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Kinematic stride cycle asymmetry is not associated with sprint performance and injury prevalence in athletic sprinters

Kinematic asymmetry in athletic sprinting

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Abstract

The aims of this study were to i) quantify the magnitude of kinematic stride cycle asymmetry in high-level athletic sprinters, ii) explore the association between kinematic asymmetry and maximal sprint running performance, and iii) investigate possible associations between kinematic asymmetry and injury prevalence. Twenty-two competitive sprinters (age 23 ±3 yr, height 1.81 ±0.06 m, body mass 75.5 ±5.6 kg, personal best 100-m 10.86 ±0.22 s) performed 2-3 flying sprints over 20 m. Kinematics were recorded in 3D using a motion tracking system with 21 cameras at a 250 Hz sampling rate, allowing assessment of six consecutive steps for each athlete. Information about injuries sustained one year prior to and after the experiment was continuously registered (type, location, severity/duration and time of year occurrence). The results showed that ≥ 11 out of the 22 participating athletes displayed large or very large asymmetry for at least 11 out of 14 variables, and all athletes displayed large or very large asymmetry for at least three variables. No correlations between individual magnitudes of asymmetry and sprint performance were significant (trivial to moderate). No significant changes in asymmetry between best and worst trial were observed for any of the analysed variables. In addition, injured and non-injured athletes did not differ in asymmetry, neither for the time-period one year prior to nor after the test. In conclusion, kinematic asymmetries in the stride cycle were not associated with neither maximal sprint running performance nor the prevalence of injury among high-level athletic sprinters.

KEY WORDS:

inter-limb differences; spatiotemporal variables: sprint biomechanics: injury occurrence; hamstring injuries

Introduction

Sprint running is a fundamental skill in many sport disciplines. An optimal sprint running technique is regulated by a complex interaction of numerous variables, including mass-specific force application, spatiotemporal variables, body configuration and lower-limb segment velocities prior to and during ground contact.[1-6] However, the human running pattern is also associated with bilateral asymmetry[7-10], most likely due to imbalances in the neuromuscular and skeletal system.[11-12] Considering this, an interesting question is whether asymmetry in specific technical variables affects overall sprint performance.

Currently, the association between asymmetry in the sprint stride cycle and maximal sprint running performance in athletic sprinters is unclear. Exell et al.[9] and Meyers et al.[13] observed non-significant, small-to-moderate correlations between maximal velocity sprinting and level of asymmetry for kinetic and kinematic variables in mid-level sprinters (mean maximal velocity 9.05 $m \cdot s^{-1}$) and 11-16 year old school boys, respectively. To date, no scientific studies have quantified the magnitude of asymmetry in sprinters with mean maximal velocity >10 ms^{-1}.

Asymmetry information is also important from a medical perspective. Inter-limb differences are typically assessed by medical staff to evaluate the effectiveness of rehabilitation programs and for establishing baselines to which the injured limb should return. Several studies have suggested that strength and power imbalances ≥ 10% are cause for concern and may place the weaker limb at a greater risk for injuries.[14-16] Schache et al.[17] observed increased inter-limb differences in a sprinting athlete for several biomechanical parameters in the nine pre-injury trials leading up to a hamstring injury in the tenth trial. However, overall information regarding the influence of sprint-specific movement pattern imbalances on injury risk remains limited.

Based on kinematic measurements of multiple steps in high-level athletic sprinters, the aims of this study were to i) quantify the magnitude of kinematic stride cycle asymmetry during maximal velocity sprinting, ii) explore the association between kinematic asymmetry and maximal velocity sprinting, and iii) investigate possible associations between kinematic asymmetry and injury prevalence. We hypothesized that kinematic asymmetries in the stride cycle would not be significantly associated with maximal sprint running performance or injury prevalence in high-level athletic sprinters.

Materials and methods

Participants

Twenty-two Norwegian competitive sprinters (age 23 ±3 yr, height 1.81 ±0.06 m, body mass 75.5 ±5.6 kg, personal best 100-m 10.86 ±0.22 s) voluntarily signed up for this study. The athletes had performed athletic sprint training since they were 15 ±5 years old. All athletes were healthy and free of injuries at the time of testing, and the study was approved by The Norwegian Data Protection Authority. All subjects signed an informed consent form before the experiment and were made aware that they could withdraw from the study at any point without providing an explanation. The study was conducted in accordance with the Declaration of Helsinki.

Procedures

All experiments were performed in a period of three days during the competition season (middle of August) in an indoor athletic venue. The section of the track around the middle of the finishing straight was used for data collection. Regarding nutrition, hydration, sleep and physical activity, the athletes were instructed to prepare themselves as they would for a regular competition, including no high-intensive training the last two days before testing. After a self-regulated warm-up procedure, each participant performed two or three (depending on physical and mental readiness) 20-m flying sprints with maximal effort. The actual data recording distance was 18 m, limited by the number of cameras. Recovery time among trials was self-regulated (6-10 min). Each individual was instructed to build up speed over a self-selected in-run distance (typically 30-50 m) before entering the measurement zone. Prior to each run, the athletes indicated that they were ready for a maximal effort. A sprint trial was considered successful if the athlete indicated directly after finishing that he was satisfied with his performance.

Information about injuries sustained one year prior to and after the experiment was continuously registered (type, location, severity/duration and time of year occurrence) through mail or phone communication. Operation definitions of injuries in accordance to the guidelines by Ekstrand et al.[18] were used. Only moderate (causing 8–28 days layoff) or severe (causing >28 days layoff) injuries were included for analysis. One athlete was withdrawn from this part of the analysis (association between asymmetry and injuries) due to incomplete reporting of injury data.

Measurements

Kinematics were recorded in 3D using a Qualisys motion tracking system with 21 Oqus cameras (Qualisys AB, Gothenburg, Sweden) at a 250 Hz sample rate. The cameras were placed at both sides of the running track and the volume of measurement was calibrated according to the manufacturer's specifications. The resolution of marker position was < 2 mm. Reflective markers (⌀ 19 mm) were placed at anatomical landmarks to identify 12 segments (head, trunk, bilaterally: arm, forearm, thigh, leg and foot) and related movements of the body: forehead and C7, bilaterally on the lateral malleolus, lateral femoral epicondyle, trochanter major, anterior superior iliac spine, posterior superior iliac spine, lateral tip of the acromion, lateral humeral epicondyle, ulnar styloid process and on both shoes: heel, hallux and above the head of the fifth metatarsal. All data were recorded using the QTM software v2.12 and all post-analysis was performed in Matlab R2014a (The Mathworks Inc., Natick, MA, USA). Marker position data were filtered using a Chebyshev Type II low pass filter (cut-off 20 Hz, 16th order). Position of CoM was calculated based on anthropometric data according to de Leva.[19]

Touchdown and lift-off of the foot was determined by a purpose-written algorithm.[20] First, the approximate epoch for each touchdown and lift-off was found by identifying the time that the height of the fifth metatarsal marker on each foot decreased to under and increased above a set threshold (40 mm), respectively. Thus, first an epoch around and slightly exceeding the actual ground contact was determined. Within this epoch, the first and last peak vertical acceleration of the metatarsal marker was used to indicate the exact time of touchdown and lift-off, respectively. In this way, contact and aerial phases for each step could be identified and variable values related to these periods calculated. Velocity of markers and calculated variables (e.g., CoM) were derived by applying numerical differentiation of the position signals. The forward velocity of CoM was used as running velocity. One step was defined as ground contact and the following aerial phase. Overall, the setup allowed for the analysis of six steps for each subject during the flying sprint trials. Maximal velocity sprinting performance was defined as mean step velocity of all the six assessed steps during the flying sprints.

The following variables were included in analyses; step length, step rate, contact time, aerial time, touchdown angle (for the stance leg), knee separation (assessed as inter-thigh angle) at touchdown, lift-off angle, thigh- and knee angle at lift-off (for the stance leg), maximal thigh flexion, range of thigh motion, rear knee flexion at maximal thigh extension, and horizontal ankle velocity (of the lateral malleolus marker for the soon-to-be stance foot) relative to CoM (based on mean velocity of the swing foot the last eight samples prior to touchdown). All these variables were included in this study as they have been frequently reported and considered crucial for performance in previous literature.[3,4,6,21-25] Angle definitions are illustrated in Figure 1.

Figure 1 about here

Statistical analyses

Statistical analyses were performed using IBM SPSS Statistics 22.0 (SPSS Inc., Chicago, IL, USA). Mean and standard deviation for all analysed variables are presented. Typical error (TE) and coefficient of variation (CV) were used to calculate within- and between-sprint variability. Superior side was defined as the lower-limb side (either left or right) displaying the highest absolute values on average for each variable in each individual, while inferior side displayed the lowest individual values for each variable. Percentage asymmetry ((superior value – inferior value / inferior value) *100) was used to calculate inter-limb asymmetry, so that averaging positive and negative symmetry indices over several participants did not lead to a zero value.[7,26] However, percentage asymmetry and CVs were not calculated for angular variables as an angle is already a ratio and does not have an absolute minimum (it is dimensionless). To express the magnitude of asymmetry, relative to variability, we used Cohen's *d* and thus also examined within- and between-sprint variability. Cohen`s *d* values were interpreted categorically as trivial (0 to 0.19), small (0.2 to 0.59), moderate (0.6 to 1.19), large (1.2 to 1.9) or very large (>2.0).[27] According to Giakas & Baltzopoulos[26], between-side differences must be greater than within-side variability for asymmetry to be significant. Based on these considerations, we calculated the percent distribution of the sample displaying Cohen's *d* values > 1. Pearson's R correlations between individual Cohen's *d* values for all variables and mean step velocity were used to explore the relationship between asymmetry and maximal sprint running performance. Moreover, paired samples T-tests were used to analyse differences in asymmetry between best and worst trial. Independent samples T-tests were used to analyse possible associations between asymmetry (based on Cohens's *d* values from best trial) and injury prevalence. Statistical significance was accepted at the P < .05 level.

Results

Table 1 about here

Table 1 shows the magnitude of asymmetry across variables. For the spatiotemporal variables (i.e., step velocity, step length, step rate, contact time, and aerial time), the majority (≥ 12 out of 22) of athletes displayed large to very large asymmetry (i.e., Cohens's $d \geq 1.2$ thus between-side variability clearly larger than within-side variability), except for aerial time (10 out of 22). Regarding the kinematic variables, only touchdown angle and inter-thigh angle at TD showed a minority with clear asymmetry (L and VL), while ≥ 11 out of the 22 participants (i.e., at least 50%) displayed large to very large asymmetry for the other variables. When considering the combined outcome of the variables per athlete, half or more displayed large or very large asymmetry for at least 11 out of 14 variables. All athletes displayed large or very large asymmetry for at least 3 out of 14 variables.

Table 1 also shows correlation values between individual magnitudes of asymmetry and sprint performance. Moderate correlations were observed for step length, maximal thigh flexion and knee flexion at maximal thigh extension, while the remaining variables displayed only trivial or small effect magnitudes. None of the correlation values reached the level of statistical significance. Moreover, paired samples T-tests revealed no significant changes in magnitude of asymmetry between best and worst trial for any of the analysed variables.

Table 2 about here

Table 2 shows within- and between-sprint variability for all analysed kinematic variables. Overall, the variability within and between sprints was practically equal within the same variable. A similar trend was observed for superior and inferior sides within the same variable. However, the TE- and CV-values were considerably lower in nearly all variables when considering one leg compared to both legs.

Table 3 about here

Table 3 shows injury pattern by severity of injuries for the included participants (n = 21). About half of all injuries (22 of 45) that occurred one year prior to and after the test were hamstring injuries/strains. Of these, 59% were in the right leg while 41% were in the left leg. Fourteen percent (3 of 22) of the sustained hamstring injuries were re-injuries, that is, an injury in which the athlete reported previously straining the hamstring muscle group on the same side during the current season. Sixty-eight percent (15 of 22) of all hamstring injuries occurred in the period April-June. Independent samples T-tests revealed no significant differences in magnitude of asymmetry (Cohen's *d* values) between injured and non-injured athletes, neither for the time-period one year prior to nor after the test. This relationship remained unchanged when only hamstring injuries were considered.

Discussion

To the authors' knowledge, this is the first study to present the magnitude of asymmetry in sprinters with mean maximal velocity >10 ms^{-1}. At least 50% of the participants had large or very large asymmetry for ≥ 11 out of 14 variables, and all athletes displayed corresponding asymmetry for at least three variables. The TE- and CV-values were considerably lower in nearly all variables when considering one leg compared to both legs. No significant associations were observed between asymmetry and performance for the included variables. Similarly, sprint-specific movement pattern imbalances were not significantly associated with injuries sustained one year prior to or after the kinematic measurements.

Knowledge regarding the association between asymmetry and performance is crucial from a coaching perspective. In this study, more than two thirds of the assessed sprinters displayed large or very large asymmetry for mean step velocity, while approximately half displayed similar inference-based magnitudes of asymmetry for spatiotemporal variables. In relative terms, the bilateral difference in step speed amounted to 0.6% on average. Although this may seem low at face value, it represents nearly half the average performance progression observed (1.3-1.4%) from the age of 18 to the age of peak performance reached in the mid-20s in competitive sprinters.[28] Still, the relatively large asymmetry did not relate to performance. The 0.6% step velocity asymmetry is considerably lower than the 4%

asymmetry for treadmill running velocity in physically active males reported by Girard et al.[10], but somewhat higher than the 0.3% difference observed in males with 9.05 $m \cdot s^{-1}$ mean maximal sprint velocity.[9] Moreover, the present percentage asymmetries for step length (2.6%) and step rate (4.0%) were higher than those reported by Exell et al.[9] (~ 1%), but in line with Korhonen et al.[7] and Girard et al.[10] Finally, the present asymmetry for contact time (4.2%) is in accordance with previous studies of slower sprinters[7,10], while the observed aerial time asymmetry (4.9%) is considerably lower than that reported by Korhonen et al.[7] and Girard et al.[10] Comparisons of other kinematic asymmetry values reported in previous studies of sprinting athletes are precluded by varying angle definitions and choice of reference value. Overall, the abovementioned comparisons between the present and previous studies reveal no clear associations between asymmetry and sprint performance level for spatiotemporal variables. This lack of association is reinforced by the fact that the current investigation revealed no significant associations between individual magnitudes of asymmetry and sprint performance level in terms of maximal velocity sprinting. Moreover, no significant changes in magnitude of asymmetry between best and worst trial were observed for any of the analysed variables. Our findings are in accordance with Exell et al.[9] and Meyers et al.[13], who observed non-significant, small-to-moderate correlations between mean velocity and level of asymmetry (both kinetic and kinematic variables) in mid-level sprinters and 11-16 year old boys, respectively. It is tempting to suggest that, because of intrinsic neuromuscular and/or anthropometrical bilateral asymmetry that most likely are present, kinetic asymmetry in the sprint stride cycle needs to occur when maximising sprint performance. However, current evidence suggests that if kinetic asymmetry occurs because of intrinsic neuromuscular asymmetry in the body, it appears randomly in relation to performance. The present observations of variable-specific asymmetries in well-trained sprinters support previous findings in distance runners and mid-level sprinters, namely that considerable bilateral asymmetry is typical for the human running pattern.[7-9,29,30]

No previous studies have utilized inference-based statistics to quantify asymmetry in sprinting athletes. Previously published studies have employed other calculation methods, including the symmetry index[7], ratios of asymmetry between left and right limbs[8] and the symmetry angle.[30,31] These approaches are either influenced by the choice of reference value or limited in that pooled data among subjects can lead to a zero value, as demonstrated by Korhonen et al.[7] Therefore, as long as a sufficient number of steps is assessed, we argue that inference-based statistics, where these limitations are not present, is most appropriate for asymmetry quantification in sprint running.

From a methodological perspective, it is crucial to possess knowledge regarding the influence of bilateral asymmetry on variability/repeatability for consecutive foot strikes. In the assessment of athletes' sprinting performance, it is necessary to consider the actual change in performance (the signal), the typical error of measurement (the noise) and the smallest practical or meaningful change.[32] According to Giakas & Baltzopoulos[26], between-side differences must be greater than within-side variability for asymmetry to be meaningful. This was the case for 45-77% of the present sprinters, depending on the variable of interest. There was a trend towards lower intra- than inter-limb variability for the analysed kinematic variables. Similarly, Zifchock et al.[31] reported that between-side variability was significantly greater than within-side variability in female distance runners. The present numbers indicate that a considerable amount of the observed consecutive-step variability is due to asymmetry, 10 to 50%, depending on the variable of interest. Because sprinting is a three-dimensional activity and the variability within and between sprints is practically equal within the same variable, we therefore recommend both-side measurements of multiple sprints. This is important information for scientists and coaches in data collection situations where the availability and cost of technology represents a limitation. For example, should the limited number of high-resolution cameras be placed on one or both sides of the running course? The former option doubles the measurement area in the running direction, while the latter option ensures measurements of both body sides.

The injury pattern among the included athletes supports previous findings in that muscle injuries is the major type of injury in sprinters, and among those, the hamstring is most commonly affected.[33,34] The athletes in this study sustained one moderate or severe hamstring injury on average during the included two-year period. No significant associations were observed between sprint-specific movement pattern imbalances and injuries sustained one year prior to or after the kinematic measurements. These retrospective and prospective observations remained consistent whether all injuries or only hamstring injuries were considered. However, this does not necessarily reject the possibility that sustained injuries can be related to asymmetry for some of the individuals.

The causes of hamstring injuries are complicated and numerous, highlighted by multifactorial aetiology models.[35,36] Previous injury is a commonly recognized risk factor for a new hamstring injury, but only 14 percent of the sustained hamstring injuries in the present study were re-injuries, indicating that other risk factors may be more pronounced. Interestingly, two thirds of all hamstring injuries occurred in the period April-June, that is, during the transition from specific preparation to competition. Based on the authors' thorough knowledge of the athletes' daily training, this period is typically characterized by large reductions in training volume, increases in training intensity/sprint speed and sudden positive changes ("spikes") in individual sprint performance development. When sprinters experience spikes in training for which they are not prepared, they may experience larger degrees of maladaptation, modifying a host of internal risk factors and thereby enhancing their predisposition to injury in subsequent training sessions or competitions.[36] Emerging evidence indicates that poor load management is a major risk factor for injury,[35,36] and there is commonly a sense among athletes and coaches in athletic sprinting that the risk of injury is greatest when the athletes are approaching their best shape. Future studies should therefore explore possible associations between training characteristics and injuries in elite sprinters.

Perspectives

This study provides novel insight on fundamental aspects of asymmetry in the sprint stride cycle in high-level athletic sprinters. Half or more of the current athletes displayed large or very large asymmetry for at least 11 out of 14 variables, and all athletes displayed corresponding asymmetry for at least three variables. Given the current study and similar findings in the literature on different level athletes, it appears that asymmetry within the sprint stride cycle is more likely the norm rather than the exception. This investigation provide novel data for practitioners, medical staff and scientists regarding the expected magnitude of lower-limb asymmetry over a range of kinematic variables in non-injured sprinters. Because asymmetry appears to be the norm, bilateral measurements of multiple steps are needed to obtain valid information of an individual's sprint running technique. Moreover, kinematic lower-limb asymmetries were not associated with neither maximal sprint running performance nor the prevalence of injury among high-level athletic sprinters. However, future longitudinal investigations of high-level athletes are required to verify whether lower-limb asymmetries in the stride cycle limit individual performance development and whether asymmetry is functional or dysfunctional for individual injury prevalence.

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Table 1. Magnitude of asymmetry across variables and association with performance

Variable	**Mean ±SD**	**Absolute asymmetry**	**Asymmetry (%)**	**Magnitude distribution (total *n=22*)**					**R**
				VL	**L**	**M**	**S**	**T**	
Step velocity ($m \cdot s^{-1}$)	10.18 ±0.25	0.06 ±0.04	0.6	8	7	2	4	1	-0.25
Step length (m)	2.25 ±0.08	0.06 ±0.04	2.7	10	2	6	3	1	-0.37
Step rate (Hz)	4.54 ±0.18	0.18 ±0.11	4.1	6	6	7	3	0	-0.21
Contact time (ms)	96 ±8	4 ±2	4.2	2	10	5	3	2	-0.21
Aerial time (ms)	124 ±6	6 ±5	4.9	7	3	6	4	2	-0.19
Touchdown angle (°)	105.2 ±1.7	1.6 ±1.0	-	6	3	8	4	1	0.04
Inter-thigh angle at TD (°)	-15.8 ±7.2	4.2 ±2.9	-	4	4	5	5	4	0.09
Lift off angle (°)	56.7 ±1.9	1.0 ±0.8	-	7	4	6	3	2	0.03
Thigh angle at LO (°)	115.4 ±4.1	2.5 ±1.8	-	8	6	6	2	0	0.27
Knee angle at LO (°)	155.4 ±5.3	4.0 ±3.0	-	7	7	5	2	1	0.10
Maximal thigh flexion (°)	20.1 ±3.9	2.8 ±2.4	-	6	5	5	3	3	-0.33
Range of thigh motion (°)	98.4 ±4.5	4.1 ±3.4	-	9	4	6	2	1	-0.20
Knee flexion at MTE (°)	38.3 ±5.0	3.7 ±3.3	-	11	3	1	5	2	0.40
Hor. ankle velocity ($m \cdot s^{-1}$)	6.49 ±0.49	0.46 ±0.34	7.3	10	3	5	2	2	0.06

Absolute asymmetry = mean difference between superior and inferior side. Asymmetry (%) = (((superior value – inferior value)/ inferior value) *100). Magnitude distribution reveals the number of athletes (out of 22) displaying either very large (VL), large (L), moderate (M), small (S) or trivial (T) asymmetry for each variable based on interpretation of Cohen's *d* values (Hopkins et al., 2009). R = correlation values between asymmetry (individual Cohen's d values) and performance (individual mean step velocity). TD = touchdown, LO = lift-off, MTE = maximal thigh extension.

Table 2. Within- and between-sprint variability for all analysed kinematic variables

Variable	**Within-sprint variability**						**Between-sprint variability**					
	All steps		**Superior side**		**Inferior side**		**All steps**		**Superior side**		**Inferior side**	
	TE	*CV (%)*	*TE*	*CV (%)*	*TE*	*CV (%)*	*TE*	*CV (%)*	*TE*	*CV (%)*	*TE*	*CV (%)*
Step velocity ($m \cdot s^{-1}$)	0.06	0.6	0.05	0.5	0.04	0.4	0.07	0.9	0.07	0.9	0.07	0.9
Step length (m)	0.05	2.2	0.04	1.7	0.04	1.6	0.02	1.4	0.03	1.8	0.02	1.5
Step rate (Hz)	0.15	3.4	0.13	2.8	0.11	2.5	0.06	1.8	0.07	2.1	0.08	2.5
Contact time (ms)	4	3.8	3	3.1	3	3.2	3	4.1	3	4.3	3	4.1
Aerial time (ms)	6	4.5	4	3.4	5	3.8	3	2.9	3	3.5	3	3.5
Touchdown angle (°)	1.6	-	1.4	-	1.3	-	0.6	-	0.8	-	0.6	-
Inter-thigh angle at TD (°)	5.5	-	4.4	-	5.5	-	3.8	-	4.1	-	4.0	-
Lift off angle (°)	0.9	-	0.7	-	0.8	-	1.0	-	1.2	-	0.7	-
Thigh angle at LO (°)	2.2	-	1.3	-	1.6	-	1.6	-	1.8	-	1.8	-
Knee angle at LO (°)	3.4	-	1.7	-	2.4	-	3.7	-	2.1	-	2.1	-
Maximal thigh flexion (°)	2.4	-	1.7	-	1.7	-	1.9	-	1.8	-	2.1	-
Range of thigh motion (°)	3.0	-	1.9	-	1.7	-	3.2	-	2.6	-	2.7	-
Knee flexion at MTE (°)	2.8	-	1.4	-	1.7	-	2.1	-	3.2	-	2.8	-
Hor. ankle velocity ($m \cdot s^{-1}$)	0.39	6.0	0.24	3.5	0.29	4.6	0.15	3.3	0.21	4.4	0.17	3.8

TD = touchdown, LO = lift-off, MTE = maximal thigh extension, TE = typical error, CV = coefficient of variation (not assessed for angular variables as an angle is already a ratio and does not have an absolute minimum).

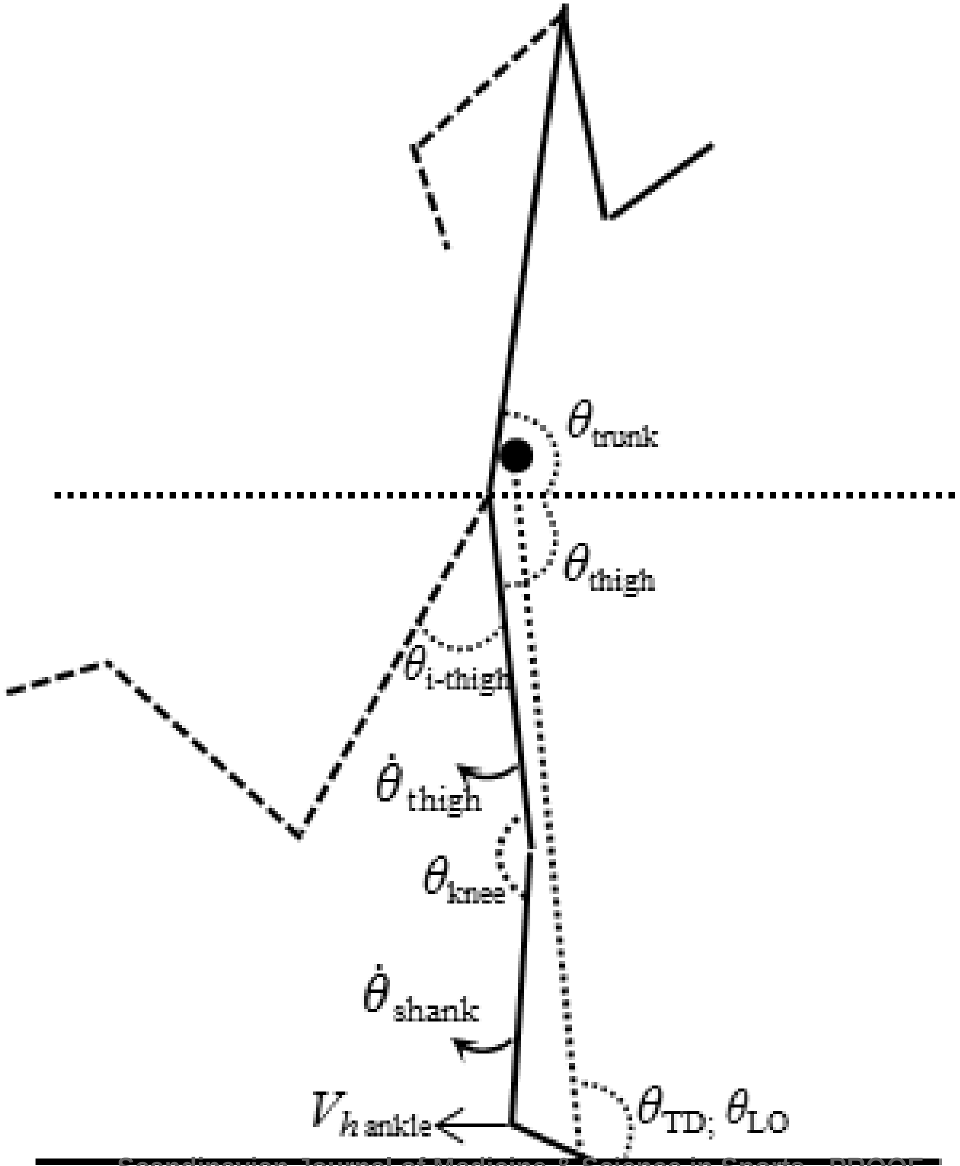
Table 3. Injury pattern by severity of injuries

	Injuries within one year prior to test		**Injuries within one year after test**		**Total**
	8-28 days	*>28 days*	*8-28 days*	*>28 days*	
Injury location					
Hamstrings	6	2	3	11	22 (49)
Lower leg/Achilles	6		4		10 (22)
Ankle/foot/toe	1	1	3		5 (11)
Groin	1	1	1		3 (7)
Knee	3				3 (7)
Lower back/pelvis				1	1 (2)
Quadriceps	1				1 (2)
Injury type					
Muscle injury/strain	9	3	4	11	27 (60)
Tendon injury	4		4		8 (18)
Overuse complaints	4		3	1	8 (18)
Sprain/ligament injury	1				1 (2)
Stress fracture		1			1 (2)
Total injuries					45

Only moderate (causing 8–28 days layoff) or severe (causing >28 days layoff) injuries were included. Values within brackets show percentage of total.

FIGURE LEGENDS

Figure 1. Definition of angles. The black dot represents centre of mass (CoM). θ_{trunk}, trunk angle relative to horizontal; θ_{thigh}, thigh angle relative to horizontal, where an angle of zero corresponds to the thigh being in alignment with the dotted horizontal line; θ_{knee}, knee angle; $\theta_{i\text{-}t\text{high}}$, inter-thigh angle; $\dot{\theta}_{\text{thigh}}$, angular thigh velocity; $\dot{\theta}_{\text{shank}}$, angular shank velocity; $V_{h\ \text{ankle}}$, horizontal ankle velocity (horizontal component of the velocity difference between the ankle and CoM); θ_{TD} and θ_{LO}, touchdown and lift-off angle, respectively (i.e., the angle relative to vertical between CoM and metatarsal marker).



θ_{trunk}
θ_{thigh}
$\theta_{i\text{-}thigh}$
$\dot{\theta}_{thigh}$
θ_{knee}
$\dot{\theta}_{shank}$
$V_{h\,ankle}$
$\theta_{TD};\ \theta_{LO}$