Stable Coordination Variability in Overground Walking and Running at Preferred and Fixed Speeds

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Abstract

Coordination variability is commonly analysed to understand dynamical qualities of human locomotion. The purpose of this study was to develop guidelines for the number of trials required to inform the calculation of a stable mean lower-limb coordination variability during overground locomotion. Three-dimensional lower-limb kinematics were captured for 10 recreational runners performing 20 trials each of preferred and fixed speed walking and running. Stance phase coordination variability was calculated for nine segment and joint couplings using a modified vector coding technique. The number of trials required to achieve a coordination variability mean within 10% of 20 strides was determined for each coupling and individual. The statistical outputs of mode (walking vs running) and speed (preferred vs fixed) were compared when informed by differing numbers of trials. A minimum of 11 trials were required for stable mean stance phase coordination variability. With fewer than 11 trials, coordination variability was underestimated and led to an oversight of significant differences between mode and speed. Future overground locomotion coordination variability research in healthy populations using a vector coding approach should use 11 trials as a standard minimum. Researchers should be aware of the notable consequences of an insufficient number of trials for overall study findings.

Keywords: *vector coding, segment coupling, joint coupling, reliability*

Introduction

The human body consists of multiple degrees of freedom which coordinate to produce movement. During repetitive, cyclic motion such as walking and running, the coordination of segments and joints inherently exhibits variability from one cycle to the next, that is, coordination used to produce a stride will always differ to some extent from the previous strides[1]. Calculating the degree of coordination variability during human movement permits insight into the ability of the system to adapt to perturbations and how coordination variability is influenced by injury or pathology[2].

Efforts to measure these systemic changes between consecutive trials in a manner that is representative of a participant's movement patterns, requires the determination of the number of trials necessary to achieve stability of the mean[3]. If too few trials are considered, the coordination variability outcomes may not represent a valid measure of an individual or group and may have a considerable effect on the reliability and subsequent interpretation of the research finding[4].

Previous research investigating coordination variability during locomotion has been informed by trial numbers ranging from 5[5,6,7] to 15[8,9]. Various features of locomotion are anticipated to contribute to the number of trials needed to reach a stable mean and suitably reflect group coordination variability outcomes; these features include mode (walking or running), speed (preferred or fixed) and surface (treadmill or overground). Due to the systematic regulation of dynamic neuromuscular control that the treadmill imposes, the environmental may moderate coordination variability throughout the stance phase. Therefore, although researchers have previously identified the need for 8 walking and 10 running strides for the analysis of coordination variability[10], the guidelines are based on treadmill-based locomotion and may not adequately extend to overground locomotion. Furthermore, kinematic variability by means of root mean square differences has been reported to be lower in

locomotion performed on a treadmill compared to overground[11] and key mechanical differences between the two environments have been emphasised[12]. As locomotion primarily occurs overground, guidelines for the number of trials (gait cycles) which inform the calculation of coordination variability in overground locomotion are warranted.

Therefore, the purpose of the research was to develop guidelines for the number of trials required to calculate stable mean lower-limb coordination variability during overground locomotion. Two research questions were developed: 1) How many trials are needed to establish the stable mean coordination variability output for different couplings? 2) To what extent is the magnitude of coordination variability impacted by the number of trials considered? We hypothesised that overground locomotion would impose less constraint on lower-limb motion, therefore requiring a greater number of trials to achieve stable coordination variability outcomes than treadmill locomotion. We additionally hypothesised the number of trials used to calculate coordination variability would significantly influence the magnitude of coordination variability outputs.

Methods

A power analysis using thigh-shank coupling (transverse and sagittal) data during walking and running, informed by previous coordination variability literature[13], established the need for a minimum of six participants within the current study (<80% power, alpha = 0.05, effect size (ES) = 1.4). For this study, five female and five male recreational runners (age: 26.4 ± 2.8 years, mass: 66.88 ± 12.34 kg and height: 1.72 ± 0.10 m) were recruited to meet the power requirements. All participants were free from injury, had not sustained any serious lower extremity injuries within the year prior to testing and engaged with regular recreational running (a minimum of once per week). Approval for the research was obtained from the University Institutional Review Board and written informed consent was obtained from all participants.

Unilateral lower-limb three-dimensional (3D) kinematic data were captured at 240 Hz using an 11-camera motion capture system (Oqus 3, Qualisys Inc., Gothenburg, Sweden). An embedded 1.2 x 0.6 m force plate sampling at 1200 Hz (AMTI, Watertown, MA) enabled synchronous recording of ground reaction force data to determine heel strike and toe-off event identification. Twenty-six retroreflective markers, including 4-marker rigid clusters were affixed to the pelvis, right thigh, leg and foot as per a customised marker set[14,15]. The same researchers placed markers for all collections. All participants wore standardised laboratory running footwear (T7; Brooks Sports, Seattle, USA).

Participants completed walking and running trials at preferred and fixed locomotor speeds (fixed running speed: 3.2 $m \cdot s^{-1}$; fixed walking speed: 1.3 $m \cdot s^{-1}$). Preferred walking and running speeds were determined using the protocol of Hamill et al.[16]. Twenty trials were completed for each gait condition in a randomised block order. All trials were completed over a 20 m runway, followed by a sufficient rest period (30s minimum) to reduce fatiguing effects. A successful trial was determined by full foot force plate contact and, for the fixed-speed trials, velocity within ± 5% of the specified speeds, measured by two timing gates positioned 6 m apart.

Markers were identified and tracked using Qualisys Track Manager (Qualisys, Inc., Gothenburg, Sweden). 3D marker coordinate data were imported to Visual 3D software (C-Motion Inc., Rockville, MD). Marker coordinate data were filtered using a low-pass bi-directional Butterworth filter at 7 Hz, determined by residual analysis calculation[17]. Angular data for knee and ankle joints, and thigh and shank segments were calculated using a Cardan X-y-z sequence of rotations[18]. Data outputs were normalized to 101 points for the stance phase (heel strike to toe-off). Stance phase events were identified when vertical ground reaction force crossed a 10 N threshold.

Inter-segment and inter-joint coordination analyses were completed using time-normalised angular data (0-100% stance). Angle-angle plots were computed for adjacent segments and joints using a modified vector coding technique[19]. Coordination variability was calculated at each frame-to-frame interval as the circular standard deviation of the consecutive coupling angle point vectors[20]. Mean stance phase coordination variability was then calculated for each individual. The variability of each inter-segment and inter-joint coordination coupling was calculated using 2, 3, 4…..20 trials for each participant in each condition. When normalised to 20 trials, mean coordination variability outputs for each coupling reached a plateau (Figure 1); therefore, a maximum of 20 trials was used to analyse the stability of the mean coordination variability outputs.

Vector coding coordination variability analysis was performed for a 2 to 20 trial range for each participant; the vector coding process was repeated 19 times for each coupling and each condition. The number of trials informing coordination variability analysis (CV*n*) outputs were compiled for each participant; a matrix of 100 x 19 was produced for each participant with rows representing stance time (1-100%) and columns representing coordination variability outputs calculated using each trial *n* (CV*n*). Each cell of the matrix was then normalized to the corresponding coordination variability output calculated from 20 trials using the following equation:

$$CV\%norm20 = \left(\frac{CV_n}{CV\ calculated\ using\ 20\ trials}\right)$$

Mean $CV\%_{norm20}$ was subsequently calculated for each CV*n* output, producing an average coordination variability across stance (1 x 19 matrix) for each participant, coupling and condition. In accordance with the criterion used by Hafer and Boyer[10], the trial *n* at which mean $CV\%_{norm20}$ reached 100 ± 10% was identified on an individual basis, indicating a < 10% difference between coordination variability calculated using 20 trials and the respective CV*n*.

Trial *n* stability (within ± 10% of the 20-trial average) was then averaged across participants for each coupling.

The maximum number of trials required to achieve stable mean coordination variability across all individuals and all couplings was determined for preferred and fixed speed running and preferred and fixed speed walking conditions. The greatest number of trials was presented as a guideline for future research (research question 1). For research question 2, mean stance phase coordination variability values were compiled when calculated using 5 trials, as the minimum used in previous research, in addition to the number of trials found to produce a stable mean (research question 1 output).

Preferred and fixed walking and running group mean speeds were compared with paired t-tests with significant differences reported at $p < .005$. Cohen's *d* ES were calculated and defined as small (.2), moderate (.5) and large (.8)[21]. Coordination variability data for research question 2 were calculated using 5 trials and the number of trials determined in research question 1. Paired t-tests and ES were used to compare coordination variability during walking vs running at preferred vs fixed speeds. A criterion alpha (α) of .05 was set *a priori* for all coupling comparisons with a Bonferroni adjustment at .005 for multiple comparisons. All statistical analyses were conducted in SPSS (IBM SPSS Statistics 23, SPSS Inc., Chicago, IL).

Results

Preferred running (2.9 ± 0.5 $m \cdot s^{-1}$) was slower and preferred walking was faster (1.4 ± 0.2 $m \cdot s^{-1}$) than fixed running (3.2 $m \cdot s^{-1}$) and walking speeds (1.3 $m \cdot s^{-1}$), respectively ($p < .001$).

Between 6 and 11 trials were required to achieve coordination variability mean stability within 10% of a 20-trial mean for all couplings considered within this study (Figure 1, Table 1). The number of trials required to assure stable mean stance phase coordination variability across couplings (i.e., coupling with the highest number of trials required to achieve stable

coordination variability) was 11 for preferred speed running and fixed speed walking and 10 for fixed speed running and preferred speed walking (Table 1).

<<Insert Figure 1 around here>>

<<Insert Table 1 around here>>

Overall, mean stance phase coordination variability was found to be underestimated when calculated using fewer trials (Figure 2). Mean stance phase coordination variability differed by up to 11.2° when 2 trials were used compared to the 20-trial mean.

As the minimum number of trials to calculate coordination variability in the previous literature was 5, paired t-tests determined the extent to which statistical comparisons of mode and speed were impacted by the number of trials used to inform coordination variability analysis (5 or 11 trials). Statistical differences in the degree of coordination variability ($p < .005$) between walking and running at a preferred speed were identified for six couplings when 11 trials were used, but only three couplings when 5 trials were used (Table 2). The differing statistical outputs were: hip flexion/knee flexion (5 trials, $p = .011$, ES = 1.66; 11 trials, $p = .001$, ES = 1.47), hip abduction/knee flexion (5 trials, $p = .030$, ES = 1.38; 11 trials, $p < .001$, ES = 3.00) and thigh flexion/shank flexion (5 trials, $p = .007$, ES = 1.38; 11 trials, $p = .005$, ES = 1.05).

<<Insert Figure 2 around here>>

<<Insert Table 2 around here>>

Discussion

The purpose of this study was to develop guidelines for the number of trials required to calculate stable mean lower-limb coordination variability during overground locomotion. To address the study purpose, we first sought to determine the number of trials needed to establish stable mean coordination variability for different joint/segmental couplings. The study findings indicated 11 trials should be used as a standard minimum for the calculation of lower-limb coordination variability in overground locomotion. To achieve a stable mean, overground preferred speed running required more strides (n = 11) than previously found for treadmill preferred speed running (n = 8)[10]. Therefore, we accept our first hypothesis. In addition to the key mechanical differences that have been identified between the treadmill and overground environments[12], some differences in mean stability findings between the current study (overground) and Hafer and Boyer's[10] previous (treadmill) findings may be accounted for by the different analysis approaches. To ensure individual differences were not washed out, the current study calculated the stable mean (within 100±10% of the 20-trial average) on an individual basis and then averaged across participants, whereas Hafer and Boyer's[10] analysis was based on the overall group stable mean.

Variability in coordinated segment and joint motion patterns increased when more trials were considered. The use of too few trials resulted in coordination variability being underestimated by up to 39% of the coordination variability found using 11 trials (11.2° difference), illustrating potential for the number of trials to have a substantial influence on study findings. Therefore, we accept our second hypothesis. The variables which were most influenced by trial number were shank rotation/foot inversion, thigh rotation/shank rotation and knee rotation/ankle inversion, for which coordination variability was up to 6° lower when calculated using 5 compared to 11 trials. In agreement with previous findings by Heiderscheit et al.[9], couplings with a rotational component had the greatest level of coordination variability

across stance, which is likely why they were found to be influenced by trial number to the greatest extent. Future research should further investigate the finding that the faster speeds of each locomotion mode (i.e. fixed running and preferred walking) required fewer trials to establish stable mean coordination variability (Table 1).

As research findings commonly rely on the interpretation of a pre-determined probability value, research question 2 was established to better understand the practical consequences of the number of input trials on the magnitude of coordination variability. In essence, how might the number of trials directly influence the statistical significance and magnitude of this effect? Not only were too few trials found to detect fewer *p*-value differences between modes of locomotion but use of 5 trials also resulted in ES being up to 1.62 smaller than when 11 trials informed the coordination variability calculation. As the study findings revealed, future research comparing coordination variability between modes of locomotion should be cautious of potential for the number of trials to have a direct impact on study outcomes.

In conclusion, the current research findings indicate the need for a minimum of 11 trials to produce a stable mean and contribute to reliable biomechanical outputs. The use of too few trials to calculate coordination variability in a healthy population was found to result in the detection of fewer statistically significant findings when comparing between locomotion conditions, with potentially notable consequences for overall study findings.

Acknowledgements

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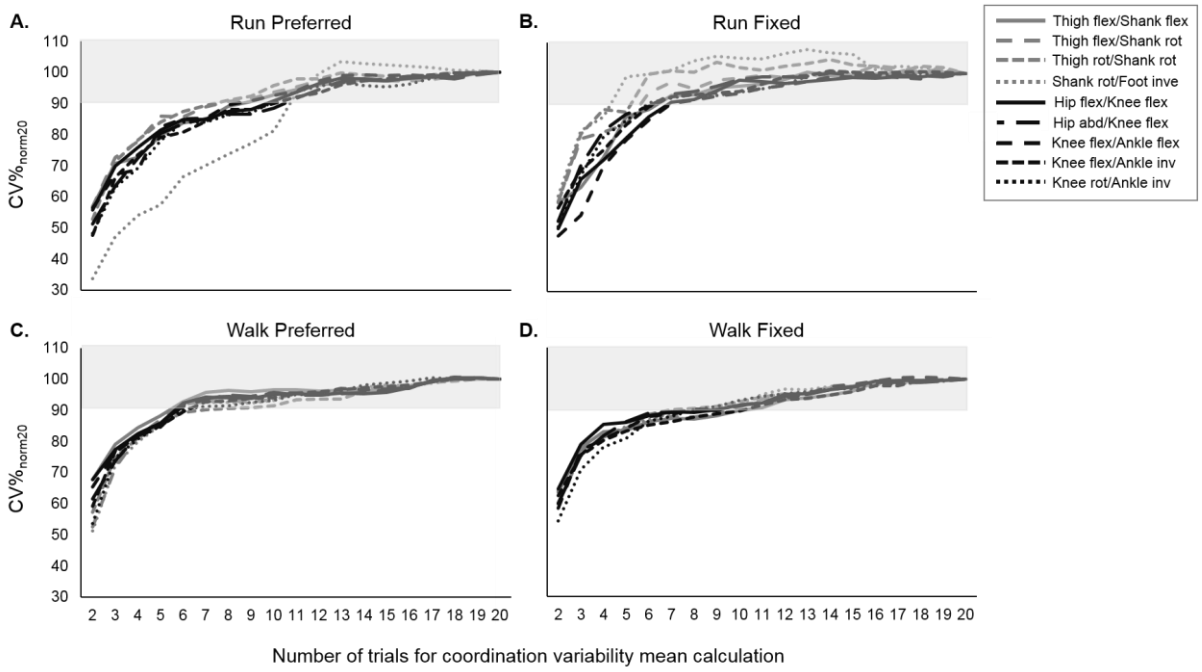

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Tables

Table 1. Group mean ± SD and the maximum number of trials required to achieve coordination variability within a 10% range of 20 trials for segment and joint couplings during walking and running at preferred and fixed speeds.

Couplings	Preferred Running	Fixed Running	Preferred Walking	Fixed Walking
Segment Couplings				
TS_{xx}	8 ± 4	9 ± 5	7 ± 5	11 ± 5
TS_{xz}	8 ± 5	10 ± 3	9 ± 5	10 ± 3
TS_{zz}	8 ± 4	7 ± 3	10 ± 5	8 ± 4
SF_{zy}	11 ± 1	6 ± 1	9 ± 5	9 ± 3
Joint Couplings				
HK_{xx}	9 ± 4	7 ± 3	8 ± 4	10 ± 5
HK_{yx}	11 ± 3	7 ± 4	8 ± 5	9 ± 5
KA_{xx}	9 ± 5	10 ± 4	6 ± 4	8 ± 4
KA_{xy}	10 ± 4	8 ± 4	8 ± 5	11 ± 5
KA_{zy}	9 ± 4	8 ± 4	9 ± 4	10 ± 4
Max threshold trial *n*	**11**	**10**	**10**	**11**

Note. TS_{xx} = thigh flexion/shank flexion; TS_{xz} = thigh flexion/shank rotation; TS_{zz} = thigh rotation/shank rotation; SF_{zy} = shank rotation/foot inversion; HK_{xx} = hip flexion/knee flexion; HK_{yx} = hip abduction/knee flexion; KA_{xx} = knee flexion/ankle flexion; KA_{xy} = knee flexion/ankle inversion; KA_{zy} = knee rotation/ankle inversion

Table 2. Paired t-test p-values for preferred vs fixed and walking vs running coordination variability comparisons when calculated using 5 and 11 trials.

Couplings	Preferred vs Fixed Running		Preferred vs Fixed Walking		Preferred Walking vs Running		Fixed Walking vs Running	
	5 trials	11 trials	5 trials	11 trials	5 trials	11 trials	5 trials	11 trials
Segment Couplings								
TS_{xx}	**< .001**	**< .001**	.485	.597	.007	**.005**	**.003**	**< .001**
TS_{xz}	**< .001**	**< .001**	.745	.208	.028	.009	.033	.017
TS_{zz}	**.003**	**< .001**	.042	.029	.107	.305	.204	.061
SF_{zy}	**< .001**	**.002**	.165	.163	.103	.214	.022	.025
Joint Couplings								
HK_{xx}	.748	.109	.152	.085	.011	**.001**	**.005**	**.002**
HK_{yx}	.759	.053	.160	.178	.030	**< .001**	**.001**	**.002**
KA_{xx}	.409	.036	.079	.17	**< .001**	**< .001**	**< .001**	**< .001**
KA_{xy}	.346	.180	.083	.104	**< .001**	**< .001**	**< .001**	**< .001**
KA_{zy}	.372	.654	.308	.101	**< .001**	**.001**	**.001**	**.001**

316 *Note*. Bold values indicate a significant difference ($p < .005$) and grey shading indicates a
317 difference in statistical interpretation between 5 and 11 trials.

Figure Captions

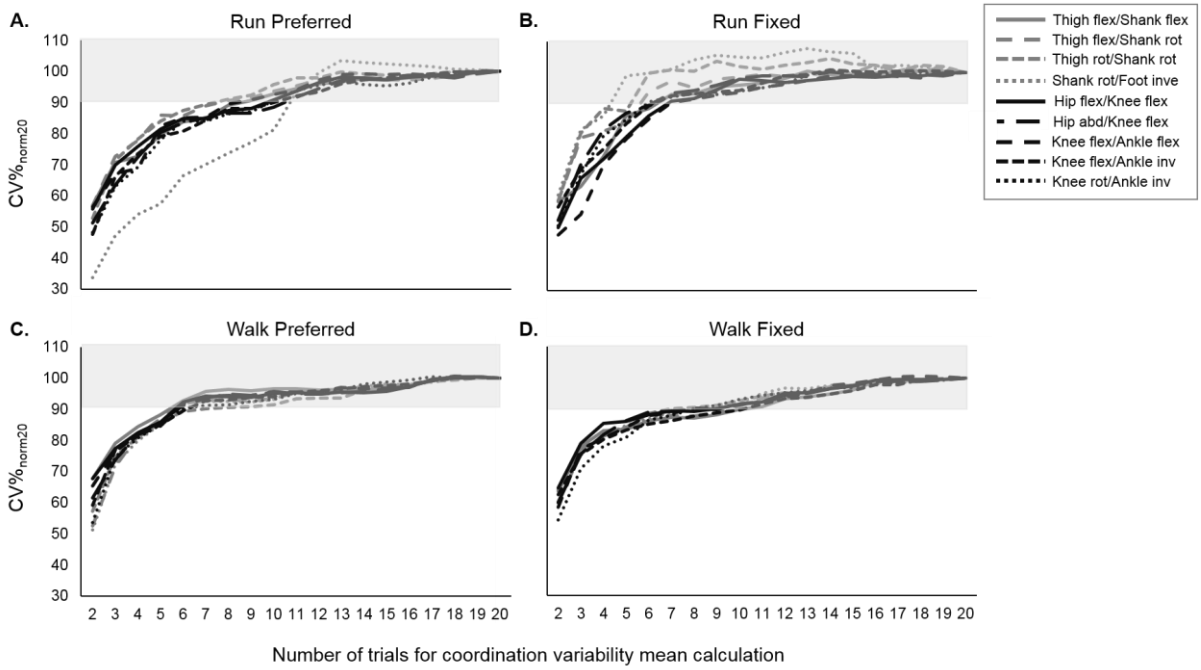
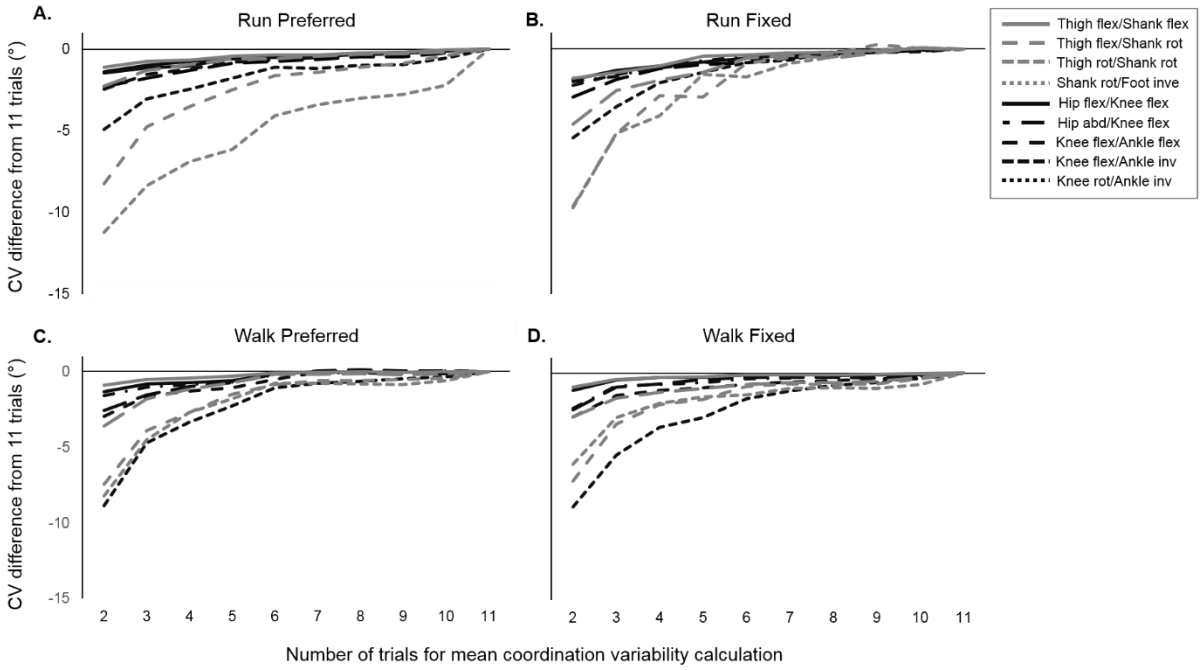


Figure 1 – Mean stance phase coordination variability (CV) as a per cent of coordination variability calculated using 20 trials ($CV\%_{norm20}$) during A) preferred running, B) fixed running, C) preferred walking and D) fixed walking for 2-20 trials. Grey shading indicates the region for which CV*n* outputs are within 100±10% of $CV\%_{norm20}$.



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327 **Figure 2** – Mean stance phase coordination variability (CV) difference from 11 trials during

328 A) preferred running, B) fixed running, C) preferred walking and D) fixed walking.