COORDINATION VARIABILITY IN OVERGROUND RUNNING AND WALKING AT PREFERRED AND FIXED SPEEDS

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Coordination variability (CoordV) is impacted by the type and speed of locomotion, however, the appropriate number of trials required for stable outputs during overground locomotion is yet to be determined. The purpose of this study was to analyse the CoordV of lower limb segment and joint couplings to determine the number of trials needed for a stable mean during running and walking at preferred and fixed speeds. Three-dimensional lower-limb kinematics were captured for recreational runners (n = 10) performing 20 trials of each condition. Using a modified vector coding technique, segment and joint couplings were derived, from which, CoordV was calculated using circular statistics. The number of trials required to achieve a mean within 100±10% of a 20 stride mean was determined for each individual. The study findings indicate the need for between 8 and 9 trials to produce a stable mean and contribute to reliable biomechanical outputs.

KEYWORDS: reliability, vector coding, segment coupling, joint coupling, gait.

INTRODUCTION: During locomotion, segment and joint coordination variability (CoordV) provide insights into the flexibility of the system for adaptation to perturbations (Hamill et al., 1999). CoordV is typically calculated using between five and 15 trials. The number of trials used to inform CoordV calculations influences the stability of the mean, which in turn, impacts the reliability of biomechanical outputs.

As a result of differing mechanical demands, the number of trials needed to produce a stable mean may differ in accordance with the type and pace of locomotion. CoordV during running has been found to vary between environments which allow for speeds to be standardised, such as a treadmill, and those which are less constrained, such as overground (Wheat et al., 2005). Previous research has investigated the number of trials required to produce stable CoordV means during treadmill running and walking at a preferred pace (Hafer and Boyer, 2017). However, due to mechanical and neuromuscular control differences, the treadmill findings do not extend to overground locomotion.

Biomechanical studies of walking and running have for different purposes, analysed gait at preferred and fixed speeds. When moving at a fixed locomotor speed, conscious coordination of segments and joints is required to maintain a set pace which may lead to greater variability. It is therefore speculated that a different number of trials may be necessary to generate a stable CoordV mean in relation to different conditions of locomotion.

The variability of both segment and joint coordination have been previously considered in lower limb research. The mechanics of coupled segments compared to coupled joints inherently integrates differing numbers of degrees of freedom, for example, when assessing thigh-shank couplings, the interaction of hip, knee and ankle motion collectively impact the kinematic outputs, however, when assessing knee-ankle couplings, the interaction of the foot, shank and thigh underpin the output. The distinctions between segment and joint CoordV may lead to a differing number of trials to be required to produce a stable mean. Therefore, the purpose of this study was to analyse lower limb segment and joint couplings to determine the number of trials needed to establish a stable mean which is necessary for the reliable calculation of CoordV in overground locomotion.

METHODS: Participants: Five females and five male recreational runners were recruited (mean age: 26.4 ± 2.8 years, mass: 66.88 ± 12.34 kg and height: 1.72 ± 0.10 m). **Protocol:** Participants completed 20 running and 20 walking overground trials at both preferred and fixed speeds. Unilateral lower-limb three-dimensional (3D) kinematics data were captured at 240 Hz using an 11 camera motion capture system (Oqus 3, Qualisys Inc., Gothenburg, Sweden). **Data analysis:** Using Visual 3D software (C-Motion Inc., Rockville, MD), the lower extremity was modelled as a rigid, linked-segment system inclusive of the pelvis and right thigh, shank and foot segments. Segment couplings included thigh flexion/shank flexion (TS_{xx}), thigh flexion/shank rotation (TS_{xz}), thigh rotation/shank rotation (TS_{zz}) and shank rotation/foot inversion (SF_{zy}). Joint couplings included hip flexion/knee flexion (HK_{xx}), hip abduction/knee flexion (HK_{yx}), knee flexion/ankle flexion (KA_{xx}), knee flexion/ankle inversion (KA_{xy}) and knee rotation/ankle inversion (KA_{zy}).
Time-normalised angular data (0-100% stance) informed the calculation of inter-segment and inter-joint coordination using a modified vector coding technique (Chang et al., 2008). The variability of each coupling angle over multiple cycles (trial n = 2-20) was then calculated at each frame-to-frame interval as the circular standard deviation of the consecutive coupling angle point vectors (Bachelet, 1981).
To assess inter-trail CoordV stability for each coupling and each condition, vector coding outputs were separately compiled for each output informed by between 2 and 20 trials (CoordV*n*) for all participants. As a maximum number of 20 trials were included, the vector coding process was repeated 19 times for each coupling and each condition. The CoordV*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 CoordV outputs calculated using each trial *n* (CoordV*n*). Each cell of the matrix was then normalized to the corresponding CoordV output calculated from 20 trials using the following equation:

$$CoordV\%_{norm20} = \left(\frac{CoordV_n}{CoordV\ calculated\ using\ 20\ trials}\right)$$

Mean $CoordV\%_{norm20}$ was subsequently calculated for each CoordV*n* output, producing an average CoordV across stance (1 x 19 matrix) for each participant, coupling and condition. For each participant, the trial *n* for which mean $CoordV\%_{norm20}$ was 100±10% was identified, indicating a <10% difference between CoordV calculated using 20 trials and the respective CoordV*n*. The mean and maximum number of trials used to inform mean $CoordV\%_{norm20}$ within 100±10% of mean 20 trial CoordV was determined across couplings for the preferred speed running, fixed speed running, preferred speed walking and fixed speed walking conditions.
Preferred and fixed speed running and walking group mean speeds were compared using paired t-tests (IBM SPSS Statistics 23, SPSS Inc., Chicago, IL).

RESULTS: Preferred running (2.9±0.5 $m \cdot s^{-1}$) and walking speeds (1.4±0.2 $m \cdot s^{-1}$) differed significantly from fixed running (3.2 $m \cdot s^{-1}$) and walking speeds (1.3 $m \cdot s^{-1}$, $p<0.001$). When examined across the stance phase, the segments and joint couplings considered were found to influence the number of trials required to achieve CoordV mean stability within 10% of the 20 trial mean values (Figure 1, Table 2). The number of trials required to achieve mean CoordV stability across couplings for preferred speed running = 9, fixed speed running = 8, preferred speed walking = 8 and fixed speed walking = 9.

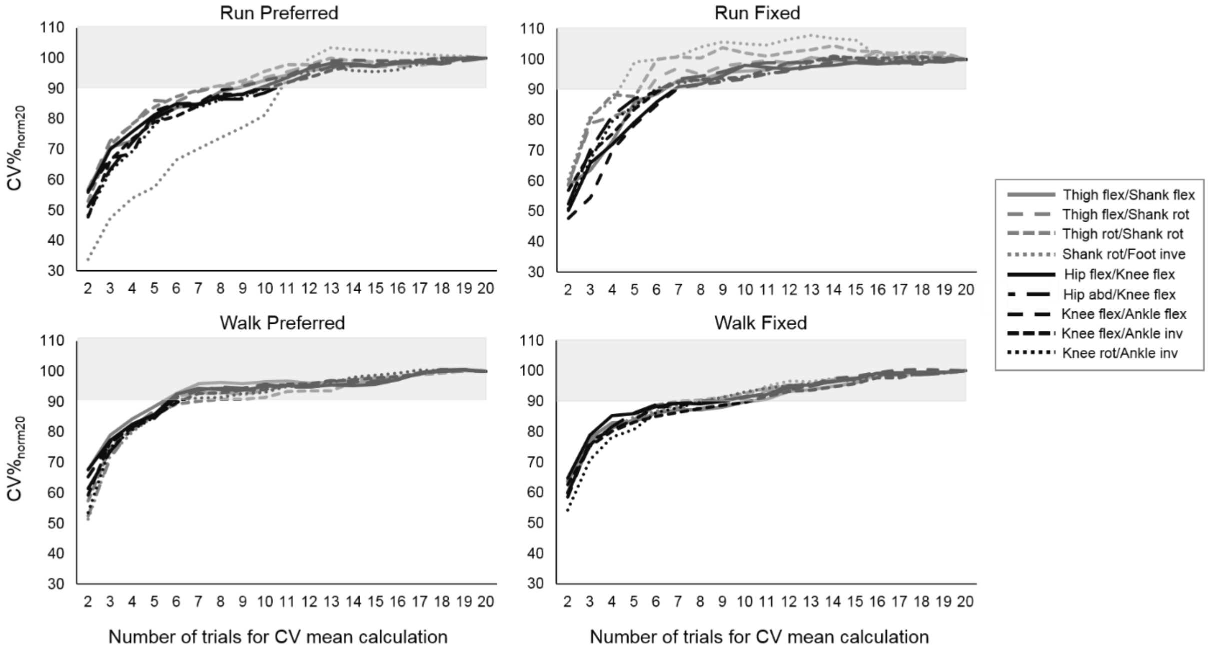

Figure 1. Representation of group mean segment and joint CoordV across stance during running and walking for 2-20 trials, presented as a per cent of CoordV calculated using 20 trials (CoordV%$_{norm20}$). Shading indicates 100±10% of CoordV%$_{norm20}$.

Table 2. Number of trials required to achieve CoordV within 100±10% range of 20 trial mean for segment and joint couplings during running and walking 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
Overall mean	**9 ± 2**	**8 ± 2**	**9 ± 1**	**9 ± 1**
Overall max	**11**	**10**	**10**	**11**
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
Overall mean	**9 ± 1**	**8 ± 1**	**8 ± 1**	**9 ± 1**
Overall max	**11**	**10**	**9**	**11**
All Couplings mean	**9 ± 1**	**8 ± 1**	**8 ± 1**	**9 ± 1**

DISCUSSION: The purpose of this study was to analyse lower limb segment and joint CoordV, to determine the number of trials needed to establish a stable mean which is necessary for the reliable calculation of CoordV in overground locomotion. Overall, between 8 and 9 trials are required for stable mean outputs, indicating many previous studies have been based on too few trials, leading to less reliable outcomes.

When comparing between running and walking, the number of trials required for mean stability was found to be greater in the slower conditions, i.e. preferred running and fixed walking.

However, this finding was not consistent between conditions, i.e. walking did not require a greater number of trials than running, indicating a nonlinear influence of velocity on CoordV. The results highlight the importance of considering the type of locomotion and speed when determining the number of trials to include in the calculation of CoordV.
Preferred speed overground running required more strides than treadmill preferred running (9 and 8 strides, respectively); whereas a stable mean was achieved with less strides for segment couplings in preferred overground walking compared to treadmill walking (9 and 10 strides, respectively) (Hafer and Boyer, 2017). 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, however, the overall group stable mean was reported by Hafer and Boyer. This may account for some differences in mean stability findings between overground and treadmill conditions. In addition, preferred speeds on the treadmill were greater for both running (0.3 $m \cdot s^{-1}$ difference) and walking (0.2 $m \cdot s^{-1}$ difference).
There was little difference between the mean number of trials needed for segment compared to joint CoordV mean stability, however, the overall range was from 6 to 11 trials. Therefore, rather than generalising across couplings, it is advisable for the number of trials to include in the calculation of CoordV to be informed by the specific coupling of interest.

CONCLUSION: To obtain CoordV, the standard deviation of an appropriate number of trials is calculated using circular statistics. The study findings indicate the need for between 8 and 9 trials to produce a stable mean and contribute to reliable biomechanical outputs. The outputs can be used as recommendations for future research to indicate the number of trials necessary to contribute to reliable CoordV outputs.

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