability measures help researchers to understand how much variation can be expected due to random fluctuation and therefore how much change is needed to increase confidence that a real difference is present between groups or has been observed in an individual (Hopkins 2000). Thus, the aim of this research was to investigate the within day, intra-tester repeatability of coordination variability calculated using the Velocity Ellipse Area method, a method which does not use circular statistics.

METHODS: Twenty athletes (10 male, 10 female) who participated in running events of 5 km distances or greater were recruited from the university triathlon and athletics clubs. Participants were between 18-35 yrs, free from neurological conditions, and had been training without injury for at least 1 month prior to their participation. All participants provided informed consent and the study was approved by the University of Bath Research Ethics Approval Committee for Health (REACH).

Each participant attended two data collection sessions separated by a minimum of three hours and a maximum of six. In each session, a lower limb marker set was applied by the same tester, a static recording of marker positions was collected, and then medial markers were removed to avoid obstruction of natural gait patterns. In the first session, images were taken of marker positions that were used to check consistency of placement when the participant returned for the next session. Participants conducted a five minute, incremental warm up starting at 8 km/h and increasing by 1 km/h each minute. They then stopped running so that the secure attachment of all markers could be checked. Following this, the participant ran for five minutes at 12 km/h with the final minute being recorded by the motion capture system.
Marker trajectory data were exported to Visual 3D (v.6, C-Motion, USA). The trajectories were filtered with a low-pass second order recursive Butterworth filter with an 8 Hz cut off frequency. Segment and joint angular velocities for the right leg were calculated and exported to MATLAB (2018b, Mathworks, Natick, USA). In MATLAB a custom script employed the foot-contact algorithm (Handsaker, Forrester et al. 2016) to identify consecutive foot strikes for each gait cycle. These foot-strike events were used to register each gait cycle to 101 temporal nodes (i.e. 0 to 100% of the gait cycle). The first 20 strides collected were used for calculation of coordination variability using the Velocity Ellipse Area method (Stock et al. 2018, Stock et al. 2018b, Stock et al. 2019) for four coupling combinations: thigh flexion/extension – shank flexion/extension, shank transverse rotation – foot inversion/eversion, hip flexion/extension – knee flexion/extension, knee flexion/extension – ankle in/eversion. These couplings were selected due to their prevalence in the literature. The angular velocity of one segment/ joint (ω_1) was plotted against another (ω_2). Ellipses were created around ω_1 and ω_2 coordinates from each of the 20 gait cycles at each temporal node using the equations provided by Duarte and Zatsiorsky (2002) with the size scaling adjusted according to the chi-squared value suggested by Mullineaux (2017). Using these approaches, an ellipse was created so that there was a 95% chance that a future data point would be situated within the ellipse. The greater the area of the ellipse the more variability there is in coordination. The minimum detectable change (MDC) was then calculated at each percentage of the gait cycle (Bland & Altman 1996). MDC is a measure of repeatability that represents the minimum change in value that 95% of pairs of observations would not exceed purely because of measurement fluctuation (Bland & Altman 1996). To quantify the magnitude of the MDC in relation to the magnitude of the coordination variability that was measured, an average ellipse area signal was calculated from all participants' data in both sessions. The MDC was then expressed as a percentage of this average value to show the magnitude of the MDC compared to that of the measure itself.

RESULTS: The two sagittal plane couplings had the smallest MDC values; their average MDCs across the gait cycle were less than half those of the couplings which included motions outside of the sagittal plane (Table 1, Figure 1). The shank rotation – foot inversion/eversion and knee flexion/extension – ankle inversion/eversion coupling MDC values were most affected by the period of the gait cycle with standard deviations about the mean gait cycle value in excess of 6000 $^{\circ 2} \cdot s^{-2}$ (Table 1, Figure 1). The relative magnitude of each MDC averaged across the gait cycle compared to the average ellipse area recorded across participants and sessions was at best 75% (hip flexion/extension – knee flexion/extension) and at worst 94% (knee flexion/extension – ankle in/eversion) (Table 1, Figure 1).

Table 1. Minimum Detectable Change in coordination variability averaged across the gait cycle and expressed as a percent of the value recorded for each coordination coupling

Coupling	Average over the gait cycle	
	MDC ($^{\circ 2} \cdot s^{-2}$)	MDC percent of value (%)
Thigh flexion/extension- Shank flexion/extension	3,400 ± 1,900	77
Shank transverse rotation – Foot in/e-version	13,000 ± 8,000	92
Hip flexion/extension- Knee flexion/extension	5,300 ± 2,700	75
Knee flexion/extension – Ankle in/e-version	11,400 ± 6,000	94

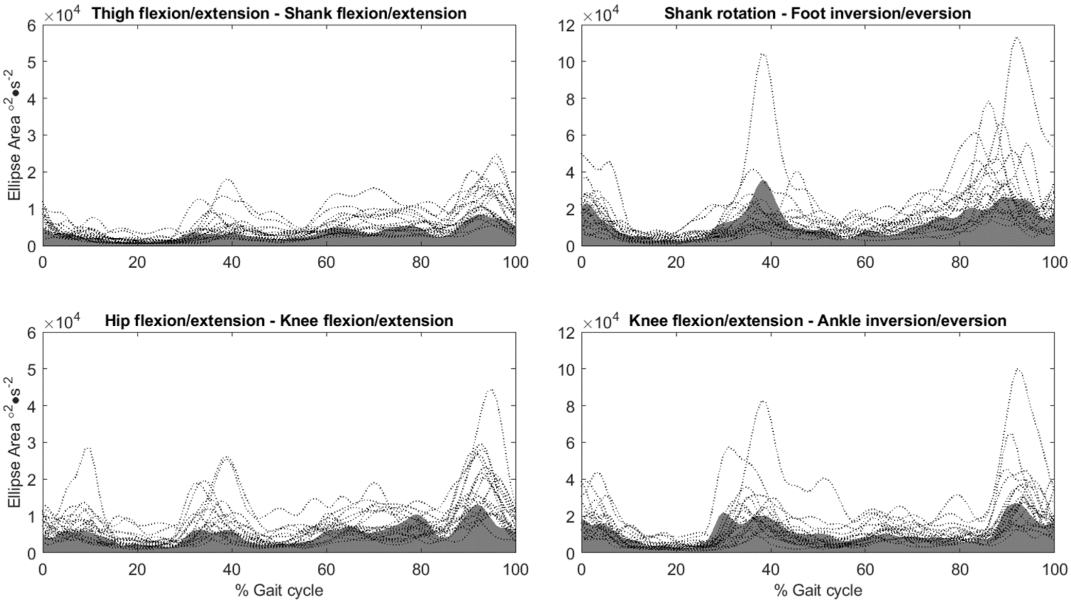

Figure 1. The minimum detectable change of coordination variablity measured using the velocity ellipse area is represented by the shaded areas. Dotted lines indicate the coordination variability for all twenty participants from the first testing session. N.B. the scaling on the plots to the left represent half the magnitude of the plots on the right.

DISCUSSION: The aim of this research was to investigate the within-day repeatability of coordination variability calculated using the Velocity Ellipse Area method during running for four commonly used coordination couplings. Minimum detectable change (MDC) time series (Figure 1) and average MDCs (Table 1) were presented and should be used in future research that investigates differences and changes in coordination variability during specific phases of running or across the entire gait cycle respectively. A metric representing the magnitude of the MDC in relation to the magnitude of the signal was also presented that was suggestive of poor repeatability. On average, the coordination variability of thigh flex/ext – shank flex/ext and hip flex/ext – knee flex/ext couplings was more repeatable than for shank rotation – foot in/eversion and knee flex/ext – ankle in/eversion.

In the best example observed, the magnitude of the MDC was 75% of the average coordination variability across the gait cycle (Table 1). Consequently, a researcher would have to observe changes of greater than 75% for a difference to be detected between sessions that was greater than can be expected due to random fluctuations. Furthermore, in those cases where the absolute value of coordination variability was lower than the MDC (e.g. in Figure 1 where any dotted lines lie within the shaded area) it would be impossible to detect a reduction in variability at a subsequent session using the MDC alone as a guideline. There are three possible reasons why the MDC may be high: 1) The MDC did not account for the distribution and heteroscedasticity of the data; 2) coordination may be highly variable between sessions; and, 3) the method used to measure variability may be too sensitive to possible outliers in the dataset and therefore exaggerate variation between sessions. Future research should look to further develop one-dimensional measures of repeatability and understand whether ellipse area calculations can be made more robust to outliers.

Compared to shank rotation – foot in/eversion and knee flex/ext – ankle in/eversion, the coordination variability of the thigh flex/ext – shank flex/ext and hip flex/ext – knee flex/ext couplings demonstrated: smaller MDCs, less variation in MDC as a function of percent of the gait cycle, and MDCs which were smaller in relation to the magnitude of the signal itself (Table 1). These findings could be explained by increased repeatability of sagittal plane movements compared to non-sagittal movements as has been observed for joint angles in gait (McGinley et al. 2009).

CONCLUSION: Researchers are often interested in detecting changes in participants or differences between groups of participants and measures of repeatability allow researchers to understand if changes and differences are meaningful. This research demonstrated one of the best possible cases for measuring repeatability (e.g. within day testing and repeat marker placement controls). However, the results indicated that large changes (often in excess of 75% of the magnitude of the average signal) would need to be observed between sessions to demonstrate meaningful change in coordination variability. Of the couplings investigated, thigh flexion/extension – shank flexion/extension and hip flexion/extension – knee flexion/extension were most repeatable, but overall, researchers may struggle to detect meaningful differences in coordination variability measured using the Velocity Ellipse Area method in its current form.

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