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Effects of an intermittent exercise fatigue protocol on biomechanics of soccer kick performance

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The purpose of this study was to examine the effects of fatigue on biomechanical indices of soccer kick performance. Ten male amateur soccer players performed maximal instep kicks prior to, in the middle and after the implementation of a 90 min intermittent exercise protocol. Three-dimensional data, ground reaction forces (GRFs) and segmental moments were measured during the kick while blood lactate and ammonia concentrations were monitored throughout the protocol. Analysis of variance designs with repeated measures indicated a significant increase in ammonia ($P < 0.01$) and lactate levels ($P < 0.01$) following fatigue. The GRFs and joint displacement curves during the kick remained unaltered after fatigue ($P > 0.01$). However, post-fatigue maximum angular velocity of the shank, the net moments acting on the shank and the resultant joint moments were significantly lower compared with the corresponding pre-exercise values ($P < 0.01$). The velocity of the ball was 24.69 m/s prior to the protocol and significantly decreased to 21.78 m/s after ($P < 0.01$). Similarly, the ball/foot speed ratio significantly ($P < 0.01$) declined from 1.40 ± 0.12 (pre-fatigue) to 1.33 ± 0.18 (post-fatigue). The present results suggest that an exercise protocol that simulates soccer game conditions results in significant impairment of soccer kick performance. This could be attributed to alterations of the function of the neuromuscular system and force generation capacity, which may have altered the mechanics of soccer kick performance.

Fatigue is indicated by a reduction of maximal force or power that is associated with sustained exercise and is reflected in a decline in performance (Rahnama et al., 2003). Numerous studies have examined the effects of various fatigue protocols on components of physical performance, such as muscle strength and power (for reviews, see Byrne et al., 2004; Millet & Lepers, 2004), but fewer have examined fatigue effects on performance of multisegment movements frequently used in sports (Nicol et al., 1991; Bruggemann, 1996; Forestier & Nougier, 1998; Rodacki et al., 2001; Madigan & Pidcoe, 2003). These studies vary, depending on the type of protocol used and the activity examined.

Some studies found significant effects of local muscle fatigue protocols on the performance of multisegment tasks such as handball throwing (Forestier & Nougier, 1998) and vertical jumping (Rodacki et al., 2001). Other studies applied sport-specific exercise protocols such as long-distance running (Nicol et al., 1991; Bruggemann, 1996), repetitive landings (Madigan & Pidcoe, 2003) or lifting (Sparto et al., 1997) and reported a significant decline in leg power, maximum isometric force and activity of the quadriceps (Nicol et al., 1991) as well as alterations in ground reaction force (GRF) and joint kinematics of running (Williams et al., 1991; Bruggemann, 1996; Mizrahi et al., 2000), landing (Madigan & Pidcoe, 2003) and lifting (Sparto et al., 1997). Although the above studies demonstrated significant effects of fatigue on biomechanics of multisegment tasks, they are specific to the protocol or the task examined.

Striking movements are common in many sports (soccer, tennis, veolleyball, etc.) and in everyday life. Kicking represents an example of such motion. Soccer kick is the result of coordinated segmental actions aiming to produce the highest possible ball velocity to a certain target (goal). Numerous studies have examined the biomechanics of kicking, mostly under non-fatigued conditions (for a review, see Lees & Nolan, 1998). To our knowledge, only one study (Lees & Davies, 1988) examined the effects of fatigue on soccer kick performance and reported a lower maximum velocity of the foot and the ball following a 6 min step exercise protocol. The authors suggested that fatigue caused a lack of coordination between the upper and lower leg (Lees & Davies, 1988). However, the exercise protocol used differs compared with the intermittent exercise protocols frequently applied in soccer (Reilly & Thomas, 1976; Rahnama et al., 2003) and full kinematic data were not presented. The examination of exercise protocols that closely simulate actual soccer conditions may provide additional useful information for the design of effective training programs.

Several authors have investigated the acute effects of prolonged intermittent exercise with bursts of acceleration, sprinting, reversals of direction and deceleration on physical conditioning variables (Bangsbo et al., 1993; Gleeson et al., 1998; McGregor et al., 1999; Drust et al., 2000). Using such protocols, some research studies have found increased electromechanical delay and knee joint laxity after fatigue (Gleeson et al., 1998), a significant decline of maximum isokinetic moment of force of both knee extensors and flexors (Gleeson et al., 1998; Rahnama et al., 2003) and an increase in time required by soccer players to dribble a ball between a line of six cones as fast as possible (McGregor et al., 1999). However, the changes in soccer kick performance following intermittent exercise protocols are unclear.

To summarize, although impairments in muscle strength and power following fatigue are well documented (Gleeson et al., 1998; Rahnama et al., 2003; Byrne et al., 2004), the importance of these changes for performance of tasks, such as kicking, is not clear. If the occurrence of fatigue in a sport such as soccer has a practical meaning and importance, then a change in kicking technique and output should be expected. Studies applying fatigue protocols reported a re-organization of the segmental movement pattern during multisegmental movements (Forestier & Nougier, 1998; Madigan & Pidcoe, 2003) and alterations in biomechanics of sport performance (Lees & Davies, 1988; Williams et al., 1991; Bruggemann, 1996; Mizrahi et al., 2000). As such, the examination of changes in the performance of multisegmental tasks following fatigue is worthwhile (Byrne et al., 2004). The purpose of this study was to examine the effects of fatigue on the biomechanical characteristics of instep soccer kick. The main hypothesis tested was that the exercise protocol would have an effect on the biomechanical indices of soccer kick performance.

Methods

Subjects

Ten experienced male amateur soccer players volunteered to participate in this study. Their age was (mean ± SD) 22.6 ± 2.0 years, their body mass was 70.2 ± 8.1 kg and their height was 177.7 ± 5.6 cm. Each had a minimum of 6 years of soccer playing experience (8.7 ± 5.2 years). All players were right footed; they gave their informed written consent and had no injury. The University Ethical Committee approved the protocol.

Study design

The subjects performed a 90 min intermittent exercise protocol, divided into two 45 min periods separated by a 15 m interval (Fig. 1). Sprint times and heat rate (HR) values were monitored throughout the protocol. Soccer instep kicks were performed before, immediately after the first and second periods of the protocol while video, GRF and blood samples were taken.

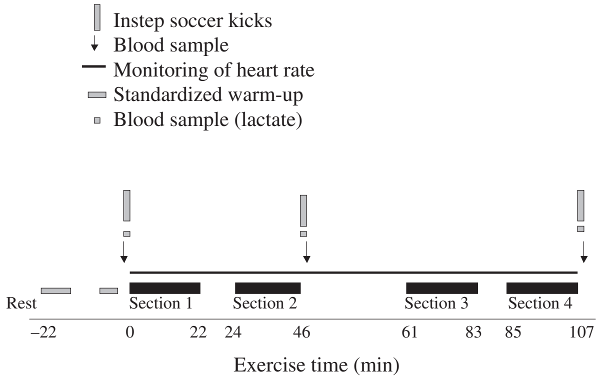

Fig. 1. Schematic diagram illustrating the exercise protocol applied in the present study.

Preliminary tests and familiarization

Two weeks before the main experimental session, maximal HR (HR_{max}) was determined for all subjects on a cycle ergometry (Monark 824E, Monark Exercise AB, Vansbro, Sweden, class A, din 32932). Each person, who was wearing a sport tester (Polar Sport tester, Polar Electro Oy, Kempele, Finland), initially cycled for 4 min at 150 W at a frequency of 50 r.p.m. Consecutively, the intensity was increased every minute 50 W until the subjects achieved their HR_{max} and could not cycle any more. Following the determination of HR_{max}, the HR corresponding to 60% and 90% of HR_{max} were calculated. Each subject also performed one section of the exercise protocol in order to familiarize with the testing procedure.

Exercise protocol

The acute endurance protocol selected to be used in the present study has been previously applied to simulate soccer field conditions (Gleeson et al., 1998) and is based on previously validated intermittent exercise protocols in soccer (McGregor et al., 1999; Nicholas et al., 2000).

The experiment was conducted on a 20 m non-slip turf outdoor corridor, which was identified by cones and floor markers. The players required to complete a total distance of 9600 m separated into four sections of 12 × 200 m. Each 200 m comprised of 60 m walking, 15 m sprinting (5 m deceleration and 5 m recovery walk), 60 m jogging and 60 m running (Gleeson et al., 1998) (Table 1). Prior to the main exercise, the subjects performed a standardized warm-up consisting of 5 min cycle ergometry at a load of 100 W, 5 min static stretching and 5 min jogging and sprinting.

Sprint times were recorded in one movement direction using two infrared photo-electric cells situated 15-m apart and interfaced to a timing system (Saint Wien Digital Timer Press H5K, Lu-Chou City, Taipei Hsien, Taiwan), with a time resolution of 0.01 s and a measurement error of ± 0.01 s. Sprint times were used to monitor subject performance during the protocol. HR of all players was measured during the entire protocol and recorded every 15 s, using short-range radio telemetry (Polar Sport tester, Polar Electro Oy). All experimental tests were conducted at ambient temperature that ranged between 15 °C and 22 °C.

Table 1. Activities during a single 200 m cycle

Pace	Distance (m)	Intensity
Walking	3 × 20	1.54 m/s
Maximum sprint	1 × 15	Maximum speed
Recovery walk	~ 5	4 s duration
Jogging	3 × 20	50–60% HR_{max}
Running	3 × 20	80–90% HR_{max}

HR_{max}, maximal heart rate determined using a cycle ergometer.

The subjects performed instep kicks prior to, at the end of the second and the fourth sections of the testing protocol. Particularly, the subjects performed three instep kicks using a two-step approach, as powerful as they could, toward a goal area (height 2.5 m; length 7.5 m) located 11 m from the ball. The three kicks were performed with an interval of 30 s between them. From the three trials, the effort where the highest ball velocity was observed was selected for further analysis.

Venous blood samples were taken prior, in the middle and immediately after the exercise protocol for the measurement of blood plasma ammonia levels (RIA method, Cobas Integra, Roche Diagnostics kits, Mannheim, Germany) (VanAnken & Schiphorst, 1974). The sensitivity of the method was 8.2 μmol/L. The coefficient of variation (CV%) was 2.2% in intra-assay and 3.6% in inter-assay. Moreover, blood samples from a finger prick were obtained at the same time periods mentioned above of the exercise protocol. Samples were immediately analyzed for blood lactate concentration by means of a lactate analyzer (Accusport, Boehringer Mannhelm, Germany).

Soccer kick analysis

The kicking motion was recorded using two JVC digital video cameras (DVL 9800u, JVC Video Manufacturing Europe GmbH, Berlin, Germany) at a rate of 120 Hz. Previous studies have used sampling rates ranging from 120 to 1000 Hz to investigate general kinematic patterns (Levanon & Dapena, 1998; Dorge et al., 1999; Barfield et al., 2002; Dorge et al., 2002; Nunome et al., 2002), especially when impact kinematics are examined (Tsaousidis & Zatsiorsky, 1996). The rate of 120 Hz indicates that images were recorded every 0.0083 s. This rate is appropriate to describe general kinematic patterns during the kick with relatively fewer frames recorded upon impact. The reader should be aware of this limitation when interpreting the present data.

The cameras were placed on tripods at a height of 1.5 m. The optical axis between the cameras was 90°. One camera was (approximately) 6 m behind and 8 m to the right of the ball while the other was 8 m in front and 9 m to the right. A calibration cube (1.80 × 1.80 × 1.80 m) with eight points was used to calibrate the space in which subjects performed the kicks. For the synchronization of the two cameras, three light-emitted diodes (LEDs) visible to both cameras was used. The first LED was switched on by an external trigger that fed a signal-to–an analog/digital board. The second was triggered upon foot contact with the plate. A switch was placed underneath the ball that, upon ball impact, triggered the LED and fed a synchronization signal to the analog-to-digital board. Because of the absence of mechanical genlock of the cameras, synchronization was performed by finding the time offset in the three events and then matching the image coordinates using cubic spline interpolation. A similar procedure has been applied to synchronize the kinematic with the GRF data.

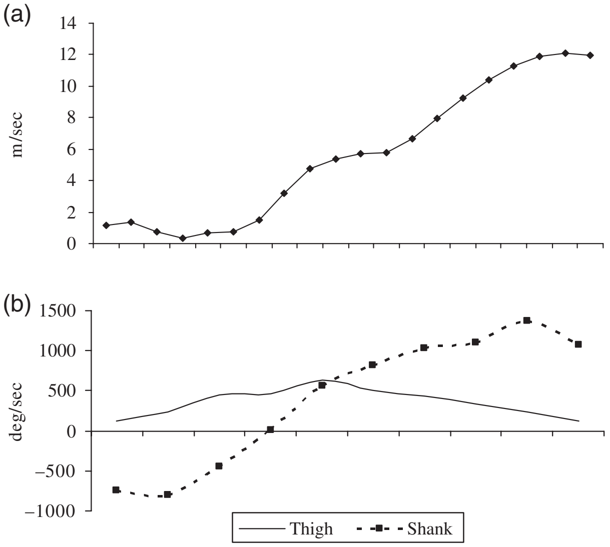

Fig. 2. Typical graphs from one subject (a), linear velocity of the foot (b), angular velocity of the thigh and shank during the soccer kick. Data are extracted from the time the swinging foot has started its backward motion until ball impact.

Reflection markers were placed on selected anatomical locations on the right and the left side of the body: on the fifth metatarsal, the heel, the lateral malleolus, the femoral epicondyle, the greater trochanter and the shoulders. Two additional markers were placed on the surface of the ball in diametrically opposite ends. The coordinates of the mean point between the two markers were then used as representative of ball position. The direct linear transformation method (DLT) was used to compute the three-dimensional coordinates of the markers using a video-based software (Kwon 3-D, Visol Inc., Seoul, Korea). The resulting displacement–time data of each marker were smoothed from the start of the movement until impact using a fourth-order (low-pass) Butterworth digital filter with zero phase lag (Winter, 1990; Dorge et al., 2002). To avoid any joint data distortion because of impact, a special procedure was followed. Particularly, ball impact point was specified within each data set. The curves were then smoothed in order to obtain a more close fit of the raw data curves over a specified small interval (around impact) of the sequence. Adjustment of the curves was achieved by permitting higher frequency variations in raw values. This resulted in smoothed curves that more closely fit the change in the raw data curves because of ball impact.

The three-dimensional coordinates were expressed in a global right-handed orthogonal reference frame whose origin was placed at ground level, with the Y-axis pointing toward the direction of the ball, the Z-axis vertically upward and the X-axis perpendicular to X and Y. The three-dimensional knee extension–flexion, hip extension–flexion and ankle plantarflexion–dorsiflexion angles were then estimated and used for analysis. For reference, 180° indicated full knee extension and normal standing position, respectively. The ankle in a neutral position was equal to 90° (angles $<90°$ indicated dorsiflexion and angles $>90°$ indicated plantarflexion). Joint and segmental angular and linear velocities were estimated based on the smoothed angular position data using numerical differentiation (Fig. 2).

The absolute magnitude of V_{ball} was calculated from the values of its vertical and horizontal components (Levanon &

Dapena, 1998). Particularly, the horizontal component of the ball velocity was calculated as the first derivative of linear regression lines fitted to their non-filtered displacements. The vertical component was calculated as the first derivative of a quadratic regression line with its second derivative set equal to $-9.81\,\mathrm{m/s^2}$ fitted to its non-filtered displacement in the available frames.

Furthermore, previous studies have also suggested that the ratio of V_{ball} to foot velocity is a good indicator of kicking success (Lees & Nolan, 1998; Levanon & Dapena, 1998). Consequently, the velocity of the center of mass of the foot (V_{foot}) was measured from the marker's coordinate data. The center of mass location of the foot was defined by the toe and heel markers (Nunome et al., 2002). Subsequently, the velocity of V_{foot} at impact was also recorded and was used to calculate the $V_{\mathrm{ball}}/V_{\mathrm{foot}}$ ratio.

GRFs of the support foot were recorded at a sampling rate of 1000 Hz using a Kistler piezoelectric dynamometer (Type 9281C, Kistler Instruments AG, Winterthur, Switzerland). The dynamometer was interfaced through Kistler amplifying units (Type 233A) to an Ariel Performance system (Ariel Dynamics Inc., San Diego, California, USA).

A standard 14-segment anthropometric model (Dempster, 1955) was used to model the body segments and to estimate segmental centers of mass (CM). Kinematic and anthropometric data were then used to estimate the moments acting on the shank using the equations developed by Putnam (Putnam, 1991). These equations have been extensively used in the past to calculate joint moments during fast unloaded movements and take into consideration the inter-segmental motion-dependent effects and the gravity of each segment (Dorge et al., 1999, 2002; Enoka, 2002). The equation describing the net moment (N_{m}) acting on the shank was the sum of the moments because of resultant muscle forces around the knee (M_{m}), the linear acceleration (M_{AT}) and angular velocity (M_{VT}) of the thigh, the vertical (M_{VH}) and horizontal (M_{HH}) acceleration of the hip and gravitational acceleration of the shank (M_{G}) (Putnam, 1991; Enoka, 2002).

Data analysis

The mean sprint times and HR values during sections 1–4 of the exercise protocol were estimated and used to illustrate the intensity level throughout the protocol.

To examine the general movement patterns in each condition, the joint angular displacement patterns were estimated. To achieve this, three time events were used: the start of the movement, ground contact and ball impact. The start of the movement was defined as the start of the second step of the kick (frame where the swinging foot landed on the surface and support foot started its forward motion beside the ball).

The time period from the beginning of data recording to ground contact (for convention, it will be referred to as the "pre-support phase") was set as 100%. Similarly, the time period from ground contact to ball impact (defined as "support phase") was set as 100%. Therefore, joint angular displacement, N_{m} and M_{m} data were averaged for every 10% of each phase.

In addition to time-series calculation, the following parameters were analyzed:

1. linear and angular velocities at impact,
2. maximal angular velocity of the thigh, shank and knee,
3. maximum GRFs,
4. average values of each moment acting on the shank (N_{m}, M_{m}, M_{AT}, M_{VT}, M_{VH}, M_{HH}, M_{G}) for each (pre-support and support) phase.

Statistical analysis

One-way analysis of variance (ANOVA) with repeated measures was applied to examine the differences in HR and sprint time values between the four sections of the protocol.

A two-way ANOVA with repeated measures was applied to examine the differences in the duration of the pre-support and the support phase between the three testing sessions. Two-way ANOVAs with repeated measures (3×10) were used to examine the differences between the three measurement sessions (pre, middle, post) in each variable over 10 data points of the pre-support phase. Separate designs were applied for support phase data. Significant interactions were followed by applying simple effects and, if significant, post-hoc Tukey tests were applied to examine significant differences between pairs of means.

One-way ANOVA tests were applied to examine the differences in maximum and average values, the $V_{\mathrm{ball}}/V_{\mathrm{foot}}$ ratio and the values at impact of each variable between the three measurements. The level of significance was set at $\alpha = 0.05$. However, because of the performance of multiple statistical tests, the α level was adjusted to $\alpha = 0.01$ using the Bonferroni technique. This reduced the possibility of making a Type I error.

Results

Indices of fatigue during the protocol

The ANOVA results indicated a significant difference in sprint times across sections 1–4 ($P < 0.01$; Fig. 3). Post-hoc Tukey's tests indicated that sprint times at sections 3 and 4 were significantly ($P < 0.01$) higher compared with the sprint time during section 1 (Fig. 3). The $\mathrm{HR_{max}}$ (determined on the cycle ergometer) was 186.8 ± 8.33 beats/min. The ANOVA indicated

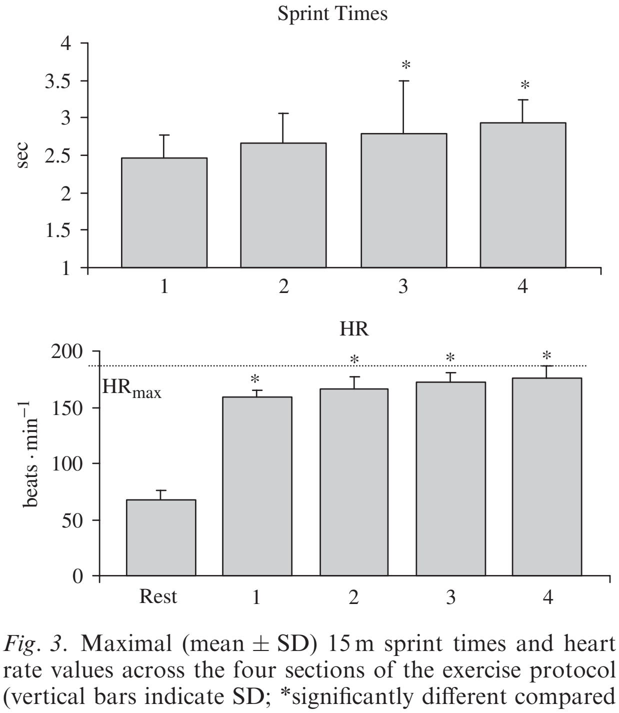

Fig. 3. Maximal (mean ± SD) 15 m sprint times and heart rate values across the four sections of the exercise protocol (vertical bars indicate SD; *significantly different compared with the pre-exercise value; the horizontal dotted line indicates the maximal heart rate ($\mathrm{HR_{max}}$)).

a significant difference ($P<0.01$) between HR values (Fig. 3). Post-hoc Tukey's tests indicated that HR values during all sections were significantly higher compared with HR values at rest ($P<0.01$).

NH_3 concentrations were $124.16 \pm 11.35\,\mu mol/L$ before, $140.09 \pm 11.17\,\mu mol/L$ in the middle and $148.70 \pm 10.12\,\mu mol/L$ after the implementation of the exercise protocol. Lactate concentrations were 1.44 ± 0.49 mmol/L before, 5.27 ± 0.93 mmol/L in the middle and 6.24 ± 1.20 mmol/L after the protocol. The repeated measures ANOVA showed a significant fatigue effect on NH_3 ($P<0.01$) and lactate levels ($P<0.01$). Post-hoc Tukey's tests indicated that the post-fatigue NH_3 value was significantly higher compared with the pre-fatigue value ($P<0.01$). Lactate values recorded in the middle and after the protocol were also significantly higher ($P<0.01$) compared with the pre-fatigue values.

Temporal parameters of the kick and GRFs

The duration of the pre-support phase was 389.00 ± 114.14, 358.41 ± 122.11 and 361.42 ± 79.16 ms during the pre-, middle and post-fatigue kicks, respectively. The duration of the support phase was 166.80 ± 19.24, 151.70 ± 16.90 and 156.70 ± 16.24 ms, respectively. The ANOVA indicated a non-significant effect of the exercise protocol on the duration of each phase and maximum GRFs (Table 2).

V_{foot} and V_{ball}

The ANOVA indicated a significant main effect of fatigue on V_{ball} and V_{foot} (Fig. 4, $P<0.01$). Post-hoc Tukey's tests indicated that V_{ball} during and after the protocol were significantly lower compared with the pre-fatigue value ($P<0.01$). Further, the post-fatigue V_{foot} was significantly lower compared with the corresponding pre-fatigue value (Fig. 4, $P<0.01$).

The V_{ball}/V_{foot} ratio was significantly different between the three testing sessions (Table 2). Post-Hoc analysis indicated that the pre-fatigue V_{ball}/V_{foot} ratio was significantly higher compared with values recorded in the middle and after the protocol (Table 3, $P<0.01$).

Angular kinematics

The ANOVA indicated nonsignificant effects of fatigue on maximal angular velocity values of the thigh (Fig. 4, $P>0.01$). In contrast, the maximum angular velocity of the shank (Fig. 4) significantly decreased in the middle and after the fatigue protocol ($P<0.01$).

There was a nonsignificant effect of fatigue on joint angular displacement phase curves of the swinging (Fig. 5) and support (Fig. 6) legs ($P>0.01$). Further, there were no significant main effects of the exercise protocol on angular displacement and velocity values of the swinging leg joints at ball impact (Table 3, $P>0.01$). The only exception was the angular position of the ankle, which was significantly different in the pre-fatigue condition compared with the value recorded in the middle and after the protocol (Table 3, $P<0.01$).

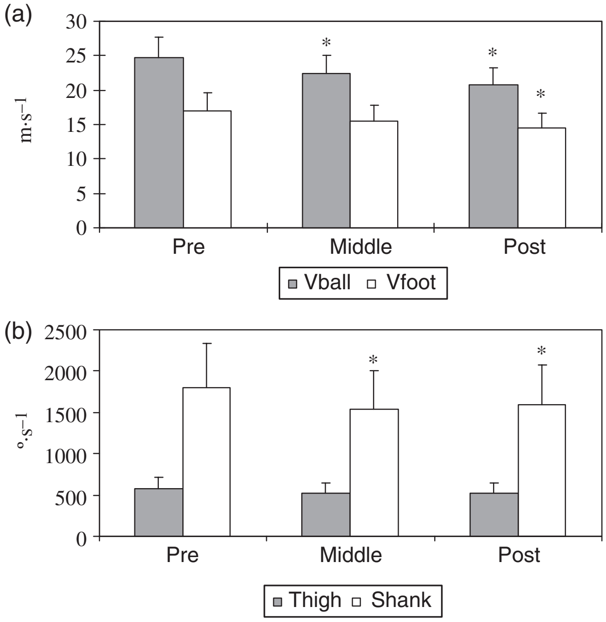

Fig. 4. (a) Maximal velocity of the ball (V_{ball}) and foot center of mass (V_{foot}) before (pre), in the middle (middle) and after (post) fatigue. (b) Maximal angular velocity of the thigh and shank before (pre), in the middle (middle) and after (post) fatigue (vertical bars indicate SD; *significantly different compared with the pre-fatigue value).

Table 2. Maximal ground reaction forces (GRFs) (mean ± SD) before (pre), in the middle and after (post) the exercise protocol

	Testing session		
	Pre	Middle	Post
Vertical GRF (N)	1707.83 ± 502.03	1818.10 ± 377.67	1693.43 ± 348.35
Horizontal GRF (N)	322.65 ± 147.01	329.26 ± 120.73	342.82 ± 149.32
Lateral GRF (N)	768.37 ± 218.25	811.72 ± 358.13	738.10 ± 280.09

Table 3. Angular position and velocity values and ball to foot center of mass speed ratio ($V_{\mathrm{ball}}/V_{\mathrm{foot}}$ ratio) (mean ± SD) of the swinging leg at impact before (pre), in the middle and after (post) the exercise protocol

	Testing session		
	Pre	Middle	Post
Angle (deg.)			
Hip	190.53 ± 16.71	192.04 ± 14.71	198.59 ± 14.34
Knee	130.30 ± 13.73	135.21 ± 15.46	133.22 ± 17.91
Ankle	144.38 ± 12.93	131.66 ± 15.85*	129.26 ± 12.99*
Angular velocity (°/s)			
Hip	125.89 ± 52.32	120.30 ± 53.84	151.40 ± 54.54
Knee	1229.90 ± 334.82	1100.29 ± 298.34	1040.32 ± 318.51
Ankle	650.89 ± 281.71	614.47 ± 259.65	592.39 ± 281.58
$V_{\mathrm{Ball}}/V_{\mathrm{foot}}$ ratio	1.40 ± 0.12	1.36 ± 0.16	1.33 ± 0.18*

*Significantly different compared with the pre-exercise value.

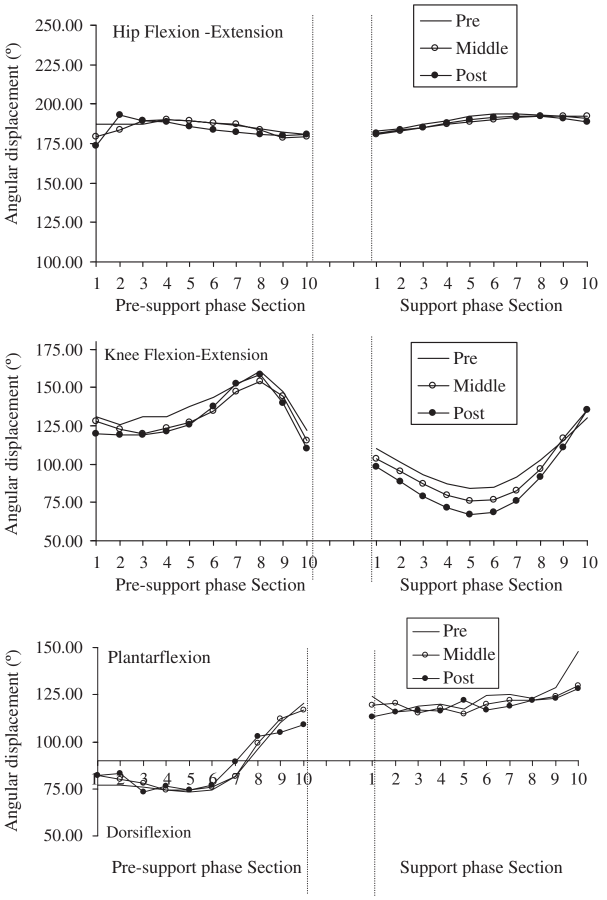

Fig. 5. Average joint angular displacement ($N = 10$) of the swinging leg during the kick before (pre), in the middle (middle) and after (post) fatigue. Diagrams on the left indicate values expressed for every 10% from the start of the movement until ground contact. Diagrams on the right indicate values expressed for every 10% from ground contact until ball impact (1: 1–10%; 2: 11–20%; 3: 21–30%; 4: 31–40%; 5: 41–50%; 6: 51–60%; 7: 61–70%; 8: 71–80%; 9: 81–90%; 10: 91–100% of each phase).

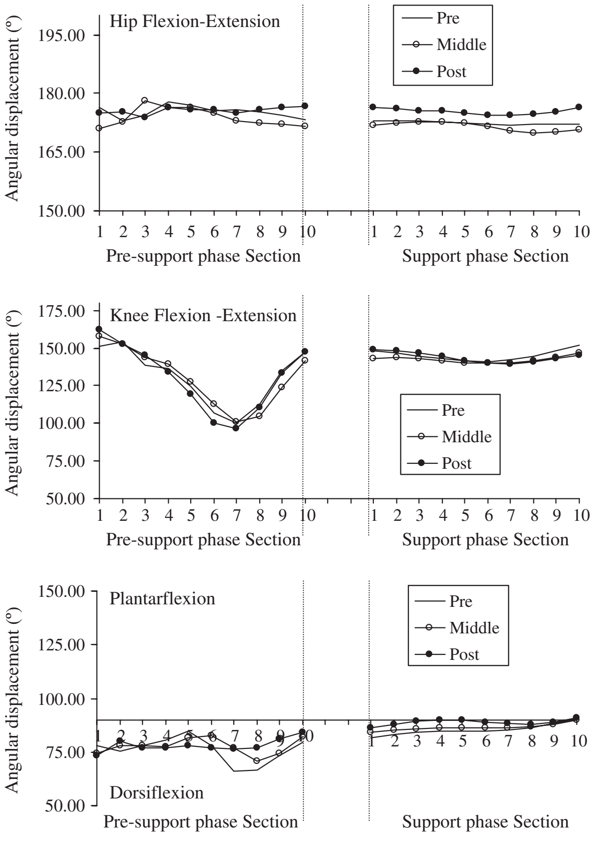

Fig. 6. Average joint angular displacement ($N = 10$) of the support leg during the kick before (pre), in the middle (middle) and after (post) fatigue. Diagrams on the left indicate values expressed for every 10% from the start of the movement until ground contact. Diagrams on the right indicate values expressed for every 10% from ground contact until ball impact (1: 1–10%; 2: 11–20%; 3: 21–30%; 4: 31–40%; 5: 41–50%; 6: 51–60%; 7: 61–70%; 8: 71–80%; 9: 81–90%; 10: 91–100% of each phase).

Kinetics

There was a significant main interaction effect of fatigue on N_{m} and M_{m} curves (Fig. 7) ($P > 0.01$).

Post-hoc analysis indicated that the post-fatigue moments during 90–100% of the pre-support phase and 0–20% and 50–80% of the support phase were significantly higher compared with the pre-fatigue values ($P > 0.01$).

The average moments acting on the shank are presented in Table 4. The average moments during the pre-support phase were not significantly affected by fatigue ($P > 0.01$). During the support phase, however, both M_m and N_m during the post-exercise kick were significantly lower compared with the pre-fatigue value ($P < 0.01$).

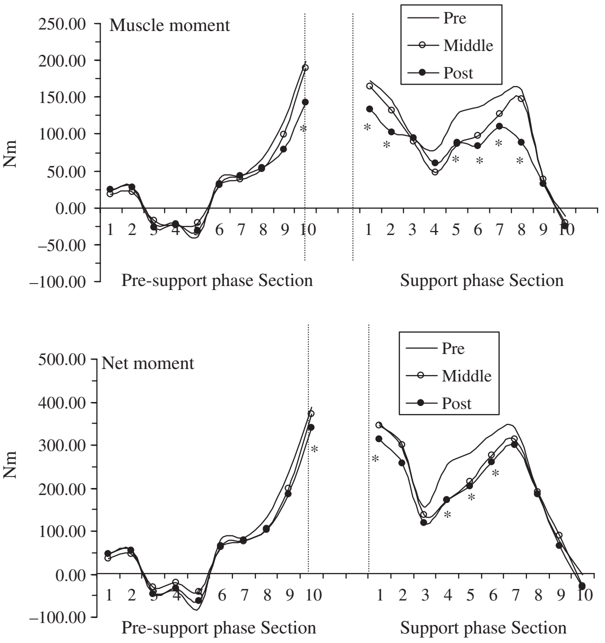

Fig. 7. Average ($N = 10$) net and resultant muscle moment during the kick before (pre), in the middle (middle) and after (post) fatigue. Diagrams on the left indicate values expressed for every 10% from the start of the movement until ground contact. Diagrams on the right indicate values expressed for every 10% from ground contact until ball impact (1: 1–10%; 2: 11–20%; 3: 21–30%; 4: 31–40%; 5: 41–50%; 6: 51–60%; 7: 61–70%; 8: 71–80%; 9: 81–90%; 10: 91–100% of each phase).

Discussion

The main findings of this study are that V_{ball} significantly decreased following the intermittent exercise protocol. This was accompanied by a decline of V_{foot}, the maximum angular velocity of the shank. As a result, the V_{ball}/V_{foot} ratio significantly declined following fatigue. Kinetic analysis also showed that N_m and M_m declined following fatigue. On the basis of these results, the main research hypothesis of this study is supported.

The present study applied an exercise protocol, which has been previously validated and used to simulate soccer field conditions (Gleeson et al., 1998). The distance covered with the present protocol (9600 m) corresponds to the approximated covered distance of soccer players during a game (Ohashi et al., 1988; Van Gool et al., 1988). Furthermore, the HR values observed in the present study (Fig. 3) are similar to those reported during a soccer game (Van Gool et al., 1988). Similarly, blood lactate concentrations are comparable with those reported for competitive soccer games (Gerisch et al., 1988) in which the values in the first half (sections 1 and 2) are higher compared with the second half values (sections 3 and 4). The above responses are similar to those reported by Gleeson et al. (1998), who applied the exact same exercise protocol.

In addition, we also found that NH_3 significantly increased at the end of the exercise protocol. Reduced muscular contractility and increased muscular fatigue have been correlated with the accumulation

Table 4. Mean (± SD) average joint, muscular and interactive moments for each phase before (pre), in the middle and after (post) the exercise protocol

	Testing session		
	Pre	Middle	Post
Pre-support phase			
N_m	105.04 ± 37.35	98.45 ± 20.45	79.40 ± 20.47
M_m	44.32 ± 9.01	56.85 ± 17.25	39.92 ± 10.08
M_{AT}	2.50 ± 1.27	2.19 ± 1.27	2.24 ± 1.03
M_{VT}	55.33 ± 6.31	58.28 ± 7.19	54.39 ± 7.84
$M_{VH}+M_{HH}$	− 0.14 ± 0.05	− 0.10 ± 0.09	− 0.20 ± 0.09
M_G	2.44 ± 0.37	2.50 ± 0.51	2.86 ± 1.33
Support phase			
N_m	231.89 ± 81.30	201.89 ± 78.61	184.54 ± 92.79*
M_m	114.91 ± 48.17	109.41 ± 49.80	78.73 ± 46.40*
M_{AT}	− 15.48 ± 8.99	− 20.52 ± 10.21	− 19.52 ± 0.33
M_{VT}	113.83 ± 15.93	109.82 ± 13.88	111.27 ± 15.14
$M_{VH}+M_{HH}$	− 0.05 ± 0.01	− 0.02 ± 0.004	− 0.07 ± 0.03
M_G	28.28 ± 4.62	25.45 ± 4.80	27.88 ± 4.05

N_m, net moment; M_m, moment because of muscle force; M_{AT}, moment because of linear acceleration of the thigh; M_{VT}, moment because of angular velocity of the thigh; $M_{VH}+M_{HH}$, sum of the moments because of vertical and horizontal acceleration of the hip; M_G, moment because of shank gravitational acceleration.

*Significantly different compared with the pre-exercise value.

of certain metabolic by-products of exercise among which is NH_3 (Lambert et al., 1993). NH_3 has been proposed to contribute to muscular fatigue (Sahlin & Broberg, 1990). The concentration of NH_3 in blood was elevated during a soccer game, indicating that the metabolic demands are very high during periods of a game (Bangsbo, 1997). Our findings are in line with those reported by Bangsbo (1997), demonstrating that our simulated game protocol was of high enough intensity to produce substantial muscle fatigue similar to the actual game. This was of critical importance in the present study in order to test the main hypothesis, as possible fatigue-induced alterations of small magnitude, in the biomechanics of the kick, might have been masked otherwise, because of the good physical condition of our subjects.

Mechanisms of soccer kick performance

V_{ball} values are similar to those reported in the literature (Levanon & Dapena, 1998; Lees & Nolan, 2002). The decline in V_{ball} following fatigue (Fig. 4) is an important finding because V_{ball} has been extensively identified as an indicator of a successful kick (Lees & Nolan, 1998; Levanon & Dapena, 1998). These results are in agreement with previous data (Lees & Davies, 1988) and provide further experimental evidence that fatigue has an effect on soccer kick performance.

V_{ball} is affected by several factors, the most important being various elements of technique (kinematic changes) (Lees & Nolan, 1998), muscle strength and power of the players (Cabri et al., 1988), approach speed, skill level, maturity (Lees & Nolan, 1998) and the mechanical characteristics of the foot and ball upon impact (Tsaousidis & Zatsiorsky, 1996). Therefore, any explanation of the changes in V_{ball} observed in the present study should consider alterations in the above factors.

The present results indicate that the exercise protocol had no effect on displacement patterns of the swinging (Fig. 5) and support leg (Fig. 6). This confirms previous studies (Rodacki et al., 2001, 2002), indicating that fatigue does not alter the main kinematic pattern of a multisegmental activity. Furthermore, the GRF values (Table 2) are similar to those reported in the literature (Lees & Nolan, 1998) and were not influenced by fatigue (Table 2). It appears, therefore, that the position of the support foot on the ground as well as the reaction forces exerted did not significantly change during fatigue. This could be partly attributed to the insignificant change of support leg kinematics after the protocol (Fig. 6). The absence of alterations in horizontal and lateral GRFs because of fatigue indicates that the stability of the soccer kick was not affected by fatigue.

One of the main mechanisms that enhances soccer kick performance is the action of the thigh, which initially slows down or reverses its motion prior to full knee extension is reached (Lees & Nolan, 1998). Thigh deceleration is mainly determined by movement of the shank (Sorensen et al., 1996), whereas shank acceleration is caused by a moment exerted around the knee as well as a motion-dependent moment arising from the thigh angular velocity (Sorensen et al., 1996). In the present study, the thigh angular velocity remained unaltered during and after the exercise protocol (Fig. 4). In contrast, shank angular velocity demonstrated a significant decline after fatigue (Fig. 4). These results partly disagree with the findings of Lees and Davies (1988), who found a higher angular velocity of the upper leg when fatigued whereas speed values of the lower leg remained unchanged. However, in the study by Lees and Davies (1988), the subjects performed a 6 min step test on a 0.5 m box at a rate of 30° steps/min which is different compared with the present intermittent exercise protocol and thus makes comparisons with our results difficult. Despite this, both studies demonstrate an alteration in the proximal-to-distal pattern of segmental motion during the kick, which may be indicative of an altered transfer of energy from the proximal (thigh) to the distal (shank) segment in the fatigued condition.

The angular velocity of the shank is mainly the result of the forces acting on the shank during the movement. Therefore, examination of N_{m} values during the movement is particularly useful. In the present study, N_{m} demonstrated two peak values during the kick (Fig. 7). The first peak was observed just prior and immediately after the support foot landed on the force plate, which corresponds to the initiation of the forward motion of the leg and the extension phase (Fig. 7). N_{m} values increase again during 50–80% of the support phase (Fig. 7), which corresponds to the instant where the maximal shank velocity is observed (Fig. 2). The present results demonstrated that during the above (maximal) periods, N_{m} significantly declined after the exercise protocol. This provides an explanation for the decline of maximum shank angular velocity following fatigue.

Although the decline of N_{m} after the protocol can explain the corresponding shank velocity decline, the factors responsible for this observation must be further analyzed. Our results indicate that N_{m} was primarily the result of two factors: M_{VT} and M_{m} (Table 4). Although M_{VT} remained relatively unchanged following fatigue (Table 4), M_{m} demonstrated a significant decline either as an average value (Table 4) or at specific phase intervals of the kick (Fig. 7). Given the relative maintenance of the other moments exerted on the shank (Table 4), a 20–22% decline of M_{m} in the post-fatigue condition may be linked to a corresponding decline of the shank angular velocity (Putnam, 1991). If the maximal angular velocity of the shank is affected by knee extension moment, then a lower contribution of knee extension muscle forces to M_m after the protocol may have taken place.

It has been suggested that the V_{ball}/V_{foot} ratio value provides an indication of kicking skill, with a higher value denoting a higher level of skill (Asami & Nolte, 1983). Based on the mechanics of collision between the foot and ball, Lees and Nolan (1998) suggested that the ball should travel 1.2 times the velocity of the foot. Levanon and Dapena (1998) reported a value of 1.33 for maximal instep kick, which is within the range of values found in the present study (Table 3). However, in the present study, the V_{ball}/V_{foot} ratio significantly decreased in the middle and after the exercise protocol (Table 3). As the decline of the V_{ball} was higher compared with the decline of V_{foot} (Fig. 4), it could be suggested that the mechanics of collision between the ball and foot might have been altered.

Several factors may affect the mechanics of football impact. Lees and Nolan (1998) reported that the effective striking mass of the foot and the firmness of the foot at impact influence V_{ball}. Based on the present kinematic results, it appears that in the kicks performed in the middle and after the intermittent exercise protocol, the ankle joint at impact was approximately 13° less plantar flexed compared with pre-fatigue kick (Table 4). Whether this indicates a higher foot deformation in the fatigued condition is not clear. Because of the small time duration of the ball-to-foot impact, further examination of ball-foot impact kinematics and kinetics under fatigued and non-fatigued conditions using high-speed movement analysis systems is necessary (Tsaousidis & Zatsiorsky, 1996).

Tsaousidis and Zatsiorsky (1996) examined the mechanics of football impact and suggested that V_{ball} is affected by two factors: First, the energy or momentum, which is a result of the coordinated movement and mechanical behavior of the foot before impact, and second, energy, which is because of the muscle work produced during the collision phase. In fact, Tsaousidis and Zatsiorsky (1996) estimated that more than 50% of the V_{ball} is imparted to the ball without any contribution of the potential energy of the ball deformation. This suggests that the momentum and energy produced prior to ball impact as well as the amount of muscle work upon impact determine the speed of the ball to a large extent. The above indicate that the decline of V_{ball} at the end of the present exercise protocol is partly because of an alteration in momentum generated prior to ball impact as well as a change in the muscle strength capacity of the players.

Fatigue effects

Previous studies have shown that blood lactate level and decreased muscle glycogen are usually connected to impaired neuromuscular performance (Ekblom, 1986). The negative impact of high levels of blood lactate on coordinative function was demonstrated in a study by Ekblom (1986), players were able to juggle the ball on average 64 times consecutively before a hard training bout, compared with three times immediately after the training bout. Similarly, Reilly and Thomas (1976) observed reduced sprinting ability in the second 45 min of the game, whereas McGregor et al. (1999) found a 5% increase in time required by soccer players to dribble a ball after a prolonged intermittent exercise protocol. The present results provide further evidence that metabolic changes during fatigue are accompanied by changes in soccer performance whereas, the higher NH_3 concentrations confirm previous suggestions (Banister & Cameron, 1990) that NH_3 elevated levels may be indicative of impairment in performance, mainly coordination and motor control.

The present results are in agreement with previous studies that applied running fatigue protocols and reported significant alterations in lower limb kinematics after fatigue (Nicol et al., 1991; Bruggemann, 1996). Alterations in performance were accompanied by a significant decline in muscle strength capacity and activation levels (Nicol et al., 1991; Bruggemann, 1996; Forestier & Nougier, 1998; Madigan & Pidcoe, 2003), which suggests that changes in technique after fatigue are partly because of alterations in the capacity of the muscles to produce force as well as changes in muscle coordination patterns. Using the same exercise protocol as in the present study, Gleeson et al. (1998) found a significant (5–20%) decline of maximal isokinetic knee extension and flexion moment of force after fatigue. This decline has been attributed to metabolic factors as well as a substantial eccentric mechanical stress loading induced by the 480 reversals in direction and concomitant arresting of momentum required during the protocol (Gleeson et al., 1998), which reduce performance time and alter lactate production during a subsequent short-term intense exercise bout (Ekblom, 1986; Bangsbo et al., 1993). Evidence would suggest that muscle strength and power impairment following intermittent exercise protocols are accompanied by excessive muscle damage (Gleeson et al., 1998; Byrne et al., 2004) with potential implications for performance (Byrne et al., 2004; Millet & Lepers, 2004). Alterations in reflex inhibition and muscle stiffness may also contribute to reduction in performance (Byrne et al., 2004; Millet & Lepers, 2004).

The above changes can partly explain the alterations in soccer kick variables found in the present study. Particularly, from an anatomical point of view, the knee extensors are the main muscles responsible for the extension of knee and the forward movement of the shank in the main acceleration phase of the kick. Dorge et al. (1999) found a higher electromyography (EMG) activity of the quadriceps muscle components at the period where peak M_m have been achieved. Others (Cabri et al., 1988) have shown that knee extension muscle strength and power of leg muscles are highly correlated with V_ball and soccer kick performance. Our results (Fig. 7) clearly verify the above findings, as M_m declined in the post-exercise condition. Consequently, it could be suggested that impairments in muscle force generation around the knee are partly responsible for the shank decline following fatigue.

As soccer kick is a multiarticular task, other factors may have also contributed to the present results. First, a possible decline of muscle force generation capacity of muscles around the hip and the ankle is also important (Madigan & Pidcoe, 2003). Currently, there are no published data on hip and ankle muscle strength alterations following intermittent exercise. If the force decline following fatigue differs between muscles, then a significant alteration of moments exerted around the joints might occur (Madigan & Pidcoe, 2003). This may also be accompanied by alterations in activity of the muscles after fatigue (Nicol et al., 1991; Bruggemann, 1996; Forestier & Nougier, 1998; Rodacki et al., 2001; Madigan & Pidcoe, 2003). Furthermore, the present study did not examine three-dimensional rotation movements because of limitations in the experimental setup. Examination of pelvic kinematics may provide additional information on the effects of fatigue on soccer kick biomechanics (Levanon & Dapena, 1998), especially when examining soccer kicks from an angled approach. Further research could examine fatigue effects on kicking performance utilizing EMG techniques.

The subjects in the present study were soccer players, who were not professionals, but trained for a minimum of 6 years, with a training frequency of more than three times plus a game match per week. This suggests that the present results are applicable only to subjects with the present characteristics. The same exercise protocol may have less effect on the biomechanics of soccer kick in professional players, whereas more alterations are expected in less-experienced players. Further study is needed to confirm this suggestion.

Perspectives

The present findings suggest that the impairment of soccer kick performance following the applied intermittent exercise protocol has functional implications for the physical preparation of soccer players. Particularly, the decline in ball speed and the previously reported decline in maximum leg strength capacity (Gleeson et al., 1998; Rahnama et al., 2003) indicate that the optimum adaptive response to strength training in soccer players may be impaired. This indicates that soccer training programs in the pre-season period should aim to enhance the ability of the player to sustain physiological stresses under fatigue conditions, in order to maintain soccer kick performance and strength throughout a 90 min soccer game. Therefore, the present results extend previous suggestions (Gleeson et al., 1998; Rahnama et al., 2003) that muscle strength and power decline following fatigue are closely linked not only to increased risk of musculoskeletal injuries but also a decline in soccer kick performance.

In terms of training, it has been suggested (Gleeson et al., 1998) that an increase of muscle strength following training does not decrease injury risk if the player is unable or reluctant to sustain correct technique in episodes of fatiguing play. As a consequence, the need for strength training in combination with training on technique in this period of the season is recommended. This provides further support to previous research studies that proposed the use of soccer-specific strength training programs (Taina et al., 1993) in the pre-season period.

In conclusion, the present study demonstrated that fatigue caused a significant decline of ball speed and angular velocity of the shank and the knee. This was accompanied by a significant decline of the net moment applied on the shank, mainly being a result of reduced strength exerted by the knee musculature at "critical" instant times during the kick. As these variables are important indicators of soccer kick success, it could be suggested that fatigue results in significant alteration of soccer kick biomechanics. These results may be useful for the design of more effective strength and technique training programs of soccer players.

Key words: endurance, soccer kicking, kinetics, ground reaction forces, kinematics, sport performance.

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