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Short communication

Gait asymmetry: Composite scores for mechanical analyses of sprint running

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ABSTRACT

Gait asymmetry analyses are beneficial from clinical, coaching and technology perspectives. Quantifying overall athlete asymmetry would be useful in allowing comparisons between participants, or between asymmetry and other factors, such as sprint running performance. The aim of this study was to develop composite kinematic and kinetic asymmetry scores to quantify athlete asymmetry during maximal speed sprint running. Eight male sprint trained athletes (age 22 ± 5 years, mass 74.0 ± 8.7 kg and stature 1.79 ± 0.07 m) participated in this study. Synchronised sagittal plane kinematic and kinetic data were collected via a CODA motion analysis system, synchronised to two Kistler force plates. Bilateral, lower limb data were collected during the maximal velocity phase of sprint running (velocity = 9.05 ± 0.37 m s^{-1}). Kinematic and kinetic composite asymmetry scores were developed using the previously established symmetry angle for discrete variables associated with successful sprint performance and comparisons of continuous joint power data. Unlike previous studies quantifying gait asymmetry, the scores incorporated intra-limb variability by excluding variables from the composite scores that did not display significantly larger ($p < 0.05$) asymmetry than intra-limb variability. The variables that contributed to the composite scores and the magnitude of asymmetry observed for each measure varied on an individual participant basis. The new composite scores indicated the inter-participant differences that exist in asymmetry during sprint running and may serve to allow comparisons between overall athlete asymmetry with other important factors such as performance.

1. Introduction

The analysis of biomechanical asymmetry in gait is useful from performance and injury (Schache et al., 2009), clinical (Beyaert et al., 2008) and technology (Buckley, 2000) perspectives. Information on a participant's asymmetry may inform the coaching–biomechanics interface (Kerwin and Irwin, 2008), for example, to improve sprint training.

The symmetry index (Robinson et al., 1987) is often used to quantify asymmetry of discrete variables. Zifchock et al. (2008) noted the possibility for artificial inflation when using the symmetry index and suggested the symmetry angle (θ_{SYM}) as a more robust measure. Giakas and Baltzopoulos (1997) investigated asymmetry and intra-limb variability, noting that for asymmetry to be significant, inter-limb differences must be greater than intra-limb variability. Gouwanda and Senanayake's (2011) recent method of calculating asymmetry did not incorporate intra-limb variability, meaning that asymmetry reported between limbs may not be significant when compared with intra-limb variability.

Previous asymmetry studies have used methods that quantify asymmetry of individual variables. Composite asymmetry scores that incorporate numerous variables would allow investigation of overall asymmetry and performance, a relationship that is, as yet, unknown (Carpes et al., 2010). In future investigations, composite scores will allow for asymmetry comparisons between athletes over time and between asymmetry and performance or injury occurrence.

This study aims to extend established measures of gait asymmetry to develop composite kinematic and kinetic asymmetry scores to quantify athlete asymmetry during sprint running.

2. Methods

2.1. Data collection

A priori approval was gained from the University's Research Ethics Committee and written informed consent obtained from all participants. Eight male sprint trained athletes performed 9–12 (mean ± SD = 11 ± 2) maximal 60 m sprint runs at a velocity of 9.05 ± 0.37 m s^{-1}. Athletes' age, mass and stature were 22 ± 5 years, 74.0 ± 8.7 kg and 1.79 ± 0.07 m, respectively. Athletes were instructed to perform a standing start as they would in training upon hearing an audible starting signal and to run maximally beyond a finishing mark located 60 m from the start line. Bilateral three-dimensional positional (200 Hz) and unilateral force

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(1000 Hz) data were collected from the 36–44 m section of each run using an automated system (CODA cx1, Charnwood Dynamics, UK) with two integrated force plates (Kistler 9287BA; Fig. 1). Athletes were instructed not to target the force plates and the start line was repositioned by one step length half way through each athlete's data collection to increase the likelihood of contralateral foot contacts with the force plates. Twelve active markers were secured to the participants, detailed in Fig. 2.

2.2. Data processing

Data were processed using custom code (MATLAB R2010a, The Mathworks, USA). Three-dimensional kinematic and kinetic data were projected onto the sagittal plane and optimally filtered using a low-pass Butterworth filter (Challis, 1999). Bilateral two-dimensional inverse dynamics analyses were performed to calculate net joint powers at the ankle, knee and hip combining the inertia data presented by de Leva (1996) and Dempster (1955) as recommended by Hunter et al. (2004).

Effects of fatigue were examined by comparing step velocity for the first and final two trials for each athlete. Step velocity was also compared for the first and second steps of each trial for all athletes to verify that athletes were at constant velocity. Eight variables were included in the composite kinematic asymmetry score (*KMAS*) based on association with successful technique (Hunter et al., 2004) and identification by expert sprint coaches (Thompson et al., 2009). Seven discrete variables were included in the kinetic asymmetry score (*KAS*) due to their association with successful sprint running and the kinematic variables (Table 1). The method of Zifchock et al. (2008) was used to calculate θ_{SYM} values for all discrete variables:

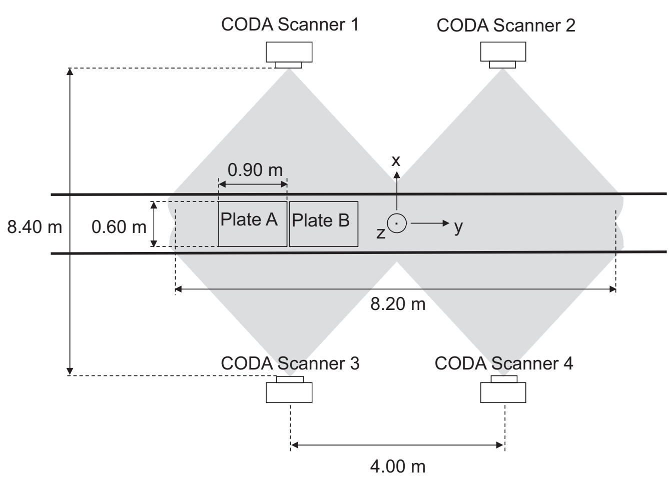

Fig. 1. Location of force plates and CODA scanners for kinetic data collection; the shaded area indicates the field of view of the CODA scanners.

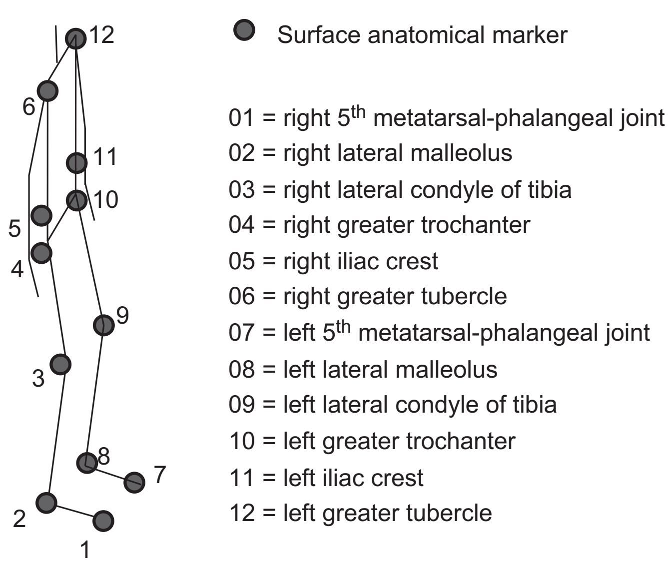

Fig. 2. Stick figure representation of athlete showing locations of surface anatomical markers.

Table 1
Nomenclature of discrete kinematic and kinetic variables included in composite asymmetry scores.

Variable	Abbreviation	Description
Kinematic variables		
Step velocity	*SV*	Measured from the touchdown of one foot to the subsequent touchdown of the contralateral foot
Step length	*SL*	
Step frequency	*SF*	
Minimum hip height	zH_{MIN}	Measured from mid-hips during contact
Maximum knee lift	zK_{MAX}	Measured during contact
Minimum knee angle	θK_{FLEX}	Measured during swing phase
Maximum hip extension	θH_{EXT}	Measured during contact
Touchdown distance	y_{TD}	Measured between toe and mass centre
Kinetic variables		
Net horizontal impulse	IMP_H	All measured from leg in contact with the ground during contact phase
Net vertical impulse	IMP_V	
Maximum vertical force	Fz_{MAX}	
Mean support moment	M_{SUP}	
Net ankle work	WA_{NET}	
Net knee work	WK_{NET}	
Net hip work	WH_{NET}	

$$\theta_{SYM} = \frac{(45^\circ - \arctan(X_{left}/X_{right}))}{90^\circ} \times 100\% \tag{1}$$

where θ_{SYM} is the symmetry angle; X_{left} the mean left side value and X_{right} the mean right side value. However, if

$(45^\circ - \arctan(X_{left}/X_{right})) > 90^\circ$

θ_{SYM} was obtained as

$$\theta_{SYM} = \frac{(45^\circ - \arctan(X_{left}/X_{right}) - 180^\circ)}{90^\circ} \times 100\% \tag{2}$$

2.3. Calculation of composite asymmetry scores

Two composite asymmetry scores are presented. Both scores include statistical comparisons of left and right values to ensure that asymmetry is reported only if inter-limb differences are larger than those for intra-limb.

2.3.1. Kinematic asymmetry score

Parametric statistics (paired *T*-tests) were used for a within athlete analysis to test for significant ($p < 0.05$) differences between left and right limbs for each variable, termed the 'absolute difference factor' (*ADF*).

Kinematic asymmetry was also calculated with respect to asymmetry of step velocity, the performance criterion in sprint running (Hay, 1994), to overcome the effect of marginal inter-step velocity changes. The 'relative difference factor' (*RDF*) included significant differences between the θ_{SYM} magnitude present in step velocity and the other kinematic variables. To calculate *KMAS*, a score of asymmetry was calculated for each variable based on the product of the summed *ADF* and *RDF* values and θ_{SYM} magnitude for mean left and mean right values across all trials:

$$KMAS(x_n) = (ADF + RDF)\theta_{SYM}(x_n) \tag{3}$$

where $KMAS(x_n)$ is the kinematic asymmetry score for variable 'x_n'; $ADF = 0/1$, where 1 implies significant left–right difference; $RDF = 0/1$, where 1 implies significantly larger θ_{SYM} magnitude for 'x_n' than SV and $\theta_{SYM}(x_n)$ is the symmetry angle for variable 'x_n'. Absolute *KMAS* values for each variable were summed:

$$KMAS = \sum_{i=1}^{n} KMAS(x_n) \tag{4}$$

where *KMAS* is the overall participant kinematic asymmetry score.

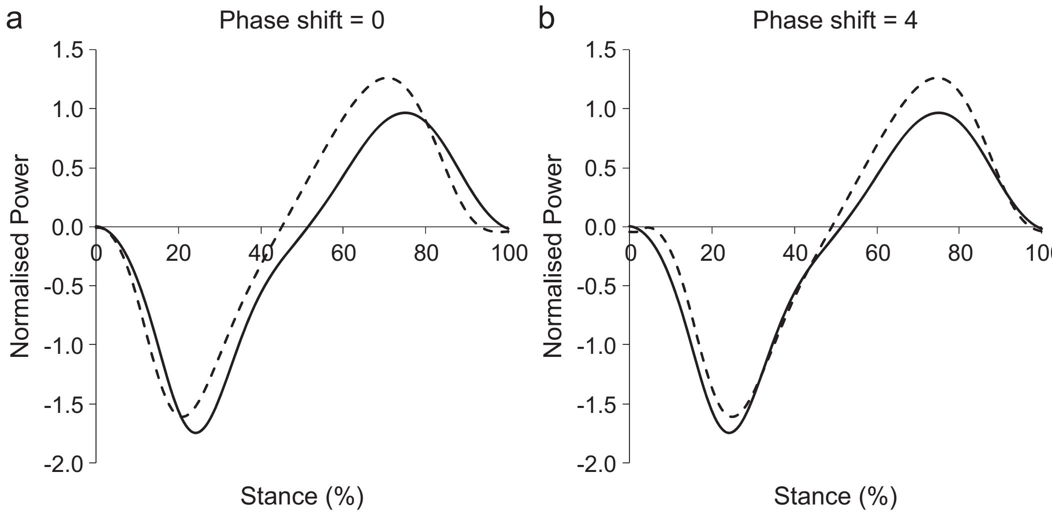

Fig. 3. Example left (dashed) and right (solid) mean power curves for the ankle joint during stance (a) before phase shift and (b) after optimal phase shift.

Table 2
Kinematic θ_{SYM} values for variables contributing to the kinematic asymmetry score.

Athlete	*SV*	*SL*	*SF*	zH_{MIN}	zK_{MAX}	θK_{FLEX}	θH_{EXT}	y_{TD}	*KMAS*
1	0.79^{*}	1.28^{*}	1.13	0.62	1.04^{*}	$3.72^{*\#}$	0.69	2.63	10.53
2	0.62^{*}	1.16^{*}	$1.68^{*\#}$	0.43	0.92^{*}	1.60	0.92^{*}	$3.76^{\#}$	10.73
3	0.32^{*}	0.79	0.81	0.69	0.81	$1.81^{*\#}$	0.69^{*}	$2.59^{\#}$	7.22
4	0.18	$1.33^{*\#}$	$1.44^{*\#}$	0.34	0.66	$4.15^{*\#}$	0.41^{*}	$6.68^{*\#}$	27.60
5	0.22	1.01	$1.12^{\#}$	0.47^{*}	0.56	$3.54^{*\#}$	$0.61^{\#}$	$1.79^{\#}$	11.07
6	0.39^{*}	1.04^{*}	$1.38^{*\#}$	0.70^{*}	$1.44^{\#}$	$3.53^{\#}$	0.55	2.56	9.86
7	0.25	0.62	0.65	0.23	0.81	$1.39^{\#}$	0.25	$3.13^{\#}$	4.52
8	0.25	0.58	0.65	0.58	$1.78^{*\#}$	1.52	$1.24^{*\#}$	$2.60^{\#}$	8.64

* Significant ($p < 0.05$) difference between left and right values, #significantly ($p < 0.05$) larger asymmetry compared to SV.

Table 3
Kinetic θ_{SYM} values for variables contributing to the kinetic asymmetry score.

Athlete	IMP_H	IMP_V	Fz_{MAX}	M_{SUP}	WA_{NET}	WK_{NET}	WH_{NET}	*PRO*	*KAS*
1	25.07^{*}	1.27	2.14	3.54	42.95^{*}	8.48	5.47	124.89	193.50
2	2.99	0.73	0.38	4.59	11.64	76.94^{*}	11.28	209.76	286.70
3	13.44^{*}	1.97	2.32	3.48	6.07	23.23	21.63	159.17	173.16
4	9.38	0.79	3.01^{*}	5.06	21.57^{*}	42.67	3.42	49.04	73.62
5	1.55	0.06	1.12	5.30^{*}	23.74	23.82^{*}	24.25	40.49	69.61
6	0.18	0.83	0.90	2.68	14.54^{*}	22.86	13.83	48.00	62.54
7	10.25	1.84	0.71	3.99	41.25^{*}	56.43	66.43	28.00	69.25
8	2.39	5.95^{*}	4.33^{*}	7.47	93.23	79.56	44.99^{*}	67.65	122.92

PRO = profile asymmetry score.

* Significant ($p < 0.05$) difference between left and right values.

2.3.2. Kinetic asymmetry score

The *KAS* was calculated as the sum of event and profile asymmetry scores as the combination of both measures has been advocated in recent sprint running research to provide greater insight into the kinetic mechanisms influencing performance (Bezodis et al., 2008). The *KAS* focussed on the underlying mechanical causes of kinematic asymmetry, rather than the kinematic descriptors and performance outcome (Hay, 1994). Therefore, the *KAS* did not include a measure of step velocity asymmetry, but included profile asymmetry analyses. Event asymmetry scores summed absolute θ_{SYM} values for discrete variables displaying a significant left–right difference. Profile asymmetry scores, based on joint power profiles normalised to 100% stance, comprised four characteristics: phase, magnitude, time and overall difference.

Phase difference between mean left and right power curves was calculated using the concept presented by Crenshaw and Richards (2006). The left power curve was shifted in 1% increments, with root mean squared difference (*RMSD*) between left and right curves calculated after each shift. Phase difference was quantified as the number of shifts required to minimise RMSD (Fig. 3); however if this value was > 50, phase difference was defined as 100 minus the number of phase shifts.

Magnitude and time asymmetry of the power curves were calculated from minimum and maximum values and contact time. The θ_{SYM} magnitude was calculated for each value, then multiplied by 1 or 0 depending on whether there was a significant ($p < 0.05$) left–right difference. The final profile analysis element considered the magnitude of the normalised power curves with 'T-tests' performed on each point and assigned a weighting of 1 (significant) or 0 (non-significant), before being summed.

3. Results

Composite asymmetry scores (*KMAS* and *KAS*) are presented for each athlete as well as the magnitude of θ_{SYM} for each variable. Kinematic θ_{SYM} values (Table 2) were all small with the largest value (6.68%) reported for touchdown distance. Kinetic variables included larger θ_{SYM} values, with the largest (93.23%, Table 3) being for net ankle work.

4. Discussion

This study's aim was to develop composite kinematic and kinetic asymmetry scores to quantify athlete asymmetry in sprint running. Novel scores were presented based on previously validated θ_{SYM} measures (Zifchock et al., 2008). The new scores uniquely incorporated the important feature of intra-limb variability (Giakas and Baltzopoulos, 1997) by excluding θ_{SYM} values for variables that did not demonstrate significantly larger asymmetry than intra-limb variability. *KAS* values were larger than *KMAS* (Tables 2 and 3), with the use of θ_{SYM} being preferred to alternatives prone to artificial inflation, such as the symmetry index (Zifchock et al., 2008).

Composite asymmetry scores could result from either large θ_{SYM} magnitudes or large numbers of variables displaying smaller but still significant asymmetry. For example, the *KMAS* values for Athletes 1 (10.53) and 2 (10.73) were similar; however significant θ_{SYM} values for Athlete 1 comprised four variables, whereas six variables were included for Athlete 2 (Table 2). Composite scores incorporating detailed kinematic and kinetic information allow comparison of overall asymmetry and identification of mechanisms underpinning an athlete's asymmetry (Exell et al., 2011). The detailed composite scores highlight the individuality of asymmetry, with all athletes displaying significant asymmetry for different combinations of variables (Tables 2 and 3). The importance of including intra-limb variability in asymmetry calculations is exemplified by the large but non-significant θ_{SYM} values exemplified by net ankle work for Athlete 8. Failure to consider intra-limb variability may result in falsely inflated asymmetry values for participants displaying a large amount of intra-limb variability (Giakas and Baltzopoulos, 1997).

A potential limitation of the presented methods is the rectification of the presented asymmetry values. Absolute rather than relative asymmetry values were integrated into the score to allow for statistical comparisons between the magnitude of asymmetry present in step velocity and other variables and to allow for asymmetry magnitude to be summed for significantly asymmetrical variables. The presented methods quantify overall asymmetry and highlight the variables for an individual athlete who displays significant asymmetry. The resulting scores are thus pre-cursors to further analyses, for example by promoting more detailed analyses of highlighted variables.

The composite scores may allow future investigation of overall asymmetry effects on performance (Carpes et al., 2010). For this study, variables were included in the scores based on their relevance to sprint running (Hunter et al., 2004; Thompson et al., 2009). The composite scores are customisable to different research requirements by allowing inclusion of additional functionally relevant variables. The methods presented could be applied to other forms of running, e.g. amputee sprinting (Buckley, 2000) and other sports where asymmetry is of interest, e.g. cycling (Smak et al., 1999) or clinical gait (Beyaert et al., 2008). Where step velocity is not the performance criterion, another criterion variable could be substituted for use in the *RDF*, or if not appropriate, could be omitted from the *KMAS* calculation.

Using the new asymmetry scores provides biomechanists, clinicians and coaches with a composite mechanical quantification of asymmetry and a detailed breakdown of an individual's asymmetry. These novel scores may provide insight into the interaction between kinematic and kinetic asymmetries within athletes (Exell et al., 2011) and allow comparison of asymmetry with factors such as performance or injury, all of which offer the potential to further understanding of human locomotion.

Conflict of interest statement

There are no conflicts of interest associated with this research.

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