Scand J Med Sci Sports 2016: ●●: ●●–●●
doi: 10.1111/sms.12759

SCANDINAVIAN JOURNAL OF
MEDICINE & SCIENCE
IN SPORTS

Strength and performance asymmetry during maximal velocity sprint running

T. Exell[1], G. Irwin[2], M. Gittoes[2], D. Kerwin[2]

[1]Department of Sport and Exercise Science, University of Portsmouth, Portsmouth, UK, [2]Cardiff School of Sport, Cardiff Metropolitan University, Cardiff, UK
Corresponding author: Dr. Timothy Exell, Department of Sport and Exercise Science, University of Portsmouth, Cambridge Road, Portsmouth PO1 2ER, UK. Tel: +44-(0)23 9284 5179, Fax: +44-(0)23 9284 3620, Email: tim.exell@port.ac.uk

Accepted for publication 10 August 2016

The aim of this study was to empirically examine the interaction of athlete-specific kinematic kinetic and strength asymmetry in sprint running. Bilateral ground reaction force and kinematic data were collected during maximal velocity (mean = 9.05 m/s) sprinting for eight athletes. Bilateral ground reaction force data were also collected while the same athletes performed maximal effort squat jumps. Using novel composite asymmetry scores, interactions between kinematic and kinetic asymmetry were compared for the group of sprinters. Asymmetry was greater for kinematic variables than step characteristics, with largest respective values of 6.68% and 1.68%. Kinetic variables contained the largest asymmetry values, peaking at >90%. Asymmetry was present in all kinematic and kinetic variables analyzed during sprint trials. However, individual athlete asymmetry profiles were reported for sprint and jump trials. Athletes' sprint performance was not related to their overall asymmetry. Positive relationships were found between asymmetry in ankle work during sprint running and peak vertical force (r = 0.895) and power (r = 0.761) during jump trials, suggesting that the ankle joint may be key in regulating asymmetry in sprinting and highlighting the individual nature of asymmetry. The individual athlete asymmetry profiles and lack of relationship between asymmetry of limb strength and sprint performance suggest that athletes are not "limb dominant" and that strength imbalances are joint and task specific. Compensatory kinetic mechanisms may serve to reduce the effects of strength or biological asymmetry on the performance outcome of step velocity.

The analysis of biomechanical asymmetry in gait is useful from performance and injury (Schache et al., 2009; Carpes et al., 2010; Ciacci et al., 2013), clinical (Beyaert et al., 2008), and technology (Buckley, 2000) perspectives. Information on a participant's lower limb asymmetry during sprint running may develop insight into individual joint asymmetry within limbs (Vagenas & Hoshizaki, 1991) as well as informing coaches and athletes about injury predisposition, enhanced performance of one limb over the contralateral limb, and possible strength imbalances. Asymmetry in walking and submaximal running has been a popular research topic for many years (Hamill et al., 1984; Vagenas & Hoshizaki, 1991; Zifchock et al., 2006; Laroche et al., 2012) and has provided information on asymmetry interactions during these movements. Knowledge of asymmetry in gait of all speeds can be beneficial in developing understanding of asymmetry present in uninjured and recently injured participants to allow asymmetry to be used as a metric when recovering from injury or identifying required rehabilitation interventions (Schache et al., 2009).

Despite the large number of investigations that have focused on asymmetry in submaximal running and walking gait (Hamill et al., 1984; Vagenas & Hoshizaki, 1991; Zifchock et al., 2006; Laroche et al., 2012), asymmetry has rarely been investigated in sprint running. From a coaching perspective, knowledge of asymmetry in sprint running may inform the nature of an athlete's training based on technical differences between the two sides of the body. Research into asymmetry during submaximal running has identified the presence of asymmetry for kinematic (Vagenas & Hoshizaki, 1991; Karamanidis et al., 2003) and kinetic (Cavanagh et al., 1985; Jacobs et al., 2005) indicators of performance and injury including joint-specific variables such as lower limb joint angles and resultant limb variables such as ground reaction forces. Furthermore, asymmetry in sprint running has important implications on biomechanical research with studies of sprint running often collecting data unilaterally due to constraints on data collection, such as the positioning of cameras or force platforms (Mann & Herman, 1985; Bezodis et al., 2008; Gittoes & Wilson, 2010). The presence of kinematic and kinetic asymmetry in the lower limbs is overlooked in traditional unilateral analyses but may be indicative of injury predisposition or technical discrepancies within athletes. Conversely, athletes may exploit "functional asymmetry", whereby asymmetry is used to enhance overall performance, as a mechanism to maximize the combined performance of the lower limbs (Vagenas & Hoshizaki, 1991) or to overcome strength imbalances.

To the authors' knowledge, limited research has investigated kinematic asymmetry during maximal velocity sprint running (Ciacci et al., 2010). The presence of kinetic asymmetry has been previously reported (Exell et al., 2012a,c); however, the interaction between kinematic asymmetry, kinetic asymmetry, and performance has not been considered. Furthermore, numerous studies investigating acceleration-phase and maximal velocity sprint running have performed unilateral analyses (Johnson & Buckley, 2001; Bezodis et al., 2008). Additionally, the presence of asymmetry has implications on the conclusions that can be drawn from unilateral experimental data and also methodological considerations when planning field-based data collection. In a study into the braking and propulsive phases of sprint running (Ciacci et al., 2010), the authors did not present asymmetry results, but, following a preliminary asymmetry assessment of a sub-group or participants, the authors noted that no differences were apparent between left and right sides. However, not all the athletes included in the study were tested for asymmetry, which, due to the individual nature of asymmetry (Cavanagh et al., 1985), may have led to asymmetry being overlooked for some athletes. However, the inclusion of a preliminary test of asymmetry prior to data collection can allow greater conclusions to be made about an athlete's technique based on data collected from one limb. For example, if unilateral data are available for an athlete in competition when performing at their best, knowledge of that athlete's asymmetry could indicate whether the analyzed limb may or may not reflect the results of the unanalyzed limb.

A further consideration and potential cause of biomechanical asymmetry during sprint running is asymmetry of limb strength. Strength asymmetry has been considered in relation to movement speed in team-sports athletes (Lockie et al., 2014), and was found to not influence overall speed performance in change of direction tasks. Menzel et al. (2013) investigated isokinetic strength asymmetry of individual lower limb joints and overall strength asymmetry during vertical jumps. These authors reported strength asymmetry to be present in both tests, but did not consider variability within each joint. Furlong and Harrison (2014) investigated asymmetry of plantarflexor activity during controlled jumping movements performed unilaterally, including the important consideration of whether asymmetry was meaningful relative to within-side changes by incorporating statistical significance testing. These authors reported that asymmetries exist in external force characteristics during jumping activities, which are compensated for to reduce asymmetry in the outcome movement. The results presented by Furlong and Harrison (2014) regarding external force asymmetry produced by the plantarflexors did not agree with previous work reporting no overall force asymmetry between limbs (Flanagan & Harrison, 2007), further supporting the idea of individual joint compensation to reduce overall limb asymmetry. Previous studies investigating strength asymmetry have reported that it does exists during extensor/plantarflexor type activities; however, strength asymmetry has not been investigated in sprint running in relation to asymmetry of biomechanical performance determinants (i.e., step characteristics and influential kinematic and kinetic variables).

Quantification and understanding of performance and strength asymmetry during the maximum velocity phase would be beneficial to both researchers and coaches. Therefore, the aim of this study was to empirically examine the interaction of athlete-specific kinematic kinetic and strength asymmetry in sprint running. The overall purpose of this study was to scientifically inform the development of coaching programs for sprint-based athletes and to inform future biomechanical research regarding the use of bilateral analyses. It was hypothesized that: (a) asymmetry profiles would be athlete-specific; (b) that there would be a positive relationship between kinematic, kinetic, and strength asymmetry for each athlete, with asymmetry in kinematic variables reflected in associated kinetic variables; and (c) that athletes displaying greater explosive strength asymmetry would be more asymmetrical during sprint running.

Methods

Participants and experimental protocol

Ethics approval for the study was gained from the University's Research Ethics Committee and written informed consent obtained from all participants. Eight male sprint-trained athletes with a minimum of 2-year competitive experience performed 9–12 (mean $\pm$ SD = 11 $\pm$ 2) maximum effort 60-m sprint runs. Athletes' mean ($\pm$SD) age, mass, and stature were 22 $\pm$ 5 years, 74.0 $\pm$ 8.7 kg, and 1.79 $\pm$ 0.07 m, respectively.

Time synchronized three-dimensional positional (200 Hz) and force (1000 Hz) data were collected from the 36–44 m section of each run using a motion capture system (CODA cx1; Charnwood Dynamics, Leicester, UK) with two integrated force plates (Kistler 9287BA; Kistler, Winterthur, Switzerland) covered with the same track surface as the surrounding running lane. Scanners were positioned 4.20 m from the center of the running lane, at a separation of 4.00 m along the lane. The scanner setup maximized the length of the field of view in the sagittal plane (approximately 8.20 m) to ensure that a minimum of two full steps (up to a length of 2.73 m) were collected from every trial. Twelve active markers were secured to participants' left and right sides during each trial, detailed in Fig. 1. The CODA and force plate systems were simultaneously aligned with the x, y, and z axes defined as medio-lateral, antero-posterior, and vertical, respectively.

Marker positional data were collected while athletes performed the 60-m sprint runs. Athletes wore their own sprinting spikes and were instructed to run with maximal effort through the data collection area to the 60 m finish line. The CODA system was triggered manually following athletes' first movements from their crouched starting position. Athletes performed trial repetitions in alignment with their regular sprint training regime. Six athletes (Athletes 1–6) performed 12 trials over two equal sessions and the remaining two athletes were available for one session and performed nine runs in that session. Trials were rejected if an athlete noticeably altered their running style during the data collection area, or if any markers became dislodged, or were out of view for a period of eight or more epochs (0.040 s). Recovery time between trials was self-selected and typically lasted for approximately 10 min. Step velocity was compared for trials completed in separate sessions by the same athlete to check that there were no significant ($P < 0.05$) inter-session differences before data were pooled from different sessions for these athletes. To measure explosive limb strength, athletes performed five maximal effort squat jumps with each foot placed on a separate force plate, which were all used for analysis. Due to constraints on data collection, position data were not available during these jump trials.

Data processing

Position and force data were processed using custom code (MATLAB, Mathworks, Natick, Massachusetts, USA). For sprint trials, sections of marker data where markers became occluded for seven or fewer epochs were filled using an interpolating cubic spline. For foot contacts that overlapped the two force plates, center of pressure data were combined using the method of Exell et al. (2012a) to calculate values relative to the CODA system coordinate frame. Instants of touchdown and take-off from the force plates were defined as the first epochs that the vertical force rose above and fell below the mean plus 2 standard deviations value of the unloaded plates, respectively. For foot contacts that did not occur on the force plates, touchdown and take-off were identified using the toe marker acceleration (Bezodis et al., 2007). The dominance of sagittal plane movements in the late acceleration and maximal velocity phases of sprint running has led to the majority of analyses focusing on this plane (Johnson & Buckley, 2001; Hunter et al., 2004; Bezodis et al., 2008). Therefore, three-dimensional kinematic data were projected onto the sagittal plane for analysis. Kinematic and kinetic data were filtered using a low-pass Butterworth filter, with cut-off frequencies (typically ~20 Hz) for each trial determined using the autocorrelation method (Challis, 1999). Bilateral two-dimensional inverse dynamics analyses were performed to calculate joint moments acting about the ankle, knee, and hip joints combining athlete-specific inertia data as described by Hunter et al. (2004). Joint power data were calculated as the product of joint moment and angular velocity.

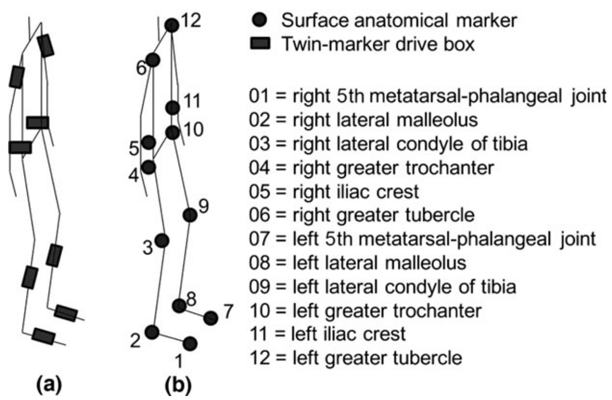

Fig. 1. Stick figure representation of athlete showing locations of CODA drive boxes (a) and surface anatomical markers (b) during data collection.

Strength data were analyzed using the limb-specific ground reaction force profiles. For each trial, vertical velocity of the center of mass (CM) was calculated from the total net force applied to both plates after subtracting body weight that was assumed to be applied equally to each plate. Cumulative impulse was then divided by the participant's mass (Harman et al., 1991). Individual limb power was calculated by multiplying CM vertical velocity by the vertical ground reaction force applied to each force plate, having subtracted half of the bodyweight value from each plate. Peak vertical force (Fj_{MAX}) and power (Pj_{MAX}) values were calculated for each limb in addition to net work (Wj_{NET}) performed by each limb, calculated by integrating the power-time profiles.

Asymmetry was calculated using the symmetry angle (θ_{SYM}) (Zifchock et al., 2008) for all discrete variables:

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

θ_{SYM} = symmetry angle value (ranging from −100% to 100%, with 0% indicating perfect symmetry)

X_{left} = left side value for variable being quantified

X_{right} = right side value for variable being quantified

However, if: $(45^\circ - \arctan(X_{left}/X_{right})) > 90^\circ$ then [2] was substituted:

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

Calculation of composite asymmetry scores

Composite asymmetry scores were used to allow comparison of overall athlete asymmetry and performance. Methods used to calculate the scores are summarized below with full explanation provided by Exell et al. (2012b). These methods of calculating asymmetry scores incorporate the important consideration of intra-limb variability in the quantification of asymmetry so that asymmetry is only considered for variables displaying a significant difference between left and right side values, termed "significant asymmetry". Following identification of the significantly asymmetrical variables for each athlete, symmetry angle values can then be summed for those variables to give an overall athlete asymmetry score. 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). A pseudo mass center (pseudoCM), calculated as the mid position of left and right iliac crest markers, was used in the calculation of variables relative to athlete's mass centers. Variables were defined and calculated as follows, with a step defined from the instant of touchdown of one foot to the instant of touchdown of the contralateral foot (Bezodis et al., 2007):

Step velocity (SV): mean horizontal rate of change in position of the pseudoCM.

Step length (SL): the change in horizontal position of toe markers.

Step frequency (SF): the inverse of step time.

Minimum hip height (zH_{MIN}): minimum vertical position of the mid-hip markers during ground contact.

Maximum knee lift (zK_{MAX}): maximum vertical position of knee for non-stance leg during ground contact.

Minimum knee angle (θK_{FLEX}): minimum knee angle for non-stance leg during swing phase.

Maximum hip extension (θH_{EXT}): maximum stance leg hip extension angle during ground contact.

Touchdown distance (y_{TD}): horizontal displacement between toe and pseudoCM at point of touchdown.

Seven discrete variables were included in the kinetic asymmetry score (KAS) due to their association with successful sprint running and the kinematic variables analyzed, all measured from the stance leg during ground contact:

Net horizontal impulse (IMP_H): net ground impulse measured in the antero-posterior direction.

Net vertical impulse (IMP_V): net ground impulse in the vertical direction.

Maximum vertical force (Fz_{MAX}): maximum ground reaction force in the vertical direction.

Mean support moment (M_{SUP}): mean value of the sum of joint moments acting about the ankle, knee, and hip (extension defined as positive).

Net ankle/knee/hip work ($WA/K/H_{NET}$): net joint work performed at the ankle/knee/hip.

Kinematic asymmetry score

Data were tested for normality using the critical appraisal approach (Peat & Barton, 2005). Measured variables were found to be normally distributed for all athletes. Therefore, parametric statistics were used for within athlete analyses to test for significant ($P < 0.05$) differences between left and right limbs for each variable, termed the "absolute difference factor" (ADF). Variables showing significant left–right differences were considered as demonstrating "significant asymmetry". Kinematic asymmetry was also calculated with respect to step velocity to reduce the effect of inter-step velocity changes. The "relative difference factor" (RDF) included significant differences between the θ_{SYM} magnitude for step velocity and the other kinematic variables. Variables not displaying "significant asymmetry" were omitted from the composite asymmetry scores. Each athlete's KMAS was calculated based on the product of the θ_{SYM}, ADF, and RDF:

$$\mathrm{KMAS}(x_n) = (\mathrm{ADF} + \mathrm{RDF}) \cdot \theta_{\mathrm{SYM}}(\mathrm{x_n}) \qquad [3]$$

$\mathrm{KMAS}(x_n)$ = kinematic asymmetry score for variable "x_n"; ADF = either 0 or 1, with 1 indicating a significant difference between left and right values; RDF = either 0 or 1, with 1 indicating a significantly greater θ_{SYM} for variable "x_n" than for SV; $\theta_{SYM}(x_n)$ = symmetry angle for variable "x_n".

KMAS values for each variable were rectified to be positive. The overall KMAS value or each athlete was then calculated as the sum of the scores for all variables:

$$\mathrm{KMAS} = \sum_{i=1}^{n} |\mathrm{KMAS}(x_n)| \qquad [4]$$

KMAS = overall kinematic asymmetry score for participant

Kinetic asymmetry score

To provide a more in-depth analysis of the mechanics underpinning the kinematic asymmetry, the KAS included both discrete (event) and profile data. Event asymmetry scores involved summing θ_{SYM} values for discrete variables displaying a significant difference between left and right limbs. Profile asymmetry scores considered continuous data of the ankle, knee, and hip sagittal plane joint kinetics during stance. Joint power was selected as the basis for the kinetic profile analyses due to the inclusion of the ability to both propel and control the lower limbs (Sadeghi et al., 2000), which are important for success in sprint running. Joint power profiles for each trial were normalized to 100% of stance using an interpolating spline. Athlete mean power profiles were calculated for both limbs with profile asymmetry scores comprising four characteristics of the power curves; phase, magnitude, time, and overall difference (Exell et al., 2012a).

Mean step velocity, KMAS, and KAS values were compared across all athletes to examine the association between kinematic and kinetic asymmetry and step velocity. Strength asymmetry data were normally distributed; therefore, relationships between strength asymmetry, step characteristics, peak force, and net joint work during sprint trials were analyzed using Pearson's product-moment correlation. Athlete KMAS and KAS values were not normally distributed (Peat & Barton, 2005). Therefore, Spearman's rank correlation coefficient values were calculated for each pair of variables, with significance set at $P < 0.05$.

Results

Mean velocity across all athletes was 9.05 ± 0.37 m/s. Composite asymmetry scores (KMAS and KAS) are presented for each athlete in addition to the magnitude of θ_{SYM} for each individual variable and each athlete's mean ($\pm$ SD) velocity across all trials, as an indicator of performance. Kinematic θ_{SYM} values (Table 1) were all <10.0%, with the largest value (6.68%) reported for touchdown distance.

Step characteristics (SV, SL, and SF) all contained small amounts of asymmetry (<1.70%) compared with the other kinematic variables, with the largest significant asymmetry value (6.7%) reported for y_{TD}. Kinetic variables included larger θ_{SYM} values, with the largest significant value (76.9%, Table 2) displayed for net knee work. Significant asymmetry between left and right limbs was evident for fewer discrete kinetic variables (13/56, 23%) than for the kinematic variables (24/64, 38%). No significant relationships were found between kinematic

Table 1. Athlete mean velocity and kinematic θ_{SYM} values for variables contributing to the kinematic asymmetry score

Athlete	Mean velocity	SV	SL	SF	zH_{MIN}	zK_{MAX}	θK_{FLEX}	θH_{EXT}	γ_{TD}	KMAS
1	8.65 ± 0.13	0.8 ± 0.5*	1.3 ± 0.6*	1.1 ± 0.8	0.6 ± 0.5	1.0 ± 0.8*	3.7 ± 2.9*,#	0.7 ± 0.4	2.6 ± 2.6	10.53
2	8.87 ± 0.20	0.6 ± 0.5*	1.2 ± 0.5*	1.7 ± 0.6*,#	0.4 ± 0.3	0.9 ± 0.6*	1.6 ± 1.4	0.9 ± 0.7*	3.8 ± 2.7#	10.73
3	9.00 ± 0.08	0.3 ± 0.3*	0.8 ± 0.5	0.8 ± 0.6	0.7 ± 0.4	0.8 ± 0.5	1.8 ± 1.4*,#	0.7 ± 0.5*	2.6 ± 1.8#	7.22
4	8.56 ± 0.07	0.2 ± 0.2	1.3 ± 1.1*,#	1.4 ± 1.1*,#	0.3 ± 0.2	0.7 ± 0.6	4.1 ± 2.4*,#	0.4 ± 0.2*	6.7 ± 2.5*,#	27.6
5	9.30 ± 0.08	0.2 ± 0.2	1.0 ± 0.9	1.1 ± 0.9#	0.5 ± 0.3*	0.6 ± 0.4	3.5 ± 1.8*,#	0.6 ± 0.4#	1.8 ± 1.6#	11.07
6	10.15 ± 0.15	0.4 ± 0.3*	1.0 ± 0.7*	1.4 ± 0.8*,#	0.7 ± 0.4*	1.4 ± 0.7#	3.5 ± 2.1#	0.5 ± 0.7	2.6 ± 2.0	9.86
7	8.69 ± 0.06	0.3 ± 0.6	0.6 ± 0.4	0.7 ± 0.4	0.2 ± 0.1	0.8 ± 0.6	1.4 ± 0.6#	0.2 ± 0.1	3.1 ± 2.5#	4.52
8	9.19 ± 0.10	0.3 ± 0.1	0.6 ± 0.7	0.6 ± 0.8	0.6 ± 0.4	1.8 ± 0.8*,#	1.5 ± 1.1	1.2 ± 0.3*,#	2.6 ± 1.3#	8.64

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

asymmetry, kinetic asymmetry, and mean step velocity. Each athlete's left and right limb results for kinematic and kinetic variables are available in the supplementary tables online.

Strength asymmetry results are presented in Table 3. Three athletes showed significant asymmetry for peak power (Athletes 1, 3, and 6) and peak vertical force (Athletes 3, 6 and 7), while one athlete demonstrated significant ($P < 0.05$) asymmetry for net work (Athlete 1). Significant correlations between strength and performance variables were only found to exist for net ankle work during sprint running (between WA_{NET} and Fz_{MAX} ($r = 0.895$) and WA_{NET} and P_{MAX} ($r = 0.761$)).

The lack of relationship between overall asymmetry and mean velocity across athletes is demonstrated in Fig. 2 ($\rho = 0.19$ and 0.40). All athletes demonstrated individual asymmetry profiles in terms of the variables that displayed significant asymmetry.

Discussion

The aim of this study was to develop understanding of the interaction between kinematic and kinetic asymmetry during maximal velocity sprint running and overall limb strength asymmetry, with the purpose of increasing mechanical understanding of asymmetry and informing future research and coaching in sprint running. Asymmetry was quantified using recently developed composite asymmetry scores (Exell et al., 2012a) based on the θ_{SYM} and incorporating the important consideration of intra-limb variability (Giakas & Baltzopoulos, 1997; Exell et al., 2012c). Using the composite scores and the detailed asymmetry results contained within them, the first hypothesis of individual athlete-specific asymmetry profiles was supported. Although there was support for interaction between kinematic and kinetic asymmetry for some variables (e.g., mean support moment and minimum hip height for Athlete 5), this interaction was not consistent across all athletes and variables. Therefore, the second hypothesis was rejected in favor of individual athlete asymmetry interactions. The third hypothesis is partly accepted, as strength asymmetry (Fz_{MAX} and P_{MAX}) was positively correlated with kinetic asymmetry during sprinting, but only for net work performed at the ankle, indicating the importance of the ankle joint in asymmetry regulation.

The θ_{SYM} score for step velocity, the performance outcome in sprint running, was small (<1%) for all athletes when compared to the other variables analyzed. However, half of the athletes (Athletes 1, 2, 3, and 6) displayed significant asymmetry in step velocity, indicating a consistently higher velocity in one step than the other. These findings related to step

Table 2. 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	25.1*	1.3	2.1	3.5	43.0*	8.5	5.5	124.9	193.5
2	3.0	0.7	0.4	4.6	11.6	76.9*	11.3	209.8	286.7
3	13.4*	2.0	2.3	3.5	6.1	23.2	21.6	159.2	173.2
4	9.4	0.8	3.0*	5.1	21.6*	42.7	3.4	49.0	73.6
5	1.6	0.1	1.1	5.3*	23.7	23.8*	24.3	40.5	69.6
6	0.2	0.8	1.0	2.7	14.5*	22.9	13.8	48.0	62.5
7	10.3	1.8	0.7	4.0	41.3*	56.4	66.4	28.0	69.3
8	2.4	6.0*	4.3*	7.5	93.2	79.6	45.0*	67.7	122.9

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

Table 3. Asymmetry of strength variables for all athletes

Athlete	Fj_{MAX}	Pj_{MAX}	Wj_{NET}
1	1.69*	0.44	2.34*
2	−0.20	−1.01	−0.09
3	−0.70*	−1.55*	−0.29
4	−0.38	−0.85	−1.80
5	0.69	0.19	1.73
6	1.15*	1.44*	2.30
7	−1.30	−0.59*	−0.26
8	−2.27	−3.16	−0.87

*Significant difference between left and right limb values ($P < 0.05$), positive value denotes R>L.

velocity indicate that asymmetry in underlying variables do contribute to asymmetry in the performance outcome but that the magnitude of that difference is small compared to other variables, perhaps to reduce the inefficiency of larger acceleration and deceleration between consecutive steps. Two of the athletes (Athletes 2 and 6) that displayed asymmetry for step velocity also displayed significant asymmetry for both step length and frequency, one (Athlete 1) displayed significant asymmetry for just step length and one (Athlete 3) for neither step length nor frequency. Conversely, Athlete 4 displayed significant asymmetry for both step length and frequency but not for velocity, due to the opposing direction of asymmetry for step length and frequency. The individual nature of step characteristic asymmetry agrees with the athlete-specific step characteristic reliance previously reported (Salo et al., 2011). Furthermore, these findings indicate that athletes may have differing step characteristic demands for left and right sides, which could influence performance differences between sides and training specificity.

Asymmetry was generally lower for step characteristics than the other kinematic variables, with θ_{SYM} values being less than 1.80%. The direction of asymmetry was opposite for step length and frequency for each athlete, whereby the step displaying a larger step length value exhibited the smaller step frequency. The lower asymmetry evidenced for step characteristics indicated that asymmetry in some variables served to reduce overall asymmetry by acting as compensatory mechanisms (Vagenas & Hoshizaki, 1991). The purpose of these compensatory mechanisms might be to reduce asymmetry present in the lower order performance variables (i.e., step characteristics) to increase control and consistency of performance.

Inter-athlete asymmetry differences were present for the remaining kinematic and kinetic variables analyzed in the group of athletes tested. The most asymmetrical variables were not consistent across

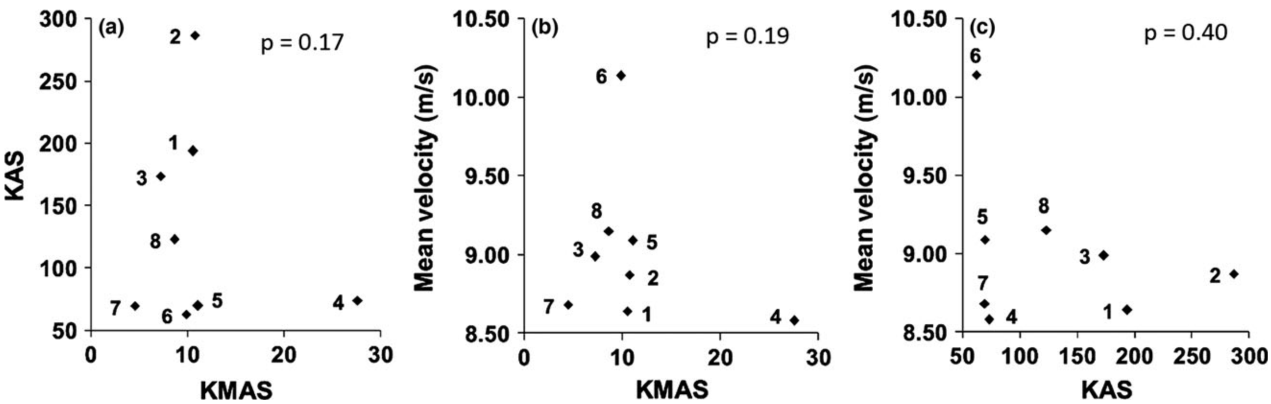

Fig. 2. Comparisons of KMAS and KAS (a), KMAS and mean velocity (b) and KAS and mean velocity (c) for Athletes 1–8, ρ = Spearman rank correlation coefficient.

athletes, with significantly asymmetrical variables being athlete-specific. The inter-athlete differences in overall KMAS and KAS and the significantly asymmetrical variables that contributed to them reinforce the importance of individual analyses (Dufek et al., 1995; Salo et al., 2011). This finding is important from an athlete coaching perspective as athletes appear to employ different mechanisms for contralateral limbs to achieve similar outcomes in performance.

Other than step velocity, the kinematic variables that displayed significant asymmetry for the most athletes ($n = 4$) were minimum knee flexion and maximum hip extension angles. Possible causes of the large occurrence of asymmetry in these sagittal plane angles compared with the other linear variables could have been strength imbalances around the joints (Vagenas & Hoshizaki, 1991) or asymmetry in the range of motion at the joint (Warren, 1984). The significant asymmetry reported for joint kinetics during sprinting in this study provides further support for possible strength imbalances. Touchdown distance was significantly asymmetrical for the least number of athletes ($n = 1$), with minimum hip height during stance being the next least ($n = 2$). Small amounts of asymmetry in minimum hip height have also been reported during submaximal running (Karamanidis et al., 2003). The low prevalence of asymmetry for minimum hip height may be due to asymmetry being undesirable for this variable as it could lead to collapse of the contact limb while the athlete is in contact with the track or increased energetic demand. However, asymmetry may exist in the individual joints of the lower limbs and be compensated for by the other joints so that the overall effect is minimized, as suggested by the support moment theory (Winter, 1980). This notion is supported by the fact that, despite seven of the eight athletes in the current study displayed significant asymmetry for net work performed at a joint, no athletes displayed significant asymmetry in this variable for more than one joint and only one athlete demonstrated significant asymmetry for support moment.

The largest kinematic asymmetry value for one variable was 6.68% for touchdown distance between the foot and mass center of Athlete 4. Increased touchdown distance has been associated with greater braking forces at touchdown (Mann & Herman, 1985); however, the asymmetry in this variable for Athlete 4 was not paired with a significant difference in net horizontal impulse. One explanation for the inconsistency between asymmetry of related kinetic and kinematic variables is the possible compensatory mechanisms acting at some joints to counteract imbalances or weaknesses at other joints, as discussed in previous studies (Sanderson & Martin, 1996; Bezodis et al., 2008). These compensatory mechanisms may be employed by the athlete to overcome strength or physical imbalances, as could be the case when kinetic asymmetry leads to an apparent reduction in kinematic asymmetry.

No relationship was found between athletes' KMAS and KAS scores. Some athletes (e.g., Athletes 6 and 7) displayed similarly low scores for both KMAS and KAS in relation to the other athletes, whereas Athlete 2 displayed a large amount of kinetic asymmetry and a moderate KMAS in comparison to the other athletes. The lack of a relationship between kinematic and kinetic asymmetry reinforces the individual nature of sprint running as athletes displayed an individual interaction between kinetic and kinematic asymmetry. Kinetic asymmetry may be the cause of kinematic asymmetry in some variables for some athletes, whereas for others, kinetic asymmetry may reduce kinematic, and hence step characteristic, asymmetry and may be a required compensatory mechanism due to strength or physical imbalances (Vagenas & Hoshizaki, 1991; Beyaert et al., 2008).

Examples of the athlete-specific relationships between asymmetry and sprint velocity can be seen for Athletes 4 and 7, who displayed similar mean velocities (8.55 and 8.63 m/s) but the kinematic asymmetry for Athlete 3 (27.60) was more than six times the magnitude of that for Athlete 7 (4.52). In addition, Athletes 6 and 7 showed similar amounts of kinetic asymmetry (KMAS = 62.54 and 69.25, respectively); however, Athlete 6's mean step velocity (10.15 m/s) was much larger than Athlete 7's (8.63 m/s). The inconsistency between asymmetry and performance suggests that asymmetry may be both functional and dysfunctional for different athletes. In athletes that have an imbalance in strength or mobility around specific joints, asymmetry may be explained through the concepts of self-organization (Kugler & Turvey, 1988) and be a functional requirement to optimize performance. Conversely, for other athletes, asymmetry may be seen as noise and indicate that one side of the body is not performing as optimally as the other, requiring technique adjustment.

For the limb strength variables calculated, four of the eight athletes showed significant asymmetry for at least one of the variables; however, the magnitude of these significant asymmetries was small (<2.5) compared with those presented during sprint running. When comparing strength and performance asymmetry, the only significant relationships were found between net ankle work during sprinting and peak force and power values in the jump tests. This finding indicates that the ankle joint is key in regulating asymmetry at the athlete–ground interface. Conflicting findings were reported for Fz_{MAX} during sprint and jump trials, with Athletes 1, 3, and 6 demonstrating significant asymmetry for the variable during the squat jumps but not during sprint running trials. Conversely, Athletes 4 and 8 were significantly asymmetrical for Fz_{MAX} during sprint running, but not during the jump tests. A possible explanation for this disagreement is the inclusion of a touchdown phase during a sprinting step that is not included during the propulsive phase of a squat jump. Another possible explanation for the differences in asymmetry between the jump tasks and sprint running and for the small asymmetry magnitude reported for jump asymmetry is intra-limb compensation that could serve to reduce asymmetry in overall limb performance (Flanagan & Harrison, 2007; Furlong & Harrison, 2014).

Peak explosive power is often used to assess sprint-specific strength (Harman et al., 1991). During jump tests, significant peak power asymmetry was reported for Athletes 3, 6, and 7; however, there was no consistent link with step characteristic asymmetry. Athlete 3 demonstrated significantly greater power for the left limb, with significantly larger step velocity also reported off of the left limb. Conversely, Athlete 6 demonstrated significantly larger peak power for the right limb during the jump tests but with significantly larger step velocity from the left take-off during sprinting. An interesting observation for Athlete 6 was the significantly larger step length from right take-off, whereas the opposite was reported for step frequency. The results for Athlete 6 indicate that the larger peak power generated by the right limb could lead to larger step length following right take-off; however, this asymmetry is not reflected in step velocity due to the opposing asymmetry for step frequency.

Only one athlete (Athlete 1) showed significant asymmetry for net vertical work during the jump tests, despite all athletes except one (Athlete 3) having significant asymmetry for net joint work at either the ankle, knee or hip during sprint trials. This finding further supports the notion of Vagenas and Hoshizaki (1991) that individual joint asymmetry may provide more insight than limb dominance when evaluating strength and performance. The lack of a consistent link between strength and performance asymmetry demonstrates that asymmetry in sprint running is not solely due to overall limb strength imbalance. However, net strength asymmetry measures such as those presented could be used in athlete screening and monitoring protocols to identify and track strength imbalances following injury.

From a data collection perspective, the asymmetry reported in the study should inform study design, specifically when choosing between unilateral and bilateral analyses. Asymmetry was inconsistent between variables and athletes and every variable included in these analyses demonstrated significant asymmetry for at least one athlete. Therefore, symmetry should not be assumed when collecting biomechanical data during sprint running. An example of the potential lost information when employing unilateral analyses can be seen for touchdown distance. If data were collected unilaterally from Athlete 4, the difference in touchdown distance between left and right sides of 0.06 m would have been hidden. Conversely, there was no difference in touchdown distance between sides for Athlete 8; however, maximum knee lift results, which were not significantly asymmetrical for Athlete 4, displayed a significant difference of 0.04 m for Athlete 8. Furthermore, pooling or averaging data for both limbs may present a large amount of variability and results in "mythical average" data that are not representative of either limb (Dufek et al., 1995). A screening test quantifying athletes' asymmetry would allow an informed decision to be made on whether unilateral data are representative of both limbs, when data are only available from one side, such as when collecting competition data for example. A profile of each athlete's asymmetry would also be beneficial from a coaching perspective as it could inform athletes and coaches about specific strength imbalances, compensatory mechanisms, and rehabilitation following injury.

A limitation of this study was the comparison of overall lower limb strength during jump tests with individual joint asymmetry during sprint performance. Building on the presented findings, future work in this area should consider the influence of strength asymmetry at individual joints of the lower limb and how these contribute to overall limb asymmetry as well as the influence of structural asymmetry.

Perspective

This research highlighted the individuality of asymmetry, with all athletes displaying significant asymmetry for different variables. Despite small asymmetry magnitudes for step velocity, all athletes demonstrated increased asymmetry for other variables. Comparing kinematic and kinetic asymmetry with sprint running performance showed no significant relationships. The interaction between related kinematic and kinetic variables also varied between athletes. These individual interactions indicate that asymmetry may be functional or dysfunctional for different athletes rather than limiting performance, supporting the limited previous research in this area (Lockie et al., 2014). Furthermore, asymmetry at specific joints may be used as a compensatory mechanism to improve performance. Based on the individual nature of asymmetry reported, it is recommended that athletes are not assumed to be symmetrical when coaching or collecting biomechanical data during sprint running. In situations, such as competition,

where only unilateral data are available, biomechanists and coaches should be aware of the potential differences in the unanalyzed limb. Asymmetry profiles for strength measures were also athlete-specific. However, there appears to be a positive relationship between asymmetry of lower limb strength and net ankle work performed while sprinting. This relationship with strength asymmetry suggests that the ankle joint is key in regulating asymmetry in sprinting.

Key words: Gait, sprinting, symmetry angle, strength asymmetry.

Funding

This work was funded by EPSRC grant number EP/D076943.

Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Table S1. Mean [±SD] kinematic values recorded for each athlete, R-L = step from right foot touchdown to left foot touchdown and L-R = step from left foot touchdown to right foot touchdown.

Table S2. Mean [±SD] kinetic values recorded for each athlete, R = right foot ground contact and L = left foot ground contact. M_{SUP}, WA_{NET}, WK_{NET}, and WH_{NET} values are normalized using the method of Hof (1999) and are, therefore, dimensionless.

References

Beyaert C, Grumillier C, Martinet N, Paysant J, Andre JM. Compensatory mechanism involving the knee joint of the intact limb during gait in unilateral below-knee amputees. Gait Posture 2008: 28: 278–284.

Bezodis IN, Kerwin DG, Salo AIT. Lower-limb mechanics during the support phase of maximum-velocity sprint running. Med Sci Sports Exerc 2008: 40: 707–715.

Bezodis IN, Thomson A, Gittoes MJR, Kerwin DG. Identification of instants of touchdown and take-off in sprint running using an automated motion analysis system. In: Proceedings of the XXV International Symposium on Biomechanics in Sports. Ouro Preto, Brazil: International Society of Biomechanics in Sports, 2007: 501–504.

Buckley JG. Biomechanical adaptations of transtibial amputee sprinting in athletes using dedicated prostheses. Clin Biomech 2000: 15: 352–358.

Carpes FP, Mota CB, Faria IE. On the bilateral asymmetry during running and cycling – a review considering leg preference. Phys Ther Sport 2010: 11: 136–142.

Cavanagh PR, Andrew GC, Kram R, Rodgers MM, Sanderson DJ, Hennig EM. An approach to biomechanical profiling of elite distance runners. Int J Sport Biomech 1985: 1: 36–62.

Challis JH. A Procedure for the automatic determination of filter cutoff frequency for the processing of biomechanical data. J Appl Biomech 1999: 15: 303–317.

Ciacci S, Di Michele R, Fantozzi S, Merni F, Mokha M. Assessment of kinematic asymmetry for reduction of hamstring injury risk. Int J Athl Ther Train 2013: 18: 18–23.

Ciacci S, Di Michele R, Merni F. Kinematic analysis of the braking and propulsion phases during the support time in sprint running. Gait Posture 2010: 31: 209–212.

Dufek JS, Bates BT, Stergiou N, James CR. Interactive effects between group and single-subject response patterns. Hum Mov Sci 1995: 14: 301–323.

Exell TA, Gittoes MJR, Irwin G, Kerwin DG. Considerations of force plate transitions on centre of pressure calculation for maximal velocity sprint running. Sport Biomech 2012a: 11: 532–541.

Exell TA, Gittoes MJR, Irwin G, Kerwin DG. Gait asymmetry: composite scores for mechanical analyses of sprint running. J Biomech 2012b: 45: 1108–1111.

Exell TA, Irwin G, Gittoes MJR, Kerwin DG. Implications of intra-limb variability on asymmetry analyses. J Sports Sci 2012c: 30: 403–409.

Flanagan EP, Harrison AJ. Muscle dynamics differences between legs in healthy adults. J Strength Cond Res 2007: 21: 67–72.

Furlong L-AM, Harrison AJ. Differences in plantarflexor function during a stretch-shortening cycle task due to limb preference. Laterality 2014: 20: 128–140.

Giakas G, Baltzopoulos V. Time and frequency domain analysis of ground reaction forces during walking: an investigation of variability and symmetry. Gait Posture 1997: 5: 189–197.

Gittoes MJR, Wilson C. Intralimb joint coordination patterns of the lower extremity in maximal velocity phase sprint running. J Appl Biomech 2010: 26: 188–195.

Hamill J, Bates BT, Knutzen KM. Ground reaction force symmetry during walking and running. Res Q Exerc Sport 1984: 55: 289–293.

Harman EA, Rosenstein MT, Frykman PN, Rosenstein RM, Kraemer WJ. Estimation of Human Power Output from Vertical Jump. Journal of Strength & Conditioning Research 1991: 5: 116–120.

Hof AL. Scaling gait data to body size. Gait and Posture. 1996: 4: 222–223.

Hunter JP, Marshall RN, McNair PJ. Interaction of step length and step rate during sprint running. Med Sci Sports Exerc 2004: 36: 261–271.

Jacobs C, Uhl TL, Seeley M, Sterling W, Goodrich L. Strength and fatigability of the dominant and nondominant hip abductors. J Athl Train 2005: 40: 203–206.

Johnson MD, Buckley JG. Muscle power patterns in the mid-acceleration phase of sprinting. J Sports Sci 2001: 19: 263–272.

Karamanidis K, Arampatzis A, Bruggemann GP. Symmetry and reproducibility of kinematic parameters during various running techniques. Med Sci Sports Exerc 2003: 35: 1009–1016.

Kugler PN, Turvey MT. Self-organization, flow fields, and information. Hum Mov Sci 1988: 7: 97–129.

Laroche DP, Cook SB, MacKala K. Strength asymmetry increases gait asymmetry and variability in older women. Med Sci Sports Exerc 2012: 44: 2172–2181.

Lockie RG, Callaghan SJ, Berry SP, Cooke ER, Jordan CA, Luczo TM, Jeffriess MD. The relationship between unilateral jumping ability and asymmetry on multidirectional speed in team sport athletes. J Strength Cond Res 2014: 28: 3557–3566.

Mann RV, Herman J. Kinematic analysis of olympic sprint peformance: men's 200 meters. Int J Sport Biomech 1985: 1: 151–162.

Menzel H-J, Chagas MH, Szmuchrowski LA, Araujo SRS, de Andrade AGP, de Jesus-Moraleida FR. Analysis of lower limb asymmetries by isokinetic and vertical jump tests in soccer players. J Strength Cond Res 2013: 27: 1370–1377.

Peat J, Barton B. Medical statistics: a guide to data analysis and critical appraisal. London, UK: BMJ Books, 2005.

Sadeghi H, Allard P, Prince F, Labelle H. Symmetry and limb dominance in able-bodied gait: a review. Gait Posture 2000: 12: 34–45.

Salo AIT, Bezodis IN, Batterham AM, Kerwin DG. Elite sprinting: are athletes individually step-frequency or step-length reliant? Med Sci Sports Exerc 2011: 43: 1055–1062.

Sanderson DJ, Martin PE. Joint kinetics in unilateral below-knee amputee patients during running. Arch Phys Med Rehabil 1996: 77: 1279–1285.

Schache AG, Wrigley TV, Baker R, Pandy MG. Biomechanical response to hamstring muscle strain injury. Gait Posture 2009: 29: 332–338.

Thompson A, Bezodis IN, Jones RL. An in-depth assessment of expert sprint coaches' technical knowledge. J Sports Sci 2009: 27: 855–861.

Vagenas G, Hoshizaki B. Functional asymmetries and lateral dominance in the lower limbs of distance runners. Int J Sport Biomech 1991: 7: 311–329.

Warren BL. Anatomical factors associated with predicting plantar fasciitis in long-distance runners. Med Sci Sports Exerc 1984: 16: 60–63.

Winter DA. Overall principle of lower limb support during stance phase of gait. J Biomech 1980: 13: 923–927.

Zifchock RA, Davis I, Hamill J. Kinetic asymmetry in female runners with and without retrospective tibial stress fractures. J Biomech 2006: 39: 2792–2797.

Zifchock RA, Davis I, Higginson J, Royer T. The symmetry angle: a novel, robust method of quantifying asymmetry. Gait Posture 2008: 27: 622–627.