ABSTRACT

Background: Sprint running is a key determinant of player performance in soccer that is typically assessed and monitored using temporal methods. Purpose: The aim of this study was to examine the relationship between ground reaction force kinetics at the first step and sprint running performance in soccer players in order to enhance the development of training and assessment methods. Methods: Nineteen semi-professional soccer players participated (mean ± s: age 21.1 ± 1.9 years, body mass 79.4 ± 7.3 kg and stature 1.79 ± 0.06 m). The participants completed 20 m acceleration sprint runs as timing gates recorded split times between 0-5 m, 5-10 m, 10-15 m, 15-20 m and 0-20 m. A force plate captured vertical, anteroposterior and mediolateral ground reaction force data (1000 Hz) of the first right foot strike stance phase. Results: Ground reaction force metrics, including peak anteroposterior propulsive force (r =0.66 to 0.751; P =0.000 to 0.002), peak vertical ground reaction force (r =0.456 to 0.464; P =0.045 to 0.05), average medial-lateral/anteroposterior orientation angle (r =-0.463; P =0.023), and average anteroposterior/vertical orientation angle (r =-0.44; P =0.03) were correlated with one or all split times between 0-5 m, 5-10 m, 10-15 m, 15-20 m and 0-20 m. Conclusions: Acceleration sprint running in soccer requires minimised mediolateral and increased anteroposterior loading in the stance phase. Multi-component ground reaction force measures of the first step in acceleration sprint runs are important for developing performance assessments, and understanding force application techniques employed by soccer players.

Key words: Kinetics, Training, Biomechanics, Running, Field Sport

Introduction

Sprint running is a key determinant of performance within soccer, and many other sports (Lockie, Murphy, Schultz, Jeffries & Callaghan, 2013; Moir, Sanders, Button, & Glaister, 2007). The majority of sprint runs associated with professional soccer are performed over short distances (0-10 m) (Di Salvo et al., 2009; Di Salvo, Gregson, Atkinson, Tordoff, & Drust, 2010). Explosive sprint runs, which are characterised by a fast acceleration from standing, walking, jogging or running have explicitly been reported to contribute to 23-30% of these sprint runs over short distances (0-10 m) (Di Salvo et al., 2010). Players have further been reported to perform approximately 11 sprint runs during a soccer match with 90% of these lasting less than 5-seconds (Andrzejwski, Chmura, Pluta, Strzelczyk & Kasprzak, 2013). Sprint running has further been reported to constitute 1–12% of the total distance covered during a soccer match (Andrzejewski et al., 2013; Mohr, Krustrup, & Bangsbo, 2003), and superior soccer players have in part, been distinguished by the ability to achieve faster sprint running performances (Cometti, Maffiuletti, Pousson, Chatard, & Maffulli, 2001). The development of acceleration sprint running performance is subsequently an essential component of soccer training that should be underpinned by the use of assessment protocols that are scientifically-informed and representative of the demands of professional soccer.

Typically, acceleration sprint running performance in professional and semi-professional soccer is assessed using split or interval time protocols (Buchheit, Simpson, Peltola & Mendez-Villanueva, 2012) and on occasions, macro-level spatio-temporal metrics have been used to examine male sprinters (Nagahara, Naito, Morin & Zushi, 2014). A study by Mendez-Villanueva, Buchheit, Simpson, Peltola, and Bourdon (2011) highlighted that sprint running performance, when measured over a 40 m sprint run in 10 m splits, can be indicative of a player's performance in actual playing conditions. As an alternative to the use of fatiguing, and sometimes unreliable split time protocols (Standing & Maulder, 2017), approaches that assess different performance measures (Bezodis, Salo & Trewartha, 2010) and sport-specific demands (have been advocated. In recent years, the potential use of individual or average step responses in assessing sprint running performances have been considered. The spatio-temporal characteristics (step frequency and step length) of the initial two steps of an acceleration sprint run have for example, been reported to be associated to acceleration sprint performance (Nagahara et al. 2014).

While the use of spatial-temporal measures in assessing sprint running performance in soccer have been typical, a recent study by Nagahara et al. (2018a) advocated the need to extend current understanding of ground reaction force (GRF) contributions in sprint running using more detailed approaches. Existing insights into the association between GRF metrics and soccer player specific sprint running performance have been sparse. Although sometimes contradictory and derived using mixed modes (e.g. treadmill or over-ground running protocols), extended insights into potentially important GRF determinants of sprint running have been achieved for wider applications. In examining average measures for a 40 m distance, greater anteroposterior propulsive ground reaction forces over the entire acceleration phase have been suggested to be important in defining sprint running performance (Rabita et al. (2015). A more recent study (Nagahara et al., 2018b) conducted a micro-level step-by-step analysis of over-ground sprint running over 60 m and demonstrated that while the step characteristics of the first step did not align to the fastest trials, a higher mean anteroposterior propulsive force within the initial four steps was associated with the fastest trial. Furthermore, it has been suggested (Colyer et al., 2018; Nagahara et al.

2018a) that the exertion of a large anteroposterior propulsive force from 55-95% of maximal velocity during an acceleration sprint run are essential for achieving better sprinting performance. In contrast, Kawamori, Nosaka and Newton (2013) reported a significant correlation between sprint running time and net anteroposterior and anteroposterior propulsive impulse at eight metres but no association with the first step kinetics. Therefore, it could be argued that an effective supplement to split time metrics would be to utilise components of the GRF to examine associations to acceleration sprint running performance.

While the relative anteroposterior impulse has often been reported to be the strongest predictor of sprint running velocity (Hunter, Marshall & McNair, 2005, Morin et al. 2015), evidence also exists to suggest that superior sprint runners do not necessarily generate greater magnitudes of resultant GRF, but direct the resultant GRF vector in a more anteroposterior direction (Rabita et al., 2015; Bezodis, North, & Razavet, 2017). Further examination of the multi-component contributions of the GRF production, including the interaction of the anteroposterior propulsive and vertical components, may accordingly be justified to extend kinetic insights for the assessment of sprint running performance in soccer. Beyond traditional GRF metrics, assessment of the ratio of force, which defines the anteroposterior component of the GRF vector as a percentage of the total anteroposterior/vertical GRF vector magnitude, has further been advocated by Morin et al., (2011) to objectively represent a performer's force application technique. Using a treadmill protocol, Morin et al., (2011) suggested that unlike the total GRF applied, the ratio of force was a determinant of overall 100 m performance that requires further investigation in training and performance improvement studies. The ability to maintain lateral balance has also been presented as a critical requisite for forward running (Arellano & Kram, 2011) but has received limited attention in studies of sprint running kinetics. Given the frequent directional changes required in soccer sprint running situations, extended assessment of medial-lateral GRF contributions in combination with anteroposterior propulsive and vertical components may also be justified.

Previous insights into sprint running kinetics have typically emerged from diverse modalities including treadmill (e.g. Morin et al. 2011) and over-ground running (e.g. Nagahara et al., 2018a), and from sport-specific cohorts (e.g. Rabita et al. 2015). Caution in integrating existing kinetic insights of sprint running performance into the development of assessment protocols for soccer is subsequently advocated. Over-ground sprint running has for example, been evidenced to elicit shorter ground contact and braking phases, and altered knee kinematics compared to equivalent velocity treadmill sprint running (McKenna & Riches, 2007) but are more reflective of the soccer-specific testing environment. Furthermore, the existing inconsistencies in the contributions of the stance phase GRF of initial steps to sprint running performance demands further clarification.

The aim of this study was to examine the association of multi-component kinetics of the stance phase during the first step to over-ground acceleration sprint running performance in soccer players. The overall purpose of the study was to facilitate understanding of GRF mechanics that may underpin overall acceleration sprint running performance and subsequently used to develop more robust and effective assessment protocols for soccer. The hypotheses were that medial-lateral components of GRF ratios, the anteroposterior impulse and GRF would correlate with acceleration sprint running performance, but vertical GRF and impulse would not.

Methods

Participants

Nineteen semi-professional soccer players participated in the study (mean±s deviation: age 21.1 ± 1.9 years, body mass 79.4 ± 7.3 kg and stature 1.79 ± 0.06 m). Recruited participants were injury free and participated in four training sessions (two x skills-based soccer and two x strength and conditioning sessions) and two soccer matches every week. All participants were right leg dominant. The study was approved by the University's' Local Research Ethics Committee, and each participant provided written informed consent prior to the onset of the data collection sessions.

Procedure

Participants' whole-body mass and height were measured prior to the onset of the trials using laboratory weighing scales (Avery Berkel Ltd, Egham, UK, model ED01) and a stadiometer (Holtain Ltd, Crymych, UK). Participants, who all wore rubber soled shoes, subsequently executed a 15 minute self-guided warm-up that included light aerobic exercise, dynamic stretching, short sprint runs and familiarisation with the sprint running protocol.

All acceleration sprint running trials were performed in a straight-line on a 110 m indoor athletics track (National Indoor Athletics Centre, Cardiff). To ensure first step contact was made with the dominant foot, participants were required to position themselves with enough distance for the participant to lean comfortably forward without breaking the beam of the initial light gate with the toes of their left foot behind the start line, and the right foot placed comfortably behind. Participants initiated the sprint run themselves and completed a 20 m sprint run where they maximally accelerated from the standing start through a five sets of Smartspeed™ PRO light gates (Fusion Sport, Grabba International Pty Ltd, London) positioned at the start line, 5 m, 10 m, 15 m, and 20 m away from the start. The light gates were set at a height level to the participant's hip. Participants completed five trials and were given a minimum of five minutes rest period between each trial. Every trial was used for further analysis.

Data Collection

The start line was positioned 0.5 m posteriorly back from the start of a 0.90 × 0.60 force platform (9287BA, Kistler, 1000 Hz), mounted underneath a Mondo (Warwickshire, UK) track surface, so that the first foot strike of the right leg would contact near the centre. Force signals were low-pass filtered (fourth-order Butterworth, 200 Hz cut-off frequency) prior to analysis.

Data Processing & Statistical Analysis

The instants of touchdown and takeoff from the force plate were defined when the vertical GRF first rose above 10 N (touchdown) and declined below 10 N (takeoff). This period from touchdown to takeoff was then defined as the contact time. Vertical (Z), anteroposterior (Y) and medial-lateral (X) GRF data were then exported for the duration of the contact time for each participant and expressed in Newtons and Newtons\body weight (BW). Peak and mean average GRFs during stance were identified and impulses were determined using the trapezium rule. Ratio and orientation of ground reaction force vectors for the YZ comparison were calculated using the procedures outlined by Morin et al. (2011). Using similar methods, corresponding measures were determined for the XY and XZ components. With the orientation angles -180 to 180 and -90 to 90 for XY and XZ comparisons respectively (See Figure I.). Table I defines the metrics calculated from the kinetic data.

Means and standard deviations for the kinetic and split time metrics were calculated for all participants. The Levene statistic was used to check the homogeneity of variance and the Shapiro-Wilk statistics was used to check for data normality. As some of the data were not normally distributed, the non-parametric Spearman's correlation analysis was conducted with an alpha level of 0.05 in order to examine the relationships between 0–5 m, 5–10 m, 10–15 m, 15-20 m and 0-20 m split times, with stance kinetic metrics.

INSERT FIGURE I HERE

Results

The group results (mean ± s) across the 0-20 m sprint run for split time and kinetic metrics are detailed in Table I. Split times continuously reduced across the 20 m running distance, demonstrating that the group accelerated during the sprint acceleration run.

INSERT TABLE I HERE

The correlation coefficients between split time results across the 20 m distance are detailed in Table II. The 0-5 m split time was found to positively correlate with 5-10 m (r =0.628; P =0.004; [95% CI: 0.244,0.842]), 10-15 m (r =0.533; P =0.019; [95% CI: 0.104,0.794]), and 0-20 m split times (r =0.760; P =0.000; [95% CI: 0.467,0.902]), respectively.

Table III presents the correlation coefficients between the split times and kinetic metrics for the first ground contact. Peak propulsive anteroposterior force (GRFay) was found to negatively correlated with 5-10 m (r =-0.751; P =0.000; [95% CI: -0.898,-0.451]), 10-15 m (r =-0.667; P =0.002; [95% CI: -0.860,0.306]), 15-20 m (r =-0.737; P

=0.000; [95% CI: -0.892,-0.426]), and 0-20 m (r =-0.655; P =0.002; [95% CI: -0.854,-0.286]) split times except 0-5 m (r =-0.292; P =0.226; [95% CI: -0.658,0.187]). Furthermore, the players that had a greater mean anteroposterior force over the entire stance phase (GRFmy) typically displayed faster split times in all the splits, except 0-5 m (r =-0.111; P =0.650; [95% CI: -0.538,0.361]). Peak vertical force (GRFz) was negatively correlated with 5-10 m (r =-0.456; P =0.050; [95% CI: -0.754,-0.003]) and 15-20 m (r =-0.464; P =0.045; [95% CI: -0.758,-0.013]) split times. The impulse metrics (IMPx, IMP-, IMP+, IMPz) and contact time (CT) were not found to be correlated with the split time results.

INSERT TABLE II AND III HERE

As illustrated in Table III, higher accelerating players over the 0-20 m interval tended to have a lower OYZmin (r =0.429; P =0.033; [95% CI: -0.031,0.739]). Improved performance over the 5-10 m interval was correlated with a lower OXYm (r =-0.463; P =0.023; [95% CI: -0.757,-0.012]) while OYZm was negatively correlated with the 15-20 m interval (r =-0.440; P =0.030; [95% CI: -0.745,0.017]).

Discussion

Sprint running performance in soccer has traditionally been tested and monitored using split or interval time protocols that can only provide macro-level temporal information. This study examined the association of multi-component kinetics of the stance phase in the first step to acceleration sprint running performance in order to scientifically inform the development of assessment protocols for sprinting performance of soccer players. In contrast to the vertical GRF and impulse, the medial-lateral components of GRF ratios, anteroposterior impulse and anteroposterior GRF in the stance phase of the first step were hypothesised to be associated with acceleration sprint running performance for the over-ground modality examined in this study.

In partial support of the hypothesis, players who demonstrated shorter split times (superior acceleration sprint running performances) over the 5-10 m, 10-15 m, 15-20 m and 0-20 m splits exerted larger peak propulsive and mean anteroposterior force in the stance phase of the first step. The finding supports a growing body of research into over-ground sprint running (Nagahara et al., 2018a; Colyer et al., 2018) that have suggested an important contribution from the anteroposterior ground reaction force to sprint running. However, the current study provides novel findings that suggest the importance of anteroposterior ground reaction force of the first step to 20 m standing acceleration sprint run performance in the semi-professional soccer players. For a well-trained soccer player the maximisation of anteroposterior GRF for the duration of the contact phase may be essential for improving performance over a 20 m acceleration sprint run. Subsequently, the peak and mean anteroposterior force production in the stance phase of the first step during an acceleration sprint run could provide a valuable metric for effectively testing and monitoring sprint running performance over short distances in soccer players.

In refute of the study hypothesis, the anteroposterior propulsive and braking impulses of the stance phase of the first step were not found to correlate to acceleration sprint running performance. Recently, Yu, Sun, Yang et al. (2016) found that anteroposterior braking force in over-ground sprint running was significantly lower during the acceleration phase than the maximal velocity phase. In an earlier study, Mero and Komi (1986) suggested that the braking phase constituted only 12.9% of the stance phase in the first step compared to 43% during the maximum velocity phase. In regards to the respective literature (Mero and Komi, 1986; Yu, Sun, Yang et al., 2016) and the findings of this study, a reduced influence of anteroposterior braking force on sprint running performance over the initial steps of a sprint run may be suggested. Caution in examining global metrics of anteroposterior force production in monitoring sprint running performance is therefore advocated. In preference, additional measurements (e.g. peak and mean results) may be favoured for effectively informing the development of acceleration sprint running performance.

In agreement with the peak propulsive and mean anteroposterior force but in refute of the study hypothesis, the peak vertical force was also correlated with acceleration sprint running performance during the 5-10 m and 15-20 m splits. The findings suggest that the soccer players that can produce a large peak vertical force in the first step of an acceleration sprint performance may have increased sprint acceleration performance towards the end of a 20 m acceleration sprint run. The vertical force component correlations were typically weaker than found for the anteroposterior component but demonstrated a unique association to the latter split (15-20 m) performance, potentially highlighting the importance of vertical ground reaction forces in late acceleration sprint running. These findings from the first step of an acceleration sprint running performance support previous suggestions from over-ground modalities that vertical force is a predictor for acceleration sprint running performance at 75% (achieved 7.5 ± 0.6 m into an acceleration sprint run) of maximal velocity (Nagahara et al., 2018a). Therefore, in order to test early and late acceleration sprint running performance using the stance phase of the first step, kinetic profiles, measurement and examination of diverse force components may be necessitated. The study findings accordingly have beneficial implications for sport scientists and, strength and conditioning coaches that aim to develop assessment methods using GRF metrics.

In partial agreement with previous examinations of first step kinetics in sprint running performances (e.g. Kawamori et al., 2013), the ground reaction force impulse of the stance phase of the first step was not correlated to sprint time for the acceleration sprint running performances of the semi-professional players in the current study. Kawamori et al. (2013) attributed a similar lack of association between split times and the first ground contact impulse to response to the use of a parallel foot standing position by participants. However, this study observed a similar lack of relationship between impulse and sprint time in a left foot forward split stance starting position. Consequently, the lack of correlation between the GRF impulse at the first step and sprint time may be attributed to the fact that there are a number of stance phases that take place over a set sprint running distance, potentially masking the contribution of the GRF impulse of the first step to the velocity of the participant. However, in a study by Lockie et al. (2013), the GRF impulse for the first, second, and last contact of a 10-m sprint was uncorrelated to 0-5 m 5-10 m and 0-10 m sprint running velocity in generic field sport athletes. Lockie et al. (2013) suggested that since field sport performers are conditioned for multiple short sprint runs during competition, most participants may have developed an impulse appropriate for effective 10 m sprint runs. Although not fully supported in the current study, the potential development of an appropriate impulse for different sprint distances warrants further research. Therefore, extended investigation of sport- and participant-specific force application techniques during acceleration sprint running may be advocated for the future.

The anteroposterior/vertical (YZ) and medial-lateral/anteroposterior (XY) GRF orientation examined for the stance phase of the first step were found to be associated with short acceleration sprint running performances for the semi-professional players. Faster accelerators over the 5-10 m split tended to have a more anteroposterior orientated vector over the entire contact phase of the first step of an acceleration run. The finding supported suggestions by Kugler and Janshen (2010) that a more anteroposterior orientated force vector over the medial-lateral vector was indicative of superior acceleration from a standing start in soccer players. In addition to the medial-lateral orientation, the average GRF orientation for the entire contact time was orientated more towards the anteroposterior in the faster accelerators for the 15-20 m split. Finally, the minimum orientation angle (OYZmin) was also found to be directed more towards the vertical than anteroposterior and was positively correlated with the entire 0-20 m split. The minimum orientation angle (closest to vertical) was produced during the initial ground contact and consequent braking phase. Therefore, the faster accelerators may have initially applied their force upon ground contact more vertically in order to reduce any anteroposterior braking forces. The GRF orientation analysis suggested that by applying a reduced anteroposterior braking GRF orientation, and an increased anteroposterior GRF orientation when compared to medial-lateral and vertical components could enhance acceleration sprint running performance. Therefore, soccer players aiming to develop acceleration sprint running performance should maximise anteroposterior GRF orientation.

Conclusion

More rapid, over-ground accelerations in soccer acceleration sprint running potentially require minimised medial-lateral loading and increased anteroposterior force application in the first step, and the development of increased vertical force orientation to benefit late acceleration. For practitioners and coaches, the additional measurement of first stance multi-component ground reaction force metrics may be important in developing fine-grained and reliable approaches to assessing and monitoring acceleration sprint running performance in soccer players.

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Table I. Split times and ground reaction force metrics (mean ± s) for the first right foot contact of a 20 m acceleration sprint.

Metric	Definition	mean ± s
Split Time 0-5 m (s)		1.12 ± 0.06
Split Time 5-10 m (s)		0.75 ± 0.02
Split Time 10-15 m (s)		0.67 ± 0.02
Split Time 15-20 m (s)		0.63 ± 0.03
Split Time 0-20 m (s)		3.16 ± 0.11
GRFx (BW)	Peak medial-lateral negative GRF relative to body weight	-0.23 ± 0.08
GRFb (BW)	Peak anteroposterior braking force relative to body weight	-0.20 ± 0.18
GRFz (BW)	Peak vertical GRF relative to body weight	2.00 ± 0.08
GRFax (BW)	Peak medial-lateral positive GRF relative to body weight	0.10 ± 0.03
GRFay (BW)	Peak anteroposterior propulsive GRF relative to body weight	0.81 ± 0.07
GRFmx (BW)	Mean medial-lateral GRF relative to body weight	-0.07 ± 0.04
GRFmy (BW)	Mean anteroposterior GRF relative to body weight	0.45 ± 0.05
GRFmz (BW)	Mean vertical GRF relative to body weight	1.23 ± 0.07
CT (s)	Contact time	0.19 ± 0.07
IMPx (BW.s)	Medial-lateral impulse relative to body weight	-0.03 ± 0.02
IMP- (BW.s)	Braking anteroposterior impulse relative to body weight	-0.002 ± 0.002
IMP+ (BW.s)	Propulsive anteroposterior impulse relative to body weight	0.104 ± 0.012
IMPz (BW.s)	Vertical impulse relative to body weight	0.206 ± 0.025
OYZm (°)	Mean YZ orientation angle	19.7 ± 1.2
OYZmax (°)	Maximum YZ orientation angle	37.9 ± 3.9
OYZmin (°)	Minimum YZ orientation angle	-14.8 ± 16.6
OXYm (°)	Mean XY orientation angle	-14.1 ± 5.2
OXYmax (°)	Maximum XY orientation angle	80.4 ± 48.9
OXYmin (°)	Minimum XY orientation angle	-136.2 ± 31.4
OXZm (°)	Mean XZ orientation angle	1.6 ± 2.1
OXZmax (°)	Maximum XZ orientation angle	23.7 ± 17.4
OXZmin (°)	Minimum XZ orientation angle	-37.0 ± 27.4

Table II. Correlation coefficient (r) for associations between split times (n=19 participants) and the 0-5 m, 5-10 m, 10-15 m, 15-20 m and 0-20 m intervals.

Split	Value	5-10 m	10-15 m	15-20 m	0-20 m
0-5 m	r	0.628*	0.533*	0.254	0.760*
	P	0.004	0.019	0.293	0.000
	95% CI	0.244,0.842	0.104,0.794	-0.226,0.634	0.467,0.902
5-10 m	r		0.762*	0.720*	0.926*
	P		0.000	0.001	0.000
	95% CI		0.471,0.903	0.395,0.884	0.815,0.971
10-15 m	r			0.712*	0.802*
	P			0.001	0.000
	95% CI			0.382,0.881	0.548,0.920
15-20 m	r				0.716*
	P				0.001
	95% CI				0.388, 0.883

*Significant (P <0.05) relationship between two variables

Table III. Correlation coefficient (r) for association between split times (n = 19 performers) in the 0-5 m, 5-10 m, 10-15 m, 15-20 m and 0-20 m intervals and GRF metrics.

	Split														
	0-5 m			5-10 m			10-15 m			15-20 m			0-20 m		
	r	P	CI 95%	r	P	CI 95%	r	P	CI 95%	r	P	CI 95%	r	P	CI 95%
GRFx	0.081	0.740	-0.387,0.516	-0.027	0.912	-0.475,0.432	0.005	0.984	-0.450,0.458	0.268	0.266	-0.212,0.643	0.120	0.626	-0.353,0.544
GRFb	0.214	0.38	-0.266,0.609	-0.007	0.978	-0.459,0.448	0.029	0.907	-0.430,0.476	0.040	0.871	-0.421,0.485	0.244	0.314	-0.236,0.628
GRFz	0.143	0.558	-0.332,0.560	-0.456*	0.050	-0.754,-0.003	-0.319	0.183	-0.675,0.158	-0.464*	0.045	-0.758,-0.013	-0.281	0.243	-0.651,0.198
GRFax	-0.233	0.338	-0.621,0.247	-0.436	0.062	-0.743,0.022	-0.186	0.445	-0.590,0.292	0.017	0.945	-0.440,0.467	-0.399	0.091	-0.722,0.067
GRFay	-0.292	0.226	-0.658,0.187	-.0751*	0.000	-0.898,-0.451	-0.667*	0.002	-0.860,0.306	-0.737*	0.000	-0.892,-0.426	-0.655*	0.002	-0.854,-0.286
GRFmx	-0.019	0.939	-0.469,0.438	-0.292	0.225	-0.658,0.187	-0.118	0.632	-0.543,0.355	0.024	0.924	-0.434,0.473	-0.130	0.595	-0.551,0.344
GRFmy	-0.111	0.650	-0.538,0.361	-0.681*	0.001	-0.867,-0.329	-.0544*	0.016	-0.800,-0.120	-0.710*	0.001	-0.880,-0.378	-0.600*	0.007	-0.828,-0.201
GRFmz	0.102	0.677	-0.369,0.531	-0.387	0.101	-0.715,0.081	-0.219	0.369	-0.612,0.261	-0.431	0.066	-0.740,0.028	-0.284	0.238	-0.653,0.195
IMPx	0.019	0.939	-0.438,0.469	-0.186	0.447	-0.590,0.292	-0.159	0.517	-0.571,0.318	0.184	0.451	-0.294,0.588	-0.061	0.805	-0.501,0.404
IMP-	0.347	0.146	-0.127,0.692	0.186	0.446	-0.292,0.590	0.293	0.223	-0.185,0.659	0.276	0.252	-0.203,0.648	0.435	0.063	-0.023,0.742
IMP+	-0.005	0.983	-0.458,0.450	-0.160	0.513	-0.572,0.317	-0.240	0.322	-0.625,0.240	-0.246	0.31	-0.629,0.234	-0.023	0.925	-0.472,0.435
IMPz	0.435	0.063	-0.023,0.742	0.196	0.422	-0.283,0.597	0.144	0.557	-0.331,0.561	0.092	0.708	-0.378,0.524	0.399	0.091	-0.067,0.722
CT	0.214	0.379	-0.266,0.609	0.246	0.310	-0.234,0.629	0.252	0.299	-0.228,0.633	0.276	0.252	-0.203,0.648	0.413	0.079	-0.050,0.730
OYZm	0.125	0.305	-0.349,0.548	-0.296	0.109	-0.661,0.182	-0.314	0.095	-0.672,0.163	-0.440*	0.030	-0.745,0.017	-0.219	0.184	-0.612,0.261
OYZmax	-0.187	0.222	-0.591,0.292	-0.212	0.192	-0.607,0.268	-0.199	0.207	-0.599,0.280	-0.113	0.322	-0.539,0.359	-0.346	0.073	-0.691,0.128
OYZmin	0.336	0.080	-0.139,0.685	0.274	0.128	-0.205,0.647	0.249	0.152	-0.231,0.631	0.285	0.118	-0.194,0.654	0.429*	0.033	-0.031,0.739
OXYm	-0.166	0.248	-0.576,0.311	-0.463*	0.023	-0.757,-0.012	-0.283	0.12	-0.653,0.196	-0.211	0.193	-0.607,0.268	-0.317	0.093	-0.674,0.160
OXYmax	-0.069	0.390	-0.507,0.397	-0.041	0.434	-0.486,0.421	-0.106	0.332	-0.534,0.365	-0.302	0.104	-0.664,0.176	-0.215	0.189	-0.609,0.265
OXYmin	0.309	0.099	-0.168,0.669	0.042	0.433	-0.420,0.486	0.126	0.304	-0.348,0.548	0.089	0.359	-0.380,0.522	0.273	0.129	-0.206,0.646
OXZm	0.193	0.215	-0.286,0.595	0.331	0.083	-0.145,0.682	0.181	0.230	-0.297,0.586	-0.035	0.443	-0.481,0.425	0.280	0.123	-0.199,0.651
OXZmax	-0.121	0.311	-0.545,0.352	-0.200	0.206	-0.599,0.279	0.081	0.370	-0.387,0.516	0.076	0.378	-0.391,0.512	-0.116	0.318	-0.541,0.357
OXZmin	0.269	0.132	-0.210,0.644	0.227	0.175	-0.253,0.617	0.136	0.290	-0.339,0.555	0.050	0.420	-0.413,0.493	0.301	0.106	-0.177,0.664

*Significant (P <0.05) relationship between split time and GRF metric

FIGURE CAPTIONS

Figure I. Orientation angle definitions and ratio of forces calculations for XY, XZ and YZ comparisons. Y is the direction of sprint running.