Soccer Fatigue, Sprinting and Hamstring Injury Risk

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Key words
- kinematics
- muscle strain
- match-play
- re-warm-up

Abstract

The aim of this study was to investigate the effect of a multi-directional soccer-specific fatigue protocol on sprinting kinematics in relation to hamstring injury risk. Nine semi-professional soccer players (Mean ± SD: Age: 21.3 ± 2.9 year; Height 185.0 ± 8.7 cm; Body Mass 81.6 ± 6.7 kg) completed the SAFT^{90}; a multi-directional, intermittent 90 min exercise protocol representative of soccer match-play. The 10m sprint times and three-dimensional kinematic data were recorded using a high-speed motion capture system (Qualisys Track Manager®) every 15 min during the SAFT^{90}. A significant time dependent increase was observed in sprint time during the SAFT^{90} ($P < 0.01$) with a corresponding significant decrease in stride length ($P < 0.01$). Analysis of the kinematic sprint data revealed significantly reduced combined maximal hip flexion and knee extension angle, indicating reduced hamstring length, between pre-exercise and half-time ($P < 0.01$) and pre-exercise and full-time ($P < 0.05$). These findings revealed that the SAFT^{90} produced time dependent impairments in sprinting performance and kinematics of technique which may result from shorter hamstring muscle length. Alterations in sprinting technique may have implications for the increased predisposition to hamstring strain injury during the latter stages of soccer match-play.

Introduction

Recently there has been an increased preponderance of hamstring muscle strain injuries in high-level soccer players, accounting for 12–16% of total injuries [26]. Such injuries are considered to have one of the highest rates of injury re-occurrence of any muscle injury [14]. However, biomechanical analysis of hamstring function is difficult considering their anatomical complexity and ability to influence movement over multiple joints [3]. Consequently, identification of injury risk factors and development of effective injury prevention strategies becomes more challenging [3].

Sprinting is the primary mechanism for hamstring strains; responsible for 57% of all hamstring injuries [26]. The hamstrings are biarthrodial muscles and undergo lengthening over two joints simultaneously during the latter part of the swing phase of the gait cycle [22] and strains may be most likely to occur at this point whilst working eccentrically to decelerate the limb and control knee extension [26]. Alternatively, injury may occur during the latter part of the stance phase when the muscle shortens forcefully to extend the hip during take-off, potentially inducing a concentric contraction injury [13].

Fatigue during soccer match-play has been associated with decreased eccentric hamstring strength [7, 19]. This may be related with increased hamstring injury risk; with nearly half of all hamstring injuries observed to occur during the final 15 min of each half [26]. Therefore, it could be hypothesised that fatigue during the latter stages of soccer match-play may cause increased predisposition to hamstring strain injury by negatively altering the biomechanics of sprinting in relation to muscle flexibility, muscular strength, or body mechanics.

Experimental research has reported a significant decrease in eccentric hamstring strength during simulated soccer match-play [7]. Therefore, if the hamstrings have insufficient strength to decelerate the limb during the latter part of the swing phase, eccentric overload could cause tearing in the musculo-tendinous unit [6]. Research has suggested that if the hamstring muscles lack flex-

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ibility at this time during the gait cycle they may be stretched beyond their ability to elongate; thus resulting in a tear [1]. Whereas reduced flexibility of the rectus femoris muscle earlier on in the gait cycle may increase lower limb velocity to subsequently place the hamstrings under greater strain [23]. In relation to body mechanics, increased forward lean and anterior pelvic tilt may increase the relative length of the hamstrings due to their biarticular nature, and therefore increase predisposition to strain injury [9].
Previous research has shown a fatiguing effect on sprinting kinematics, however the fatiguing protocol was not indicative of soccer-specific match-play [15]. The objective of the current study therefore, was to examine the effects of the $SAFT^{90}$ protocol on sprinting kinematics in consideration of movement mechanics previously detailed relating to hamstring injury risk. It was hypothesised that with fatigue, subjects would display reduced efficacy of the hamstring muscles, reflected by slower sprint times, reduced stride length and theoretical muscle length based on joint position, and increased thigh and shank velocity.

Methods

Participants

Nine male, semi-professional soccer players (Mean ± SD; Age: 21.3 ± 2.9 years; Height 185.0 ± 8.7 cm; Body Mass 81.6 ± 6.7 kg) took part in the investigation. All players were right foot dominant (defined as their preferred 'kicking' leg). Subjects were included in the study if they were not injured or rehabilitating from an injury at the time of testing. Ethical approval for the study was obtained in accordance with the Departmental and University ethical procedures, and written informed consent was obtained prior to data collection.

Experimental procedure

The $SAFT^{90}$ protocol employed was developed to replicate the physiological and mechanical demands made during soccer match-play [11], and is based on contemporary time-motion analysis data obtained from 2007 English Championship Level match-play (Prozone ®). The field test incorporates utility movements, and frequent acceleration and deceleration as is inherent to match-play, with the movement intensity and activity maintained using verbal signals on an audio CD. The design of the course was based over a 20 m agility shuttle run incorporating four positioned field poles (Fig. 1). Subjects perform the course by running backwards or sidestepping around the first pole, then running forwards through the course navigating the middle three poles. A 15 min activity profile was developed and repeated six times during the full 90 min simulated soccer match. The activity profile was performed in a randomised and intermittent fashion, and incorporated 1269 changes in speed and 1350 changes in direction over the 90 min. Table 1 shows the distances covered and time spent in each of the activities during the $SAFT^{90}$ and match-play data.
Prior to all testing, subjects performed a standardised warm-up procedure. This involved 5 min on a cycle ergometer at 60 watt, 5 min of static and dynamic stretches for the major lower limb muscle groups and 5 min light jogging and familiarisation with the $SAFT^{90}$ and sprint track. Subjects completed the $SAFT^{90}$ divided into two 45 min periods interceded by a 15 min passive rest period which was performed on a non-slip indoor surface. Subjects performed three maximum 10 m sprints at 0, 15, 30, 45, 46, 60, 75 and 90 min during $SAFT^{90}$. Kinematic data of one complete stride of the dominant leg and sprint times were recorded. One week prior to actual testing, subjects completed a 30 min familiarisation session with the $SAFT^{90}$ exercise protocol and test equipment involved.
The subjects performed no vigorous exercise 24 h prior to testing, or had consumed any caffeine or alcohol. Testing was conducted at the beginning of the 2007/2008 English soccer season, with the training load and amount of match-play performed as standard to the competitive season.

Sprint data collection

Three dimensional motion analysis was carried out using 14 Proreflex infrared cameras (Qualisys, Inc. Sweden; 658 × 500 pixels) with the sample frequency set at 200 Hz. Along with six wall mounted cameras, eight additional cameras on 1.5 m tripods were strategically positioned around the 10 m sprint track between 4 and 12 m. This was to ensure each marker could be

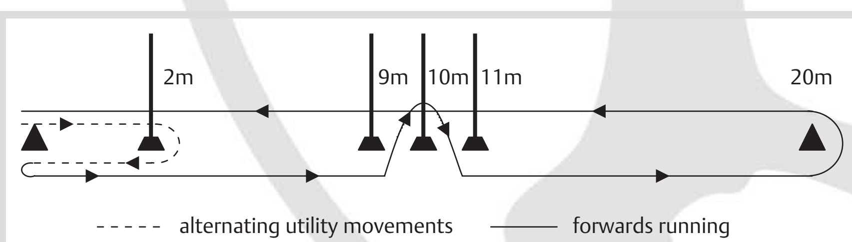

Fig. 1 Diagram of the $SAFT^{90}$ field course.

Table 1 Distance covered and time spent in each activity during $SAFT^{90}$ and Match-play.

Activity	Distance (km)		Time (s)	
	$SAFT^{90}$ (Lovell et al., 2008)	Match-play (Prozone®)	$SAFT^{90}$ (Lovell et al., 2008)	Match-play (Prozone®)
standing (0.0 km·h^{-1})	0.00	0.02	240	248.14
walking (5.0 km·h^{-1})	3.36	3.60	2958.80	3150.82
jogging (10.3 km·h^{-1})	5.58	5.81	2002.44	1915.82
striding (15.0 km·h^{-1})	1.50	1.46	360.00	344.36
sprinting (≥20.4 km·h^{-1})	0.34	0.27	44.16	26.55
total:	10.78	11.08	5605.40	5685.69

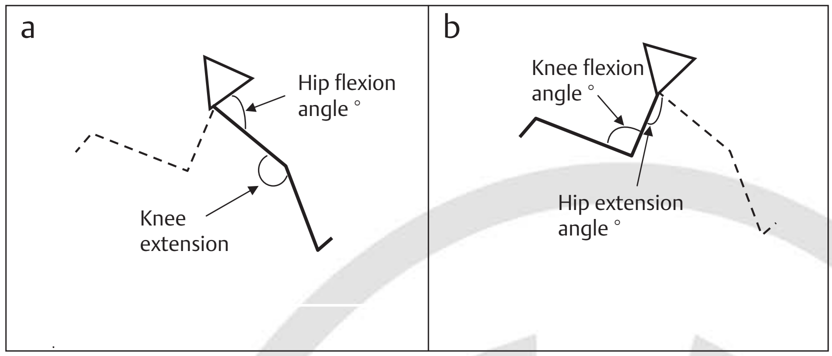

Fig. 2 Diagrammatic representation of calculations for indications of: **a**. Combined hip flexion and knee extension angle. **b**. Combined hip extension and knee flexion angle.

visible by at least two cameras at all times throughout a complete stride cycle of the dominant limb. Prior to data collection, the capture volume of approximately $4.5 \times 1.1 \times 1.5\,m^3$ was calibrated in accordance with guidelines provided by Qualisys (Qualisys, Inc. Sweden). To do so, a dynamic method was used whereby a two-marker wand of known length (749.9 mm) was moved around the whole capture volume while a stationary reference object, a L-frame (dimensions: 850 × 650 mm) containing four markers of known locations to the system, was used to define a right-handed coordinate system for motion capture. Twenty-two reflective markers (25 mm spheres) were placed on selected lower limb anatomical landmarks to calculate motion of the pelvis (relative to the horizontal), hip and knee in the saggital plane. Markers were attached using double-sided adhesive tape, and to ensure dislodged markers could be replaced precisely in their original position, marker positions were traced on the skin with ink.

Subjects performed three 10 m sprints, with 1 min rest intervals, every 15 min during the SAFT^{90}. This is considered a relevant sprint distance in modern soccer and is in line with recent match-play data (22). The 10 m course was marked out as a separate track, parallel to the SAFT^{90} course, with infrared photoelectric cells, interfaced to a timing system (Newtest System, Newtest Oy, Oulu, Finland), with a further 3 m marked out for a running start. To ensure subjects performed one complete dominant sprint cycle at close to maximum speed within the camera capture area and without altering their stride, subjects were familiarised with the track and camera recording area during the warm-up.

The Qualisys Track Manager (QTM) software® was used to record sprint trials. A fourth-order zero-phase-shift Butterworth digital low-pass (10 Hz) filter was applied to filter out high frequency noise. Data was exported to C-motion Visual 3D software® to model lower limb segments, including the pelvis and dominant lower limb.

Using the sprint kinematic data recorded during the latter part of the 10 m sprint, the most successful trial was selected for further analysis. This was defined as the trial in which all data was successfully collected within the capture area. During the stride cycle captured, relevant dependent variables for the dominant leg were selected relating to potential associations regarding risk factors for hamstring injuries (hamstring and rectus femoris theoretical muscle length based on joint position, pelvic tilt and lower limb angular velocity) discussed previously. The dependent variables included: stride length (measured along X axis from placement of calcaneus marker of dominant limb from touch down and toe-off during stride cycle), maximum shank centre of mass velocity (VCM), maximum thigh VCM, maximum hip flexion angle, maximum hip extension angle, maximum knee flexion angle, maximum knee extension angle, maximum anterior pelvic tilt angle and maximum posterior pelvic tilt angle. Additionally, a combined maximal hip flexion and knee extension angle was calculated and used to indicate hamstring length (observed during the latter part of the swing phase; ▶ **Fig. 2a**). A combined maximum hip extension and knee flexion angle was calculated and used to indicate rectus femoris length (observed during the end of the recovery phase; ▶ **Fig. 2b**). The averaged 10 m sprint times were also recorded.

Data analysis

Descriptive statistics of outcome measures included means and standard deviations (±SD). Sprint performance repeatability was assessed using the intraclass correlation coefficient (ICC) between the three sprints at each of the eight test times during the SAFT^{90}. Differences between dependent variables at the eight time points were tested for significance employing repeated measures analyses of variance (ANOVA), with least-significant difference post hoc tests used. Pearson correlation coefficient was calculated to investigate the relationship between sprint times and stride length. Statistical analysis was processed using SPSS statistical software (version 14.0, Chicago, IL®) with significance level $\alpha = 0.05$. Effect sizes were determined using the partial Eta-squared (Eta) method. When applied to ANOVA, it has been suggested that an effect size of 0.1 represents a small effect size; 0.25 a medium effect; and 0.4 a large effect [16].

Results

Sprint times and stride length

The ICC of sprint times at each of the eight test trials during the SAFT^{90} showed a high level of repeatability in sprinting performance for subjects with all values above 0.83. There was a significant time dependent increase in sprint time of 8.18 % during the SAFT^{90} fatiguing protocol ($P < 0.01$; Eta = 0.63). Sprint time significantly increased during each half of the SAFT^{90} by 5.54 % and 3.24 % ($P < 0.01$) for the first and second halves respectively. Mean sprint time immediately before and after half-time was not significantly different ($P > 0.05$). A significant difference in stride length was also observed during SAFT^{90} ($P < 0.01$; Eta = 0.51). Post hoc tests identified a significant decrease in stride of 16.95 % ($P < 0.02$) during SAFT^{90}. There was also a significant correlation between decreased stride length and increased sprint time during SAFT^{90} ($r = 0.933$; $P < 0.01$).

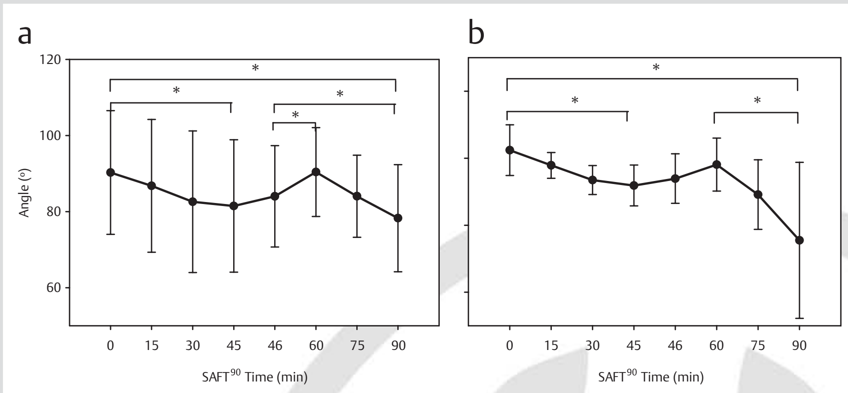

Fig. 3 **a.** Combined maximal hip flexion and knee extension angle during SAFT90. **b.** Combined maximal hip extension and knee flexion angle during SAFT90. *Significant difference between time points (p<0.03).

Kinematic parameters

Maximum hip flexion angle revealed a significant effect of fatigue (P<0.01; Eta=0.33), with a significant reduction in maximum hip flexion angle between 0 and 90 min of the fatiguing protocol (0 min: 81.5±9.8 vs. 90 min 68.6±4.4°; P<0.04). Maximum hip extension angle was also significantly higher after each half of the simulated soccer match-play protocol (0 min: −8.5±2.7 vs. 45 min: −14.8±3.0° and 46 min: −10.5±1.0 vs. 90 min: −15.3±1.4°; P<0.04).

A significant difference was observed in maximum knee extension angle with fatigue (P<0.001; Eta=0.37) with a significant decrease in range during the full 90 min protocol (0 min.7±2.8 vs. 90 mins: 20.9±3.6°; P<0.01). However, a significant increase in maximum knee extension angle was observed during the first 15 min of the second half (46 min.6±2.7 vs. 60 mins: 11.6±2.7°; P<0.01). Maximum knee flexion angle increased during each half of the exercise protocol, however these findings were statistically non-significant (P>0.05).

Combined maximal hip flexion and knee extension angle revealed a significant time dependent difference during the SAFT90 (P<0.02; Eta=0.49; ▶ **Fig. 3a**) with a significant reduction observed during each half respectively (P<0.02). However, a significant increase was observed between the first 15 min following the half-time interval (P<0.02). Combined maximal hip extension and knee flexion angle also revealed a significant effect of fatigue (P<0.01; Eta=0.38; ▶ **Fig. 3b**). A significant decrease was observed during the first half of the SAFT90 (P<0.03) and during the second half between 60–90 min (P<0.03).

There was a significant difference in maximum anterior pelvic tilt angle during SAFT90 (P<0.01; Eta=0.53) with a significant increase being observed during each half respectively (P<0.04). There was no significant change in maximum posterior pelvic tilt angle during SAFT90 (P>0.05).

Segmental centre of mass velocities

A significant difference was observed during SAFT90 for both thigh VCM (P<0.01; Eta=0.43) and shank VCM (P<0.01; Eta=0.75; ▶ **Fig. 4**). Thigh VCM observed a significant decrease during the first half (P<0.04) and second half of the protocol after 60 min (P<0.04). A significant increase in maximum thigh VCM was observed for the first 15 min following the half-time interval (P<0.04). Shank VCM identified a significant increase during each half of SAFT90 respectively (P<0.02). Also, immediately following half-time there was a significant reduction in maximum shank VCM during the first 15 min (P<0.02).

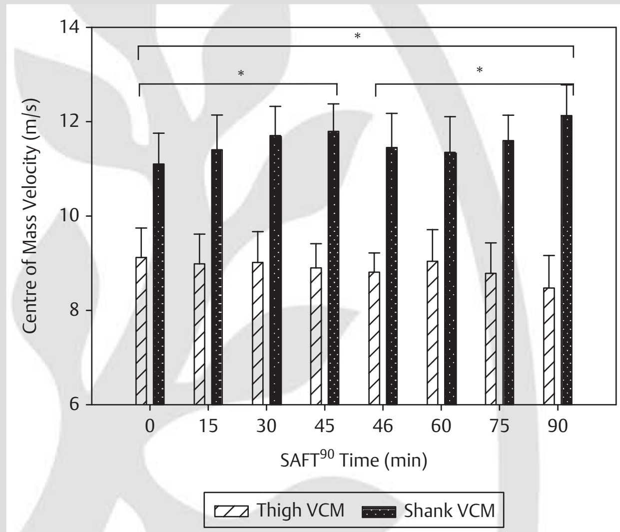

Fig. 4 Maximum (±SD) thigh and shank VCM during SAFT90. *Significant difference between time points (p<0.04).

Overall, the results indicated a time dependent alteration in sprinting kinematics with fatigue during SAFT90 (▶ **Fig. 5**) resulting in increased sprint time and corresponding decreased stride length.

Discussion

The present study investigated the effect of a 90 min, multidirectional, soccer-specific fatiguing protocol on sprint times and lower limb kinematics. During testing, the correlation observed between increased sprint time and reduced stride length during SAFT90 in support of the study hypothesis, concurs with findings by Krustrup et al. [10]. The authors reported a decline in sprint performance after completing, and temporarily during, actual soccer match play, which was attributed to reduced glycogen levels in individual muscle fibres [10]. Findings from the present study may provide a mechanical explanation for the slower sprint times with fatigue.

A decrease in maximum knee extension angle with fatigued sprinting was observed in the present study which contradicts previous research reporting increased maximum knee extension angle [15]. It has been argued that this increased knee

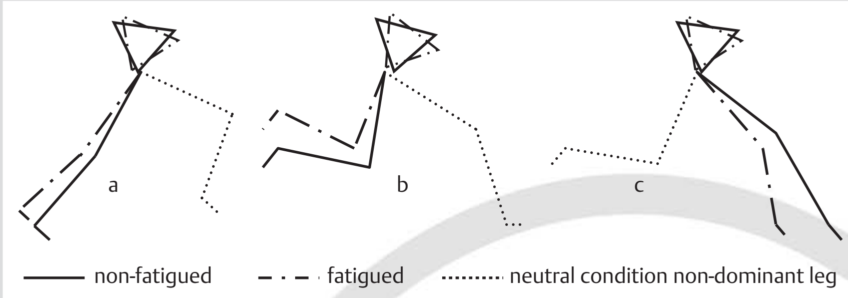

Fig. 5 Schematic representation of sprinting stride comparison between non-fatigued and fatigued condition. **a** = take off, **b** = recovery part of swing phases, **c** = end of swing phase/initial contact.

extension may be the result of reduced ability of the fatigued hamstrings to limit the end point of forward leg motion [15]. However, the fatigue protocols employed by Pinniger et al. [15] did not reflect soccer match-play, and may have induced more acute fatigue and hence have different effects compared to the fatigue induced by SAFT^{90}.

It was hypothesised that with fatigue, the hamstrings would be shorter, especially during eccentric actions involved in sprinting. Subsequently, reduced maximum combined hip flexion and knee extension angle, used to indicate hamstring muscle length, and decreased stride length were observed towards the ends of each half of the SAFT^{90}. This work concurs with results of Hanon et al. [8] who, despite dissimilar fatiguing protocols employed, demonstrated reduced hamstring muscle length with fatigue. Reduced maximum combined hip flexion and knee extension angle, suggesting reduced hamstring length, may pose a possible mechanism for increased risk of hamstring strain, as if the hamstrings are stretched beyond their ability to elongate and tear to the musculo-tendinous unit may occur [1].

Another factor that may contribute to a higher risk of injury when fatigued is the lower limb segmental velocity. In support of the initial hypothesis, a significant increase in shank segmental velocity at the ends of each half of the SAFT^{90}was observed. This, and the concurrent decreased hamstring length, suggested by a reduced combined maximum hip flexion and knee extension angle during the swing phase of sprinting, may result in the lower leg being "whipped" through [23], potentially creating additional strain on an already tight musculo-tendinous unit and increasing injury risk. Furthermore, during the late swing phase of sprinting the hamstrings work eccentrically to decelerate the forward motion of the lower leg [21]. However, it has been reported that fatigue associated with simulated multi-directional soccer match-play causes a decrease in eccentric hamstring strength [19]. This could potentially impair the ability of the hamstrings to decelerate the limb effectively to avoid risk of injury, especially within a reduced range of motion and with increased lower limb velocity as observed.

The quadriceps muscle group may also play a role in the aetiology of hamstring injury: in case of rectus femoris tightness there may be a rise in the passive elastic recoil of the tendon [5]. This in turn could increase lower limb velocity, which must be counteracted by the eccentrically contracting hamstrings, therefore imposing a greater load and increasing their chance of failure [5]. In the present study a significant increase in combined maximum hip extension and knee flexion angle, used to indicate rectus femoris length, was observed at the end of the recovery part of the swing phase during the latter stages of each half of the SAFT^{90}. This finding may be linked to the increased shank segmental velocity results observed towards the ends of each half of the exercise protocol.

The results revealed a significant increase in maximum anterior pelvic tilt angle with fatigue during the SAFT^{90}. This may be associated with increased lumbar lordosis, which is common in sports involving kicking actions as a result of over-development of the psoas muscles commonly used in kicking [18]. In relation to sprinting technique, increased forward lean of the body associated with greater anterior pelvic tilt may predispose the hamstrings to injury by increasing their relative length [9]. The anteriorly tilted pelvis may be a potential attempt to increase the hamstrings range of motion as it was shown in the present study that maximum combined hip flexion and knee extension angle reduces during the latter stages of SAFT^{90}. However, this compensatory mechanism may conversely create an additional strain on the muscle group, thereby increasing risk of injury [25].

The alterations in sprinting kinematics observed with fatigue during the simulated soccer match-play protocol primarily manifested immediately prior to the ends of each half. However, similar values and overall technique changes were also observed immediately after the 15 min half-time interval. Interestingly, at 60 min during the SAFT^{90} players showed an improvement in sprinting performance as well as a recovery towards non-fatigued sprinting technique as demonstrated during the start of the first half of the exercise protocol, although which subsequently deteriorated towards 90 min. This may suggest that players are at a similar risk of hamstring injury when sprinting immediately after half-time, due to a sustained 15 min period of inactivity, as they are at the ends of each half, due to fatigue. In support of this, an increased amount of injuries sustained has been observed immediately following half-time during soccer match-play [18]. Furthermore, it was reported by Greig [7] that during a 90 min football-specific treadmill protocol, eccentric hamstring strength was lower immediately after half-time than prior to it. Therefore, with the relationship between reduced eccentric hamstring strength and increased hamstring injury risk generally acknowledged, these findings along with those from the present investigation would support the theory of increased risk of hamstring injury at the beginning of the second half of soccer match-play.

Research investigating performance following half-time [12] has reported impaired sprint performance prior to the start of the second half of a friendly soccer match, which the authors attributed with lowered body temperature recorded at this time. This reduced body temperature following half-time may affect muscle functioning to impair sprinting performance and also reduce flexibility of the musculo-tendinous unit to increase risk of injury, in support of the observed significantly lower maximum

combined hip flexion and knee extension angle at 46 min compared to 60 min in the current study. This may give support for further investigation into half-time re-warm-up strategies to improve early second half performance and reduce injury risk.
Findings from the present study are based on accurate data collection during the testing procedures; however, markers occasionally became detached during the 90 min exercise protocol. Although these were replaced as precisely as possible using the marked positions on the skin, this limitation should be considered when reviewing the results. Furthermore, although hamstring and rectus femoris muscle lengths were estimated using a combined hip and knee angle calculation, these do not indicate actual muscle length or flexibility. Therefore, a direction for future investigation could be to examine changes in hamstring muscle flexibility during soccer-specific fatigue, as this may have further implications regarding hamstring injury risk.

Conclusion

Findings from the present study indicate that exercise simulating the physiological and mechanical demands of soccer match-play produced a time dependent alteration in sprinting kinematics. The SAFT^{90} protocol resulted in impaired sprinting performance at the ends of each half of the simulated soccer match due to fatigue, and also immediately following the half-time interval, likely due to a period of inactivity. Furthermore, decreased flexibility of the hamstring muscle group was indicated during fatigued sprinting, with reduced maximum combined hip flexion and knee extension angle observed during the late swing phase of the sprinting cycle. This combined with increased lower limb segmental velocity, potentially due to elastic recoil from the increased rectus femoris length observed earlier in the stride cycle, and increased anteriorly tilted pelvis with fatigue, may increase strain on the hamstrings. These new insights into hamstring injury mechanism provide a good knowledge base to develop injury prevention strategies.

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Erratum

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The eFirst version and the print version of the article contains an error in the affiliation list.
The correct affiliation for **M. Lohkamp** is "[1] **Department of Sport, Health & Exercise Science, University of Hull, Hull, United Kingdom**".