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Associations between Hamstring Fatigue and Sprint Kinematics during a Simulated Football (Soccer) Match

ERIK WILMES[1], CORNELIS J. DE RUITER[1], BRAM J. C. BASTIAANSEN[2], EDWIN A. GOEDHART[3], MICHEL S. BRINK[2], FRANS C. T. VAN DER HELM[4], and GEERT J. P. SAVELSBERGH[1]

[1]Amsterdam Movement Sciences, Department of Human Movement Sciences, Faculty of Behavioural and Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam, THE NETHERLANDS; [2]Center for Human Movement Sciences, University of Groningen, University Medical Center Groningen, Groningen, THE NETHERLANDS; [3]FIFA Medical Centre of Excellence, Royal Netherlands Football Association, Zeist, THE NETHERLANDS; and [4]Department of Biomechanical Engineering, Delft University of Technology, Delft, THE NETHERLANDS

ABSTRACT

WILMES, E., C. J. DE RUITER, B. J. C. BASTIAANSEN, E. A. GOEDHART, M. S. BRINK, F. C. T. VAN DER HELM, and G. J. P. SAVELSBERGH. Associations between Hamstring Fatigue and Sprint Kinematics during a Simulated Football (Soccer) Match. *Med. Sci. Sports Exerc.*, Vol. 53, No. 12, pp. 2586–2595, 2021. **Purpose:** Neuromuscular fatigue is considered to be important in the etiology of hamstring strain injuries in football. Fatigue is assumed to lead to decreases in hamstring contractile strength and changes in sprinting kinematics, which would increase hamstring strain injury risk. Therefore, the aim was to examine the effects of football-specific fatigue on hamstring maximal voluntary torque (MVT) and rate of torque development (RTD), in relation to alterations in sprinting kinematics. **Methods:** Ten amateur football players executed a 90-min running-based football match simulation. Before and after every 15 min of simulated play, MVT and RTD of the hamstrings were obtained in addition to the performance and lower body kinematics during a 20-m maximal sprint. Linear mixed models and repeated measurement correlations were used to assess changes over time and common within participant associations between hamstring contractile properties and peak knee extension during the final part of the swing phase, peak hip flexion, peak combined knee extension and hip flexion, and peak joint angular velocities, respectively. **Results:** Hamstring MVT and sprint performance were significantly reduced by 7.5% and 14.3% at the end of the football match simulation. Unexpectedly, there were no indications for reductions in RTD when MVT decrease was considered. Decreases in hamstring MVT were significantly correlated to decreases in peak knee angle ($R = 0.342$) and to increases in the peak combined angle ($R = -0.251$). **Conclusions:** During a football match simulation, maximal voluntary isometric hamstring torque declines. This decline is related to greater peak knee extension and peak combined angle during sprint running, which indicates a reduced capacity of the hamstrings to decelerate the lower leg during sprint running with fatigue. **Key Words:** INERTIAL MEASUREMENT UNITS, FATIGUE, HAMSTRING STRAIN INJURY, RATE OF TORQUE DEVELOPMENT, SPRINTING, LOWER BODY KINEMATICS

In football, hamstring strain injury (HSI) is the most common muscle injury (1). Approximately 57% of all HSIs are sustained while sprinting, and they most frequently occur toward the end of each half during competitive matches (2). This indicates that neuromuscular fatigue may be an important mediating factor in the etiology of the injury. It is known that fatigue develops as a result of repeated sprints and limited rest between bouts (3). This leads to reductions in hamstring maximal voluntary torque (MVT) generating capacity and rate of torque development (RTD), which have been observed during and after simulated and actual football match-play (4–6), as well as changes in sprinting kinematics (7).

Reductions in hamstring MVT generating capacity and RTD are believed to impair the ability to decelerate the leg during late swing phase in sprinting (4). The hamstrings undergo lengthening over the knee and hip simultaneously during this phase, as the knee is extending and the hip is flexing. At the same time, the hamstrings must contract to decelerate the lower limb (8–10). Whenever the hamstrings fail to produce the required forces, or if they cannot produce these forces quickly enough, excessive muscle strains can occur. As a consequence, the risk of sustaining a HSI may increase with neuromuscular fatigue.

Increased HSI risk may be indicated during play by measuring changes in sprinting kinematics. Significant decreases in

Address for correspondence: Erik Wilmes, M.Sc., Van der Boechorststraat 7, 1081 BT Amsterdam, The Netherlands; E-mail: e.wilmes@vu.nl.
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the peak combined knee and hip flexion/extension angles (Fig. 1) have been found during each half of a simulated football match, suggesting lower peak hamstring muscle length in the terminal swing phase of sprint running during fatigue (7). Moreover, higher shank velocities were found, which may, together with the concurrent decreased hamstring length, be indicative for a higher chance of stretching the hamstring musculotendinous units beyond their mechanical limits.

Although football-specific fatigue-induced changes of hamstring MVT, RTD, and sprinting kinematics have been studied in isolation, the relation between these changes is unknown. In addition, recent advancements in motion analysis systems provide the opportunity to measure kinematics with wearable inertial sensors outside laboratory settings and without hindering players in their movements, allowing for measurements during training or match-play (11). Accordingly, such systems may be used to quantify changes of sprinting kinematics caused by fatigue. Therefore, the objective of current study was to examine the effects of football-specific fatigue on hamstring MVT, hamstring RTD, and sprinting kinematics in a single fatiguing protocol, whereby the potential to assess fatigue by measuring changes in sprinting kinematics using an inertial-based motion analysis system was explored. This is important because changes in sprinting kinematics may be indicative for increased HSI risk. Therefore, it would be a great advantage if fatigue-induced changes of kinematics could be captured during training and matches. Moreover, these kinematic data may be crucial to monitor acute fatigue, which may, together with heart rate, local positioning measurements, or GPS data

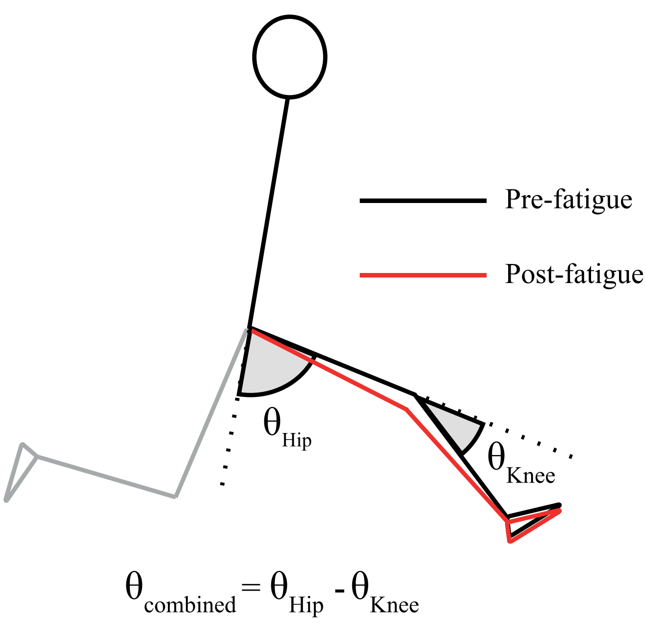

FIGURE 1—Joint angle definitions and effects of fatigue on peak knee extension and peak hip flexion. The hip flexion/extension angle is defined as the angle between the longitudinal axis of the pelvis and the longitudinal axis of the thigh. The knee flexion/extension angle is defined as the angle between the longitudinal axis of the thigh and the longitudinal axis of the shank. The combined angle is a theoretical measure of hamstring length, peak hamstring length during sprinting may be indicative of HSI risk.

(12), help coaches, embedded scientists, and medical staff members improve the quantification of load and load-response in individual players and to assess their risk of overload and injury (13).

The approach was to measure football-specific fatiguing effects in a controlled experimental setting. A 90-min football-specific aerobic field test (SAFT90) was used to simulate the physiological and biomechanical intensity distribution of a football match (7). Before and after every 15-min segment, a 20-m sprint test, a hamstring RTD test, and a hamstring MVT test were conducted. EMG activity of the biceps femoris long head (BFlh) and medial hamstrings (MH) was synchronously recorded with the RTD and MVT trials. Moreover, sprint performance and sprinting kinematics were obtained using an inertial-based motion analysis system. It was hypothesized that during neuromuscular fatigue, sprint performance, hamstring MVT, EMG, and RTD would decrease. Based on previous research, increases in peak knee extension velocity during the latter part of the swing phase and reductions in peak combined knee and hip flexion/extension angle were expected (7). Significant associations between reductions in hamstring MVT and increases in peak knee extension and extension velocity were anticipated, because fatigued hamstrings are likely to be less capable of decelerating the lower limb during the final part of the swing phase in sprint running.

METHODS

Participants

Ten healthy mid to high level amateur male football players (age, 21.9 ± 4.2 yr; height, 188 ± 4.1 cm; weight, 77.9 ± 9.5 kg) from different clubs without any hamstring injuries in the last 12 months participated in the study. The participants had at least one practice and one match per week and were recruited at the local football club and university. All participants were informed about the experimental procedures, and all signed consent before participation. Ethical approval was given by the scientific and ethics review board of the faculty of Behavioral and Movement Sciences of the Vrije Universiteit Amsterdam (VCWE-2019-070R1).

General Procedures

The study consisted of two separate sessions, a familiarization session and an experimental session at least 3 d after the familiarization. During the familiarization session, participants were thoroughly introduced to the SAFT90 by completing one 15-min segment, as well as to the procedures used to assess hamstring MVT, RTD, and sprint performance. The SAFT90 protocol was completed individually on an outdoor artificial turf to ensure comparable conditions between participants. On the test days, ambient temperatures ranged between 15°C and 25°C. Before the start, and immediately after every 15-min segment participants executed a 20-m sprint test, of which the time and lower body kinematics were assessed. In addition, hamstring RTD and MVT were assessed immediately after each 20-m sprint test. The 15-min break between the two halves of the SAFT90 was conducted as passive seated rest. Participants were free to drink water before the SAFT90, during the 15-min break, and after completion of the protocol.

The SAFT90 protocol is a running-based football-specific aerobic field test based on time–motion analysis of English Championship level matches that consists of six equivalent 15-min segments (14). The protocol was designed with the intention to simulate the physiological and biomechanical demands of a football match and has been validated to mimic the internal load, external load, and fatigue response of actual football matches in amateur and semiprofessional football players (14,15). Participants completed a 20-m agility course at varying velocities and with alternating utility movements (sidesteps and forward–backward running). Movement velocities included standing (0 $km \cdot h^{-1}$), walking (5.5 $km \cdot h^{-1}$), jogging (10 $km \cdot h^{-1}$), striding (15 $km \cdot h^{-1}$), and sprinting (maximal effort). The protocol included 444 cutting maneuvers, 888 changes in direction, and 1269 changes in movement velocity. Movement velocity and alternating utility movements were dictated by an MP3 audio file. Participants executed a standard 10-min competition warm-up followed by 10 min of rest before the start of the SAFT90.

Data Acquisition

Lower body kinematics. Participants were equipped with five inertial measurement units (MPU-9150, Invensense San Jose, CA) attached to the sacrum, thighs and shanks (size, 35 × 25 × 15 mm; total weight, 11.0 g). The sensors were fixated to the skin at locations where soft tissue artifacts were thought to have minimal effects. The sacrum sensor was placed on the middle of the lower back (L4) just above the waistband, the thigh sensors on the iliotibial tract at about half the length hip to knee, and the shank sensors on the bony part of the shin at approximately one third of the length knee to ankle. Before attachment, time-synchronization was performed by the simultaneous introduction of a mechanical peak in the accelerometer signals (16). Raw data of each sensor were stored on a local SD card at a sample frequency of 500 Hz to allow for offline analysis. Sensor-to-segment calibrations and kinematic calculations were performed according to Wilmes et al. (11).

MVT and RTD. After the 20-m sprint test, participants were immediately secured in a custom build adjustable rigid dynamometer (Fig. 2). Participants were lying prone on a wooden platform with their hips tightly pressed to the surface with a horizontal beam across the buttocks that was fixed on either side. Both knees were resting on the platforms' surface while the foot of the dominant leg was tightly fixed to a force sensor (KAP-E force transducer 2KN, A.S.T.—Angewandte System Technik GmbH, Dresden, Germany) using a velcro strap. The velcro strap allowed participants to completely relax between contractions and prevented ballistic collisions with the force sensor in response to hamstring activation. The surfaces of the platform, the horizontal beam, and the velcro strap were covered by a thin layer of foam (2 cm) to avoid discomfort, which would negatively affect torque production, keeping the effects of padding on RTD as small as possible.

RTD measurements started exactly 1 min after the sprint test, whereby participants were instructed to contract "as fast as possible." At each RTD measurement, participants performed six "fast" contractions that were separated by 15 s of complete relaxation. Care was taken that subjects reached at least over 65% of their pilot-MVT during these contractions (17). Subsequently, one MVT measurement was performed after 30 s of rest. We chose this order of measurements because we presumed that an MVT contraction would have greater effects on subsequent RTD contractions than the other way around because the RTD contractions were only very short in duration. Moreover, the rest intervals were chosen, such that there was enough time to recover from the short isometric contractions, while limiting recovery between SAFT90 segments. Participants were instructed to contract "as hard as possible" and to keep pushing for 2 to 3 s during the MVT trial. During the MVT trials and before the RTD tests participants were verbally encouraged.

FIGURE 2—Custom build adjustable rigid dynamometer.

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Two additional MVT trials separated by 30 s of rest were performed before the start of the SAFT90 to provide a reliable reference. The highest reference attempt was used for further analysis. Force signals were sampled at a frequency of 5 kHz, and immediately converted to knee moments by multiplying the applied force by the distance of the knee joint to the force transducer. Before each experimental session, the dynamometer was adjusted to the participant, so that all tests were performed with a 10° knee flexion angle (0° being full extension), because HSIs typically occur at long muscle lengths (4).

EMG activity. EMG activity of the BFlh and MH (semitendinosus and semimembranosus) of the dominant leg was recorded during the MVT and RTD tests. Pairs of surface electrodes (Ambu® BlueSensor N; AMBU A/S, Ballerup, Denmark) were applied to each muscle following SENIAM recommendations with a center to center interelectrode distance of 10 mm (18). Hair was removed, and the skin was cleaned with alcohol. A reference electrode was placed on the fibular head of the same leg. All electrodes were taped to the skin to prevent them from falling off during the SAFT90. EMG signals were amplified (g.BSamp; g.tec Medical Engineering GmbH, Schiedlberg, Austria) and simultaneously recorded with the force signals at a sample frequency of 5 kHz using an AD converter (NI USB-6221; National Instruments Netherlands B.V., Woerden, The Netherlands).

Sprint performance. Sprint performance was assessed with a 20-m sprint test. Participants were required to stand still with one leg on the starting line, whereafter a start signal was given. The start time was defined as the moment at which the angular velocity of one of the thighs crossed a threshold of $50°\cdot s^{-1}$. End times were recorded using an additional time-synchronized inertial measurement unit fixed to a mechanical timing gate placed at the 20-m mark (16). Participants were instructed to run through the timing gate as fast as possible and to only start decelerating after the gate.

Data Processing

Lower body kinematics. Knee and hip flexion/extension angles and flexion/extension angular velocities of the dominant leg captured during 20-m sprints were used for data analysis. The kinematic parameters analyzed are potentially associated with an increased HSI risk and were the following: peak knee extension during the latter part of the swing phase, peak hip flexion, peak knee extension velocity, and peak hip flexion velocity. In addition, peak combined angle (Fig. 1) and peak combined angular velocity were obtained as theoretical measures for hamstring length and hamstring elongation velocity, respectively. The peak values captured during the final four completely measured strides of each 20-m sprint were averaged to improve reliability.

MVT, RTD, and EMG activity. Torque signals obtained during the MVT and RTD tests were smoothed to remove signal noise using a median filter with a 5-ms moving window, followed by a 5-ms window moving average filter. Maximal voluntary torque values were defined as the highest 500-ms average torque, and EMG was also obtained from this same interval. Raw EMG signals of the BFlh and MH were filtered with a fourth-order Butterworth bandpass filter with cutoff frequencies of 20 Hz and 500 Hz. Subsequently, the EMG signals were rectified and expressed as a percentage of 500 ms mean values obtained in the same muscle during MVT before the SAFT90 ($t = 0$). EMG activity levels of the MVT trials after each subsequent 15-min SAFT90 segment were determined as the 500-ms mean activity level during the highest 500 ms mean torque.

In the RTD trials, muscle activity onsets were determined using a two-step method. First, the activity onset of each muscle was approximated by visual inspection of the rectified EMG signals. Second, the exact onset was determined for each individual muscle using the integrated profile method with a 2.5-ms window around the first activity onset approximation (19). EMG onset was then defined as the first activity onset found in either one of the measured muscles.

Baseline torque, produced by the weight of the leg pulling at the force transducer, was defined as the 100-ms average torque before EMG onset. Time of torque onset was specified as the moment at which torque crossed a 0.5-N·m threshold above baseline. The torque-time integrals (TTI) were computed from 0 to 50 ms (TTI50), 0 to 100 ms (TTI100), and 0 to 150 ms (TTI150) posttorque onset. The maximum RTD (MRTD) was determined as the maximum 10 ms average of the differentiated torque signal.

The reliability of RTD measurements depends on the participants complete relaxation of the hamstrings. Any pretension or "countermovement" performed was objectively assessed using the slope of the torque signal during a 100-ms interval starting 80 ms before EMG onset and ending 20 ms post-EMG onset. This interval was chosen as the electromechanical delay was found to be at least 20 ms, thus any contraction induced torque increase always occurred at least 20 ms after EMG onset. The slope of the torque signal over this 100-ms time interval was calculated by least square fitting a first-order polynomial. A positive slope before torque onset indicated that the participant exerted pretension on the force sensor, whereas a negative slope meant that the participant performed a "countermovement" (i.e., a dip in the torque signal). If the slope exceeded an absolute value of $1.5\ N\cdot m\cdot s^{-1}$, the trial was discarded (20). This is crucial for these kinds of measurements because parameters of fast torque development are highly sensitive to subtle changes in torque before the actual contraction (i.e., a small increase in torque rise leads to a substantial increase in TTI50) (20). Typical examples of a correct RTD attempt and a RTD attempt with a "countermovement" of the same participant are shown in Figure 3. It can be observed that a subtle "countermovement," which is only visible when zoomed in, leads to a considerable increase in TTI50. Of 480 total attempts (10 participants $\times$ 8 trials $\times$ 6 attempts), 150 attempts were discarded because the absolute fitted torque-slope exceeded $1.5\ N\cdot m\cdot s^{-1}$.

Therefore, after discarding the trials with pretension or a "countermovement" using these objective criteria in the data analysis, the average values of the three best remaining attempts

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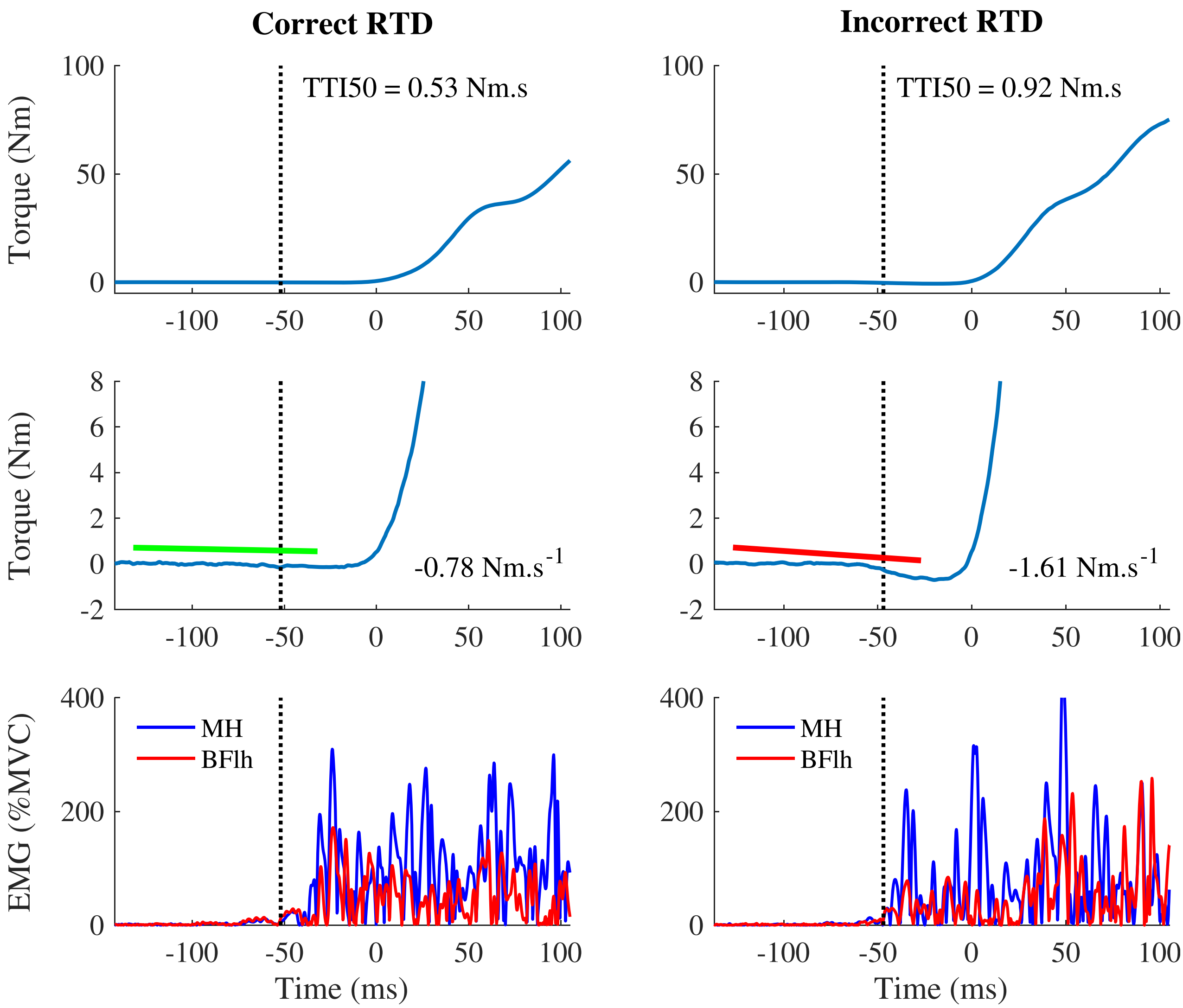

FIGURE 3—Typical traces RTD attempts. In the left figures, typical traces of a correctly executed RTD attempt are shown. In the right figures, typical traces of an incorrect RTD attempt (with countermovement) is shown for the same participant. The time is defined relative to the moment of torque onset (*t* = 0 ms). The vertical dotted line denotes the time of EMG onset. An attempt was accepted when the absolute fitted torque-slope between 80 ms before EMG onset and 20 ms after EMG onset was smaller than 1.5 N·m·s^{-1} (as shown in green in the left middle figure: −0.78 N·m·s^{-1}). An attempt was discarded when the absolute fitted slope was greater than 1.5 N·m·s^{-1} (as shown in red in the right middle figure: −1.61 N·m·s^{-1}).

(based on the TTI50) were used for further analysis. Measures of torque rise show considerable variation between attempts, therefore, using an averaged value across several attempts at each time point is considered best practice (21). On 8 of 80 occasions (10 participants × 8 trials), participants produced only two valid attempts; on seven occasions, participants produced only one valid attempt; and on one occasion, the participant did not produce any valid attempt. If there were three or less valid attempts remaining, the average values of all remaining valid attempts were used for data analysis. Previous studies by our research group have shown good test–retest reliability of TTI and MRTD measures using similar procedures for the quadriceps muscles, with intraclass correlation coefficients ranging from 0.81 to 0.96 (20,22).

Statistical Analysis

All outcome measures are presented as means ± standard deviation. Within session reliabilities of hamstring, MVT and RTD values were assessed by computing intraclass correlation coefficients (ICC (3)) and coefficients of variation between the first (before SAFT90) and second (after 15 min of SAFT 90) measurement of the experimental session.

The effects of SAFT-half and time within both SAFT-halves on MVT, RTD, EMG, sprint time, and kinematic variables were examined with linear mixed models using the "nlme" package (23) in R version 4.0.3 (24). The SAFT half and time within SAFT-half were included in the models as fixed factors. Including an interaction term between half and time within half, to investigate if changes differed between halves, did not significantly improve the explained variances of the models and was therefore not included as a fixed factor. Slopes and intercepts for individual participants were entered as random factors, so that the models allowed for interindividual differences in baseline values and fatigue response. Compound symmetry of the variance-covariance matrix was assumed. Cohen's *d* values were calculated for each fixed effect as a measure of effect size and were interpreted as small (0.2), moderate (0.5), and large (0.8) (25).

Common within participant associations between MVT, RTD, and kinematic variables were evaluated using repeated-measures correlation coefficients. Repeated-measures correlations represent the shared association among individuals between two variables over repeated measurements on a group level. Repeated measures correlation coefficients were calculated using the "rmcorr" package (26) in R version 4.0.3 (24). All statistical tests were executed with a significance level of $\alpha = 0.05$. *A priori* power calculations were conducted with G*Power 3.1 software for prefatigue and postfatigue MVT and RTD values presented in Marshall et al. (4), indicating that for an assumed conservative correlation of 0.5 between measurements and a power of 80%, six to nine participants were needed to detect an effect of fatigue at significance level ($\alpha = 0.05$) (27). This is in accordance with the sample sizes used in similar studies (4,7,28,29).

RESULTS

Hamstring MVT and RTD, and sprint test results throughout the running-based football match simulation are summarized in Table 1 and Table 2, respectively. Within session, reliability tests revealed ICC values above 0.84 for all variables (MVT, 0.96; TTI50, 0.94; TTI100, 0.88; TTI150, 0.84; MRTD, 0.85), whereas coefficients of variation values ranged 5.1% to 21.7% (MVT, 5.1%; TTI50, 21.7%; TTI100, 17.7%; TTI150, 12.6%; MRTD, 8.7%).

Significant main effects of half and time within half on MVT, corresponding normalized EMG values (Table 1), and sprint performance (Table 2) were observed, indicating the fatiguing effects of the SAFT90 on these dependent variables. Interestingly, the fatiguing effects on EMG activity during the MVT trials were greater for the BFlh compared with the MH. Unexpectedly, there were no significant effects of half and time within half on any of the TTI values, except a moderate significant effect of time within half on TTI150.

Significant decreases between each playing half of peak hip flexion and peak knee extension were found, whereas the peak hip flexion angle also significantly decreased within each half (Fig. 1). No significant effects were observed for the peak combined angle. In addition, no effects of half or time within half were found for peak joint angular velocities, except for a moderate increase in peak combined angular velocity between the first and second playing half.

A significant common within participant association between hamstring MVT and knee angle at peak knee extension (Fig. 2A) was observed. Of 10 participants, two participants showed a correlation coefficient that conflicted with the association found on a group level. In addition, significant repeated measurement correlation coefficients were found between hamstring MVT and hip angle at peak hip flexion (Fig. 2C), and peak combined angle (Fig. 2E), whereby one and two participants respectively showed a contradicting relationship compared with the associations found on a group level. No significant associations of hamstring MVT with peak joint angular velocities were revealed (Fig. 2B and 2D), nor with peak combined angular velocity (Fig. 2F). None of the RTD values was significantly correlated to any changes in the kinematic parameters ($R = -0.067$ to 0.222; $P = 0.064$–0.991).

DISCUSSION

The aim of the present article was to examine the effects of football-specific fatigue on sprinting kinematics, sprint performance, hamstring MVT, and hamstring RTD. Sprint performance, hamstring MVT, and hamstring EMG deteriorated significantly throughout the SAFT90, evidently showing the presence of neuromuscular fatigue among participants. Moreover, decreases in hamstring MVT were associated with

TABLE 1. Hamstring test results.

				RTD			
	MVT (N·m)	EMG MH (%MVT)	EMG BF (%MVT)	TTI50 (N·m·s^{-1})	TTI100 (N·m·s^{-1})	TTI150 (N·m·s^{-1})	MRTD (N·m·s^{-1})
First Half (min)							
0	105.0 ± 17.0	100 ± 0	100 ± 0	0.39 ± 0.20	2.27 ± 0.71	5.60 ± 1.14	1182 ± 179
15	98.8 ± 20.4	92.9 ± 17.8	89.8 ± 11.3	0.38 ± 0.26	2.19 ± 0.92	5.42 ± 1.38	1195 ± 210
30	96.0 ± 18.7	92.7 ± 16.6	82.2 ± 15.1	0.36 ± 0.22	2.09 ± 0.83	5.14 ± 1.35	1163 ± 188
45	95.5 ± 16.6	91.3 ± 14.7	83.9 ± 14.2	0.34 ± 0.25	1.91 ± 0.99	4.77 ± 1.66	1159 ± 264
Second half (min)							
0	95.1 ± 15.8	98.0 ± 13.2	90.3 ± 16.8	0.31 ± 0.15	1.95 ± 0.75	4.93 ± 1.20	1106 ± 189
15	94.0 ± 16.8	87.8 ± 10.8	82.7 ± 13.3	0.36 ± 0.24	2.04 ± 0.91	5.04 ± 1.47	1237 ± 384
30	91.8 ± 15.8	84.9 ± 20.3	74.0 ± 12.7	0.34 ± 0.12	2.08 ± 0.57	5.19 ± 0.88	1072 ± 171
45	90.3 ± 18.1	82.1 ± 21.8	74.4 ± 18.6	0.29 ± 0.14	1.77 ± 0.79	4.51 ± 1.44	1081 ± 299
Main effect time within half							
Mean	−2.4	−3.8	−5.6	−0.01	−0.07	−0.16	−13
95% CI	−3.6 to −1.2	−6.8 to −0.9	−7.7 to −3.5	−0.03 to 0.01	−0.15 to 0.02	−0.32 to 0.00	−48 to 22
Cohen's *d*	0.949	0.613	1.273	0.187	0.376	0.490	0.174
P	<0.001	0.014	<0.001	0.447	0.129	0.049	0.480
Main effect half							
Mean	−6.0	−6.0	−8.6	−0.03	−0.13	−0.26	−43
95% CI	−8.6 to −3.4	−10.4 to −1.6	−12.6 to −4.7	−0.08 to 0.01	−0.31 to 0.06	−0.59 to 0.07	−115 to 28
Cohen's *d*	1.101	0.651	1.040	0.332	0.179	0.382	0.294
P	<0.001	0.009	<0.001	0.178	0.332	0.123	0.234

MVT values with corresponding EMG values, and RTD values throughout the football match simulation, as well as linear mixed modeling results for hamstring tests. For each effect, the mean of the effect, the 95% CI, effect size (Cohen's *d*), and *P* values are shown.

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TABLE 2. Sprint test results.

	Sprint Time (s)	Knee Angle at Peak Knee Extension (°)	Hip angle at Peak Hip Flexion (°)	Peak Combined Angle (°)	Peak knee Extension Velocity (°·s^{-1})	Peak hip Flexion Velocity (°·s^{-1})	Peak Combined Angular Velocity (°·s^{-1})
First half (min)							
0	3.58 ± 0.12	31.2 ± 6.1	77.8 ± 10.0	18.0 ± 7.0	904 ± 95	742 ± 74	934 ± 102
15	3.74 ± 0.14	30.7 ± 7.9	77.1 ± 9.51	19.0 ± 8.9	892 ± 80	683 ± 146	912 ± 56
30	3.75 ± 0.15	30.4 ± 8.2	75.5 ± 9.12	18.6 ± 6.8	859 ± 86	667 ± 132	906 ± 69
45	3.78 ± 0.10	29.4 ± 7.6	75.1 ± 10.4	19.3 ± 7.9	881 ± 96	670 ± 146	900 ± 55
Second half (min)							
0	3.82 ± 0.13	28.2 ± 6.9	75.6 ± 9.03	18.1 ± 5.2	929 ± 81	687 ± 108	951 ± 87
15	3.78 ± 0.12	28.7 ± 6.3	74.4 ± 10.9	19.0 ± 6.2	876 ± 92	708 ± 145	940 ± 71
30	3.83 ± 0.16	27.7 ± 7.2	74.0 ± 9.58	21.1 ± 7.0	879 ± 120	706 ± 146	947 ± 78
45	3.85 ± 0.22	26.4 ± 7.7	72.9 ± 10.8	21.2 ± 8.4	879 ± 116	699 ± 150	912 ± 55
Main effect time within half							
Mean	0.04	−0.6	−0.9	0.7	−12	−10	−11
95% CI	0.01 to 0.06	−1.8 to 0.6	−1.8 to 0.0	−0.2 to 1.7	−29 to 4	−25 to 5	−26 to 4
Cohen's *d*	0.682	0.237	0.495	0.386	0.366	0.306	0.350
P	0.006	0.333	0.045	0.115	0.135	0.212	0.154
Main effect half							
Mean	0.11	−2.7	−2.1	1.2	7	10	24
95% CI	0.07 to 0.14	−4.0 to −1.3	−3.2 to −1.1	−0.3 to 2.6	−12 to 26	−10 to 29	7 to 42
Cohen's *d*	1.323	0.951	0.965	0.375	0.172	0.235	0.675
P	<0.001	<0.001	<0.001	0.127	0.482	0.336	0.007

Sprint performance and potential kinematic risk factors throughout the football match simulation, as well as linear mixed modeling results of the 20-m sprint test. For each effect, the mean of the effect, the 95% CI, effect size (Cohen's *d*), and *P* value are shown.

decreases in knee angle at peak knee extension, increases in peak combined angle and decreases in peak hip flexion angle during the final part of the swing phase.

Concomitant to a significant decrease in hamstring MVT, corresponding EMG activity of the BFlh and MH also declined, implying a reduced central neural drive to the hamstrings. Between pre- and post-SAFT90 hamstring MVT declined by 14%, which is smaller compared with the 24% decrease found by Marshall et al. (4), but comparable with findings of Greco et al. (30), who reported a decrease in peak isometric knee flexor torque of 18% after a football specific intermittent fatiguing protocol performed by professional players. Interestingly, the fatiguing effects of the SAFT90 were approximately 45% greater for the BFlh activity compared with MH activity during MVT trials, which is similar to what has been found by Marshall et al. (4) using the same fatiguing protocol. Rimmer et al. (31) found an average decrease of 11% in BFlh activity during late swing phase after fatigue from repeated sprints, whereas MH activity remained about the same, suggesting greater fatigue in the BFlh compared with the MH after repeated sprints. Although a different fatiguing protocol was used in the present study, our results are in line with this suggestion and may explain why BFlh is more often affected in HSIs than the MH (32).

No fatiguing effects of the SAFT90 on hamstring RTD were observed for the short TTI intervals (0–50 ms and 0–100 ms), as opposed to previous findings concerning hamstring RTD measurements during simulated football (4,30), as well as after actual football match-play (33,34). However, these studies assessed hamstring MVT and RTD within the same trials instructing the participants to generate force as fast and hard as possible. It is important to note that peak RTD values are found to be 20% to 46% higher when the instruction is given to contract "as fast as possible" instead of "as fast and hard as possible" (35). As a consequence, separating RTD and MVT measurements results in more reliable measures of the maximal capacity to rapidly generate torque (21). By focusing to contract "as fast as possible," the participants in the present study were able to maintain their capacity for explosive torque development during the short-lasting fast contractions, while this may not be the case when confronted with a double task. In the present study TTI150 tended to decrease throughout each SAFT half (confidence interval [CI], −0.32 to 0.00, $P = 0.049$), but these small decreases disappeared when the TTI150 was expressed as a percentage of MVT at that same moment (Effect time within SAFT half; $P = 0.575$, Effect SAFT half; $P = 0.926$). Thus, relative to MVT, the RTD measures did not change; there was no additional effect of fatigue on the capacity for explosive torque development.

Relatively large differences of fatigue-induced changes in sprinting kinematics were observed between participants, which is not surprising as different effects of fatigue on sprinting kinematics have been reported in the literature (7,28,31). In the present study however, on a group-level peak hip flexion (effect time within SAFT half CI, −1.8, to 0.0; $P = 0.045$, effect SAFT half CI, −3.2 to −1.1; $P < 0.001$) and knee angle at peak knee extension (effect time within SAFT half; CI, −1.8 to 0.6, $P = 0.333$, effect SAFT half; CI, −4.0 to −1.3, $P < 0.001$) significantly decreased throughout the SAFT90. Peak combined angle did not increase significantly, but the CIs were not symmetric around zero (effect time within SAFT half CI, −0.2 to 1.7; $P = 0.333$; effect SAFT half CI, −0.3 to 2.6; $P = 0.127$). These results match those observed by Small et al. (7) for the most part, although they reported a decline in peak combined angle. This could be explained by a smaller reduction of peak hip flexion angle in present study. Although peak hip flexion and peak combined angle do not necessarily occur at the same instance in time, these results suggest that in present study the increase in knee extension had a bigger contribution to the change in peak combined angle compared with the decrease in hip flexion.

The changes in sprint kinematics mentioned above were significantly correlated to decreases in hamstring MVT (Fig. 4),

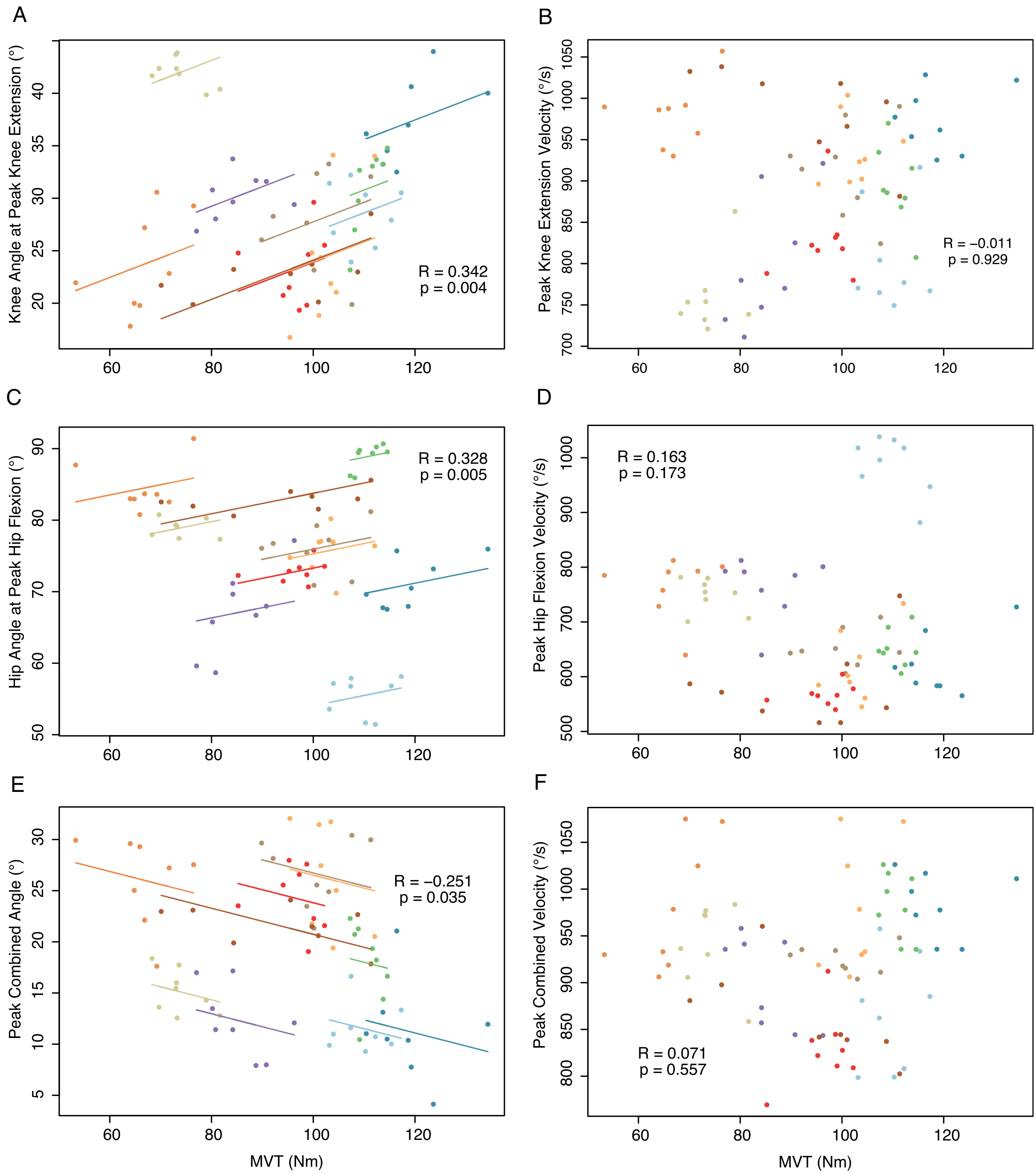

FIGURE 4—Repeated measurements correlation plots. (A) Hamstring MVT and knee angle at peak knee extension, (B) hamstring MVT and peak knee extension velocity, (C) hamstring MVT and hip angle at peak hip flexion, (D) hamstring MVT and peak hip flexion velocity, (E) hamstring MVT and peak combined angle, (E) hamstring MVT and peak combined velocity. Each color represents the data of an individual participant. The parallel lines indicate the common within participant association between variables when a significant association is found. The R-values presented are the correlation coefficients of the common within participant associations (i.e., the association that is shared among participants), and the *P* values denote their significance.

which provides further evidence that increases of peak knee extension and peak combined angle during sprinting may result from hamstring fatigue. Because an increase in peak combined angle theoretically shows an increase of peak hamstring length, it might be speculated that participants who show a relatively large fatigue-induced increase of peak combined angle during sprinting are subject to a higher HSI risk because their hamstrings operate closer to the mechanical limits. When such fatigue-related kinematic changes would approach a yet to be established threshold, these could potentially be used as an indication for player substitution or immediate training adaptation to keep HSI risk within acceptable limits.

On average, 20-m sprint times were increased by 7.5% after completion of the SAFT90, which is comparable to what other studies using similar fatiguing protocols have found in amateur and semi-professional players (7,29). For professional football players, however, decreases in sprint performance after a football match are generally smaller (~3%) (5,36), which suggests that the fatiguing effects of the SAFT90 may have been greater than what they would be during professional football matches. This difference could be explained by the SAFT90 protocol being based on professional level football while the present participants were amateur players of likely lower fitness level. Moreover, in the present study participants performed extra maximal sprints and hamstring tests before and after each 15-min SAFT90 segment, which may have led to additional fatigue. As a consequence, the effects of fatigue on MVT, sprint kinematics, and the associations between these variables may have been somewhat stronger in the current study than what they would be during an actual football match with better-trained players.

CONCLUSIONS

This study shows that hamstring MVT significantly decreases throughout a running-based football match simulation, without an additional decrease in the hamstrings capacity to explosively generate torque. Moreover, this is the first study to demonstrate that football-specific hamstring fatigue is associated with a decrease in knee angle at peak knee extension and an increase in peak combined angle during the late swing phase of sprint running. These fatigue-induced changes of sprint kinematics can be measured using a wearable inertial-based motion analysis system, which in the future may allow coaches and embedded scientists to quantify the fatigue response to training and competition.

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