Influence of acute endurance activity on leg neuromuscular and musculoskeletal performance

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Purpose: The purpose of this study was to investigate the effect of endurance activities designed to simulate the physiological demands of soccer match-play and training, on leg strength, electromechanical delay, and knee laxity.

Methods: Eight recreational soccer players completed four exercise trials in random order: 1) a prolonged intermittent high intensity shuttle run (PHISR) which required subjects to complete a total distance of 9600 m in a form simulating the pattern of physical activity in soccer match-play (activity mode; rest-to-work intervals; approximately 90 min duration), 2) a shuttle-run (SR),(3) a treadmill run (TR) which required subjects to complete an equivalent distance at a running speed corresponding to 70% ·VO_{2max}, and 4) a control condition consisting of no exercise.

Results: Results from repeated measures ANOVA revealed significant condition (PHISR; SR; TR; control) by time (pre; mid; post) interactions for peak torque (PT: knee extension and flexion; 1.05 rad·s^{-1}), EMD and anterior tibio-femoral displacement (TFD) (P < 0.05). Impairment to indices of knee joint performance was observed in PHISR, SR, and TR trials. The greatest decrement occurred in PHISR and SR trials (up to 44%). Knee extensor and flexor strength performance near to full knee extension (0.44 rad knee flexion) was not changed following the functionally-relevant endurance activities.

Conclusions: Even though strength performance near to full knee extension was preserved following acute endurance activities, the risk of ligamentous injury may be increased by concomitant impairment to EMD and anterior TFD.

The anterior cruciate ligament (ACL) is the principal ligamentous restraint to anterior tibio-femoral displacement and is the most commonly injured of the major knee joint ligaments (47). There is accumulating evidence of an ACL injury epidemic via noncontact aetiologies in team sport athletes (27).

A conceptual model that defines the limits of normal knee movement comprises primary ligamentous
restraints interacting with the other static stabilizers (osseous geometry, capsular structures, and menisci) and with the dynamic muscle stabilizers (16,19). An unfavorable interaction of the dynamic and static stabilizing factors may predispose teamgame players to increased threat of ACL disruption (22). In particular, optimal functioning of the dynamic muscle stabilizers of the knee joint may be fundamental to the prevention of or limit the severity of ligamentous injury (35).

The knee flexor muscle group is thought to promote dynamic knee joint stability by regulating anterior tibiofemoral displacement (TFD) and tibio-femoral rotation, while activation of the knee extensor muscle group may provoke an anterior tibial shear force and threat to ACL integrity (16,19). Therefore, the dynamic stabilization of the knee joint provided by the knee flexor musculature may be compromised by limited strength capacity and by excessive knee extensor strength. Cadaveric and in vivo models have demonstrated that the ACL shows the greatest mechanical strain close to full knee extension (between 0 rad and 0.52 rad of knee flexion (rad = full knee extension)) (8). Thus the knee joint positioned approximately in this range would be most vulnerable to adverse forces and injury compared with intermediate joint positions.

During soccer match-play, repetitive stress cycles experienced by the knee joint during the execution of approximately 1000-1180 changes in activity (4) in conjunction with the potential intrusion of fatigue-related processes may present a substantive challenge to knee joint integrity. Few authors have investigated the acute effects of prolonged intermittent exercise with bursts of acceleration, sprinting, reversal of direction, and deceleration on the neuromuscular responses of the knee joint. The latter type of intermittent exercise is more representative of the actual physiological demands of soccer which involve running of a predominantly aerobic nature (albeit at different speeds) interspersed with short periods of intense anaerobic exercise (4). This exercise, which has an overall oxygen uptake ($\cdot$VO$_2$) approximating 70%-75$\cdot$VO$_{2\text{max}}$ (4,40) and mean heart rates exceeding 160 beats·min$^{-1}$ (40), imposes a greater metabolic strain on the body than continuous exercise at the same overall work output (4) and would be expected to present a more substantial stress to the knee joint. The range for distances covered by soccer players during elite competitive games approximates 8000 to 12000 m (4,40), although this figure may be reduced for less accomplished players. However, continuous running exercise remains as an integral part of contemporary preseason training practices in English Endsleigh League professional soccer (31) and so is representative of a type of training stimulus experienced by soccer players during the league season. The aforementioned stimuli may represent the extremes of a continuum of the type of stresses experienced routinely by the knee joint from within the environment of soccer.

Contemporary training practices in soccer represent a hostile environment in which to maintain knee joint integrity. For example, a 2-yr study of injury patterns in Endsleigh League Division One clubs showed that 35% of all knee ligamentous injuries occurred during training (18). Similarly, more than 50% of all injuries to the knee joint and its stabilizing musculature (hamstrings) occurred during training in elite Portuguese soccer players during a 2-yr period (41). It may be important to evaluate the neuromuscular responses of the knee joint across a range of stresses that represent those inherent within soccer training and competitive matches and that provide a framework of increasing mechanical
and metabolic demand. Such data may permit the identification of neuromuscular deficiencies of the knee joint resulting from stresses within the environment of soccer which may be attenuated subsequently by specific conditioning interventions.

Alongside strength performance of the dynamic muscle stabilizers, two further aspects of neuromuscular and musculoskeletal performance may be important markers of knee joint robustness and resistance to injury. While the mechanical properties of the ACL have been investigated by means of in vitro studies (34), there have been only a few studies of the influence of acute bouts of physical exercise on anterior tibio-femoral displacement (TFD) which is considered an indirect marker of ACL performance. The in vivo mechanical properties of the ACL during exercise may be related closely to the mechanisms of rupture (39).

Furthermore, the neuromuscular system has a limited reaction time response to dynamic forces applied to the knee joint. This electromechanical delay (EMD), which is defined as the time delay between the onset of muscle activity and onset of acceleration (33), may be associated with the unrestrained development of forces of sufficient magnitude to damage ligamentous tissue during prolonged intermittent exercise (30). The EMD is determined by the time taken for the contractile component to stretch the series elastic component of the muscle (51). There have been few studies of the influence of acute repetitive loading associated with soccer match-play and training on EMD.

The aim of the present study was to investigate selected neuromuscular and musculoskeletal responses of the knee to 1) prolonged, intermittent, high intensity running with reversals of direction; 2) prolonged continuous running interspersed with regular reversals of direction, and 3) prolonged continuous running. The latter represented a range of the type of stimuli applied commonly to soccer players during the league season.

**METHODS**

**Subjects.** Eight recreational soccer players (age 23.2 ± 3.7 yr; height 1.76 ± 0.05 m; body mass 71.9 ± 11.0 kg; VO2max (predicted) 48.6 ± 4.5 mL·kg⁻¹·min⁻¹ (mean ± SD)) gave their informed consent to participate in this study in accordance with the policy statements of the American College of Sports Medicine. Assessment protocols were approved by the local Health Authority Medical Ethics Committee. No subject was receiving rehabilitation for injuries of the hip, knee, leg or ankle, or was symptomatic at the time of testing.

**Familiarization and preliminary tests.** Following a session in which the subjects were exposed to and familiarized with the test procedures, maximal oxygen uptake (VO2max) was estimated by means of a progressive multistage shuttle run test (38). From this estimate of VO2max, running speeds corresponding to 55%, 70%, and 95% VO2max were calculated using the tables for predicted VO2max values (38). The subjects performed subsequently each experimental exercise condition for a 10-min period to familiarize themselves with the prescribed running speeds and exercise procedures.
Experimental design. Subjects completed four exercise trials. Within each trial, subjects performed a standardized warm-up and one of the following experimental conditions presented in random order: 1) a prolonged intermittent high intensity shuttle run (PHISR) which required subjects to complete a total distance of 9600 m in a form simulating the pattern of physical activity (activity mode; rest-to-work intervals; approximately 90 min duration) in soccer match-play (four sections of 12 × 200 m cycles of activity, each comprising 60 m walking (1.54 m·s⁻¹), 15 m sprinting (5 m deceleration and 5 m recovery walk), 60 m jogging (55% ·VO₂max), and 60 m running (95% ·VO₂max)); 2) a shuttle-run (SR) which required subjects to complete a total distance of 9600 m in four sections of 2400 m at a running speed corresponding to 70% ·VO₂max, 3) a treadmill run (TR) of 9600 m in four sections of 2400 m at a running speed corresponding to 70% ·VO₂max, and 4) a control condition (CON). The PHISR and SR trials were conducted on a nonslip floor over 20 m, identified by cones and floor markings (Fig. 1), and so required subjects to make repeated reversals of movement direction (480 per exercise trial). The CON trial consisted of a duration equivalent to that of the PHISR task (approximately 90 min) during which no exercise was performed. The protocol is shown schematically in Figure 2, and the sequence of activities within each 200 m exercise cycle of the PHISR is shown in Table 1.

![Figure 1-Schematic of the 20-m course used during the PHISR and SR experimental conditions.](image-url)
Figure 2-Schematic of the protocol involving PHISR, SR, TR, and CON experimental conditions. Timings for PHISR experimental condition are shown.

| Table 1. Activities during a single cycle (200 m) of the PHISR. |

The trials were presented in random order to offset any training or sequencing effects and separated by at least 10 d to allow normal muscle glycogen and electrolyte concentrations to be re-established (20). Subjects were instructed to refrain from strenuous activity on the day before testing and on test days and to maintain constant exercise levels throughout the experimental period. All subjects were tested as near to the same time of day as possible (± 1 h). Subjects were encouraged verbally throughout each trial and were not aware of their performance scores until after completion of the study.

The standardized warm-up consisted of 5 min cycle ergometry at an exercise intensity of 88 W, 5 min static stretching of the involved muscle groups before any assessment, and a further 5 min of jogging, stretching, and striding before the exercise trial. The running and walking speeds during each 20 m of the PHISR and SR were dictated by an audio signal recorded from a microcomputer (RiscPC, Acorn Computers Ltd., Cambridge, UK).

Dry and wet bulb temperatures were recorded intermittently during the exercise trials using a whirling hygrometer (Brannan Thermometers, Cumberland, UK). There were no significant differences in environmental conditions between experimental exercise trials. The temperature and relative humidity...
of the sports hall was maintained at 20 ± 0.9°C and 56 ± 3.6%, respectively.

**Assessment protocols.** Sprint times were measured during the PHISR trial in one movement direction by two infra-red photo-electric cells (RS Components Ltd.), situated 15 m apart and interfaced to a timing system with millisecond resolution (Fig. 1). The mean score of the final eight of the twelve sprints undertaken during each exercise section of the PHISR was recorded.

Heart rate was monitored continuously using short-range telemetry (Sport Tester, PE3000, Polar Electro Fitness Technology, Kempele, Finland) and averaged over 15-s sampling periods throughout the PHISR and SR trials. Heart rate samples were archived to microcomputer (RiscPC, Acorn Computers Ltd., Cambridge, UK) and processed by means of software (Polar HR Analysis V. 4.0, Polar Electro Fitness Technology) to estimate the mean heart rate during each exercise section of the PHISR and SR trials. Heart rates were recorded manually during the TR trial at 60-s intervals using the latter system.

Duplicate arterialized 20-mL capillary blood samples (6) were obtained from a finger prick before exercise and then following each section of the PHISR, SR, and TR trials (1-2 min into recovery) (Fig. 2). Samples were immediately analyzed for blood lactate concentration using a lactate analyzer (Analox GM7, Analox Instruments Ltd., London, UK).

Overall perceived exertion (RPE), representing an integration of all exercise sensations (9), and differentiated rating of perceived exertion (RPE(leg)) were assessed at the end of each section of the PHISR, SR, and TR trials (Fig. 2). The latter index required subjects to focus on the sensations of muscle and joint strain in the exercising legs to rate the intensity of local effort (36).

**INDICES OF ISOKINETIC LEG STRENGTH**

**Subject and isokinetic dynamometer orientation.** Subjects were fixed to the testing apparatus (Lido 2.1, Loredan Inc., CA). Subjects were seated with the angle between the back and seat of the dynamometer chair set at 1.57 rad and the angle between the chair and horizontal frame set at 0.26 rad to the horizontal. To localize the action to the proper muscle groups, subjects were securely strapped at the hip, waist, chest, and shoulders with an additional restraint applied to the thigh close to the involved joint. The dynamometer's lever arm was strapped to the involved leg just above the ankle joint. The lever length between the ankle cuff and the lever arm axis of rotation was standardized for each subject during day-to-day trials. The axis of rotation of the dynamometer was aligned midway between the lateral condyle of the tibia and the lateral epicondyle of the femur consistent with the anatomical axis of the knee joint.

**Gravity moment correction.** Automated compensation procedures for gravitational errors in recorded torques during maximal voluntary contraction in the vertical plane were undertaken just before testing. Angle-specific torque data generated by the passive flexion of the involved leg and the weight of the input accessories (including the lever arm) were used by the dynamometer's software to correct for the
Effects of gravity over the full range of movement.

**Instructions to subjects.** All instructions to subjects were given via standardized written instruction cards. Subjects were not given feedback of results until after the completion of the prescribed number of trials. The same test administrator performed all measurements.

**Exercise bouts.** In each experimental trial, pre-, mid- and post-trial gravity corrected indices of knee extension and flexion peak torque (PT) and angle-specific torques (AST: 0.44 rad knee flexion [0 rad = full knee extension]) at 1.05 rad·s\(^{-1}\) (60°·s\(^{-1}\)) were estimated for the preferred limb. This was done by interrogating three reciprocal concentric maximal voluntary muscle actions during each of duplicate exercise bouts separated by 180 s of passive recovery. Mean scores of these bouts were recorded to offset the inferior measurement reproducibility associated with ASTs close to full knee extension (21).

**Index of knee laxity.** In each experimental trial, pre- and post-trial assessments of anterior tibio-femoral displacement were undertaken in the preferred leg to describe knee laxity using a laboratory instrument constructed specifically to measure anterior TFD (24,25). The apparatus and subject orientation during assessment are shown schematically in **Figure 3**. The apparatus was constructed to provide an adjustable rigid chair-like framework and was designed to maintain the knee in a standardized position during the measurement of anterior TFD. The preferred leg was secured by self-stick straps and a clamping device at the distal femur and tibia, respectively. The knee joint was maintained at 0.44 rad of flexion (0 rad = full extension) and foot position at 0.26 rad of external rotation and 0.35 rad of plantar flexion. The subject was seated in an upright position with a 0.26 rad angle between the back and seat supports.

![Figure 3-Subject and anterior tibio-femoral displacement (TFD) measurement apparatus orientation.](image-url)

Instrumentation to measure anterior TFD consisted of two linear inductive displacement transducers (DCT500C, RDP Electronics Ltd., Wolverhampton, UK: 0.025 m range). The latter incorporates spring-loaded plungers which were adjusted accurately in three planes to provide perpendicular attachment to...
the patella and tibial tubercle. During measurements, both transducers were secured to the skin surface using tape and could move freely only in the anterior-posterior plane relative to the supporting framework. The instrument monitored only the relative motion between the patella and tibial sensors and so facilitated the exclusion of measurement artifacts caused by extraneous movements of the leg during the application of anterior displacement forces.

Anterior force was applied in the sagittal plane at a rate of 67 ± 7 N·s⁻¹ [mean ± SD] and in a perpendicular direction relative to the tibia by an instrumented force-handle incorporating a load cell (Model 31E500N0, RDP Electronics Ltd., Wolverhampton, UK: range 500 N). This device was positioned behind the leg at a level 0.02 m distal to the tibial tubercle. The transducers were interfaced to an IBM compatible microcomputer via a 16 channel A/D 12 bit converter (Model PC-28A, Amplicon Liveline Ltd., Brighton, UK). Data from all transducers were sampled at 50 Hz.

Measurements on each knee were preceded by two practice trials. During each measurement, subjects were instructed to relax the musculature of the involved limb. Rapid but gentle manual anterior-posterior drawer oscillations were used to facilitate relaxation and to establish a neutral tibio-femoral position from which all measurements were initiated. Indices of anterior TFD were calculated as the mean of three intra-session replicates of the net displacement of the patella and tibial tubercle transducers at an anterior tibial displacement forces of 200 N applied in the sagittal plane. The latter level of applied force is associated with superior measurement reproducibility compared with that in lower levels of force (25) and is tolerated well by asymptomatic subjects.

The displacement transducers were calibrated against known lengths throughout the range of linear operation specified by the manufacturer (0.025 m). The SEE associated with the recording of displacement was ± 1.6×10⁻⁵ m. The force transducer was calibrated against known masses through a biologically valid range (0 N - 220 N) with correction for the mass of the apparatus and angle of force application. The SEE associated with the application and recording of the applied force was ± 0.003 N. Throughout the period of testing, the calibration of the force and displacement transducers was verified against objects of known mass and length, respectively.

**Index of electromechanical delay.** In each experimental trial, pre-, mid- and post-trial estimates of electromechanical delay (EMD) responses were assessed by recording the electromyographic activity (EMG) of m. biceps femoris of the preferred leg during separate supine gravity-loaded knee flexion movements in the sagittal plane. The m. biceps femoris was selected for investigation as a contributor to the restraint of anterior tibio-femoral displacement in the knee joint and the restraint of the lateral rotation of the femur relative to the tibia, both of which are implicated in the disruption of the ACL (23).

The subject was placed in a prone position on a wooden padded table with the knee flexed passively to 0.44 rad (25°). The lower leg was supported at a position 0.1 m proximal to the lateral malleolus by a rigid adjustable system. The latter system incorporated an opto-switch interfaced to the EMG recording system to insert a marker coincident with the detection of movement of the tibia away from the padded
After a verbal warning, a randomly ascribed auditory signal was delivered to the subject within 1-4 s. On receipt of the signal the subject flexed the knee as quickly as possible. The moving limb was decelerated by the test administrator manually at approximately 1.57 rad of knee flexion and then returned to the starting position passively for a suitable delay period (10 s). Following two practice attempts, this procedure was administered six times. Potential distractions to the subject were minimized, and only two investigators were present in the laboratory in addition to the subject during data capture. Subject and measurement apparatus orientations are shown in Figure 4.

The EMGs were recorded with bipolar surface electrodes (self-adhesive, silver-silver chloride, 10 mm diameter, interelectrode distance 40 mm center to center) applied to the preferred leg following standard skin preparation (interelectrode impedance < 5000 [OMEGA])). Electrodes were placed longitudinally distal to the belly of the m. biceps femoris on the line between ischial tuberosity and lateral epicondyle of the femur.

The EMG signals were preamplified at the cutaneous site, filtered through a band-width of 20-500 Hz before further signal amplification and analog to digital conversion at 2000 Hz (ME3000P; MEGA Systems, Kuopio, Finland). The reference electrode was fixed on the preamplifier and placed over the lateral femoral epicondyle.

To ensure the same electrode placement in subsequent trials, a map of the thigh of each subject was made. This was done by marking on acetate paper the position of the electrodes, moles and small angiomas.

The EMGs were archived to hard disk and subsequently processed by software (ME3000 Professional v0.1.21: MEGA Systems, Kuopio, Finland) to identify the EMD, defined as the time interval from the change in electrical activity of the biceps femoris muscle to movement of the tibia from the lower limb support (51). An example of the output is displayed in Figure 5.
Figure 5 - An example of an EMG recording to illustrate the determination of electromechanical delay (EMD).

The reproducibility of the index of EMD was assessed across the pre-exercise trials for the five intra-trial replicates for each subject. The group mean coefficient of variation (V%) was 6.1 ± 3.3%. The mean of six trials was used to determine EMD.

**Statistical analyses.** The selected indices of isokinetic leg strength and anthropometry were described using standard statistical procedures (mean ± SD).

**Comparison of absolute PT and AST scores.** Absolute scores for PT and AST at 0.44 rad of knee flexion at the selected lever-arm velocity (1.05 rad·s⁻¹) were compared using a 3 (time [pre-, mid-, and postexercise trial]) × 2 (knee motion [extension and flexion]) × 4 (exercise trial [PHISR, SR, TR, CON]) factorial repeated measures ANOVA.

**Comparison of anterior tibio-femoral displacement and electromechanical delay.** Scores for anterior TFD were compared using a 2 (time [pre- and post-exercise trial]) × 4 (exercise trial [PHISR, SR, TR, CON]) factorial repeated measures ANOVA. Scores for EMD were compared using a 3 (time [pre-, mid-, and postexercise trial]) × 4 (exercise trial [PHISR, SR, TR, CON]) factorial repeated measures ANOVA.

Heart rates and blood lactate concentrations were compared using a 4 (time: sections 1-4) × 4 (exercise trial [PHISR, SR, TR, CON]) factorial repeated measures ANOVA. Sprint times across the PHISR exercise trial (sections 1-4) were compared using a one-way repeated measures ANOVA. Ratings of perceived exertion (RPE and RPE(leg)) were compared using a nonparametric Friedman test across each exercise trial (sections 1-4).

Data transformations were applied to conform to the assumptions underpinning the use of analysis of variance where appropriate. The multivariate test statistic Pillai's Trace (V) was used to examine the former parametric models or where the additional assumptions underpinning the use of univariate tests were evident, an averaged F test statistic was used. Performance indices across assessment occasions were compared using post-hoc multiple comparisons, where appropriate.
An *a priori* alpha level of 0.05 was applied in all statistical procedures. Based on the results from preliminary testing, the experimental design was expected to offer an approximate 0.80 power of avoiding a Type-II error when employing a least detectable difference of 12 N·m, 6 ms and 0.25 mm during comparisons of absolute torque, electromechanical delay and anterior tibio-femoral displacement scores, respectively (29). All statistical analyses were programmed using SPSS/PC+ (V5.0) software.

**RESULTS**

The influence of exercise trials on peak torque. Group mean peak torque scores for pre-, mid- and post-assessments during PHISR, SR, TR, and CON experimental conditions for knee extension and flexion movements are presented in Table 2. Repeated measures ANOVA showed a significant assessment time by exercise trial by knee motion interaction for PT (Pillai’s Trace \( V = 0.99; F(2,6) = 178.2; P < 0.005 \)). While peak torque was decreased progressively compared with the pre-exercise assessment across mid- and post-exercise assessments in the PHISR, SR, and TR exercise trials, the CON exercise trial remained constant. Second, the reduction in PT compared with pre-exercise levels was more substantial in PHISR and SR exercise trials at the mid-assessment compared with that in the TR exercise trial for both extension (11% and 11% vs 4%, respectively) and flexion (9% and 11% vs 6%, respectively) movements. Third, while there was further substantial reduction in PT in both PHISR and SR exercise trials at the post-assessment compared with that in the TR exercise trial, PT during knee flexion in the SR trial showed a greater reduction (18% and 18% vs 5%, respectively) compared with that during extension movements (20% and 12% vs 4%, respectively).

![Table 2](image)

**TABLE 2.** Group mean PT (N·m) at pre-, mid- and post-assessments during PHISR, SR, TR, and CON experimental conditions for knee extension and flexion movements of the preferred limb at 1.05 rad·s\(^{-1}\) (\(N = 8\)). Data are mean and SD.

The influence of exercise trials on AST. Group mean AST scores for pre-, mid- and post-assessments during PHISR, SR, TR, and CON experimental conditions for knee extension and flexion movements are presented in Table 3. Repeated measures ANOVA demonstrated that assessment time by exercise trial by knee motion interactions for AST were not significant.
TABLE 3. Group mean AST (0.44 rad knee flexion) (N·m) at pre-, mid- and post-assessments during PHISR, SR, TR and CON experimental conditions for knee extension and flexion movements of the preferred limb at 1.05 rad·s\(^{-1}\) (\(N = 8\)). Data are mean and SD.

The influence of exercise trials on electromechanical delay. Group mean electromechanical delay scores for pre-, mid- and post-assessments during PHISR, SR, TR, and CON experimental conditions are shown in Table 4. Repeated measures ANOVA demonstrated a significant assessment time by exercise trial interaction for EMD (\(F(6,42) = 2.5; P < 0.05\)). While EMD was increased compared with the pre-exercise assessment across the PHISR, SR, and TR exercise trials compared with the CON exercise trial, which remained constant, the SR trial (19% increase) was associated with a more substantial increase in EMD compared with the PHISR and TR trials (12% and 12% increases, respectively).

TABLE 4. Group mean EMD (ms) of the m. biceps femoris at pre-, mid- and post-assessments during PHISR, SR, TR, and CON experimental conditions for the preferred limb (\(N = 8\)). Data are mean and SD. Measurements were recorded during supine gravity-loaded knee flexion movements in the sagittal plane with the knee flexed to 0.44 rad (25°).

The influence of exercise trials on knee laxity. Group mean anterior TFD scores for pre-, mid- and post-assessments during PHISR, SR, TR, and CON experimental conditions are shown in Table 5. Repeated measures ANOVA demonstrated a significant assessment time by exercise trial interaction for anterior TFD (\(F (3.21) = 5.9; P < 0.005\)). While anterior TFD was increased compared with the pre-exercise assessment across the PHISR, SR, and TR exercise trials compared with the CON exercise
trial, which remained constant, the PHISR and SR trials (44% and 48% increases, respectively) were associated with a more substantial increase in anterior TFD compared with that in the TR trial (24% increase).

**TABLE 5.** Group mean anterior TFD (mm) at pre- and post-assessments during PHISR, SR, TR, and CON experimental conditions for the preferred limb (N = 8). Data are mean and SD. Measurements were undertaken using an applied force of 200 N applied in the sagittal plane with a knee flexed to 0.44 rad (25°).

**The influence of the PHISR trial on 15 m sprint times.** Group mean 15-m sprint time scores in exercise sections 1-4 during the PHISR are shown in Figure 6. Repeated measures ANOVA demonstrated significant differences in sprint times across sections 1-4 of the PHISR trial (Pillai's Trace (V) = 0.97; F(3,5) = 53.8; P < 0.0005). Student-Newman-Keuls post-hoc procedures indicated that the sprint times during sections 3 and 4 (2.66 ± 0.15 s and 2.73 ± 0.17 s, respectively) were significantly increased compared to during section 1 (2.60 ± 0.10 s) (P < 0.05). Section 4 sprint times were greater than during section 3 and section 2 (2.62 ± 0.15 s) (P < 0.05).

**Figure 6-Group mean 15-m sprint time (s) during the PHISR (N = 8).** Assessments at exercise sections 1-4. Data are mean and SD.

**The influence of exercise trials on markers of physiological, metabolic and perceptual strain.** Group mean blood lactate concentration and close during PHISR, SR, and TR experimental conditions are shown in Figures 7 and 8, respectively. Sample data from a single subject for heart rate (beats·min⁻¹) during the PHISR and SR experimental conditions are shown in Figure 9. Figures 10 and 11 present...
corresponding group mean rating of perceived exertion and rating of perceived exertion (leg), respectively.

Figure 7-Group mean blood lactate concentration (mM) for PHISR, SR, and TR experimental conditions (N = 8). Assessments at pre and exercise sections 1-4. Data are mean and SD.

Figure 8-Group mean heart rate (beats·min⁻¹) for PHISR, SR, and TR experimental conditions (N = 8). Assessments at exercise sections 1-4. Data are mean and SD.

Figure 9-Example of data from a single subject for heart rate (beats·min⁻¹) to the PHISR experimental condition. Data are mean heart rate recorded during repeated 15-s sampling
Repeated measures ANOVA showed a significant assessment time by exercise trial interaction for blood lactate concentration (Pillai's Trace (V) = 0.98; $F (2,6) = 20.3; P < 0.05$). While blood lactate concentrations during the TR exercise trial remained relatively constant (range: 1.9-2.3 mM) across sections 1 to 3 at moderate levels, with a decrease at section 4 (1.7 mM), PHISR and SR trials showed an overall decrease across sections 1 to 4 from initially higher levels (ranges: 4.4-3.3 mM and 4.0-1.8 mM, respectively).

Repeated measures ANOVA showed no significant assessment time by exercise trial interaction for heart rate, indicating that the patterns of response were similar between exercise trials. Results indicated no significant differences in the heart rate among the exercise trials. There were significant differences in heart rate among the assessment times ($F(3,21) = 13.4; P < 0.0005$). Post-hoc procedures showed that the heart rate during section 4 (mean across exercise trials: 170 beats·min$^{-1}$) was significantly higher than during sections 1 to 3 (166, 167 and 167 beats·min$^{-1}$, respectively).
nonparametric analyses showed that rating of perceived exertion and rating of perceived exertion (leg) during PHISR, SR, and TR exercise trials increased significantly across sections 1 to 4 ([\chi^2(df = 3) > 10.6; P < 0.01] and [\chi^2(df = 3) > 15.4; P < 0.01], respectively).

**DISCUSSION**

Physiological, metabolic, and perceptual strain associated with PHISR, SR, and TR activities. The results suggest that PHISR trial represented substantively the physiological stress experienced by soccer players during match-play. For example, the overall heart rate associated with the PHISR trial (range across section 1-4: 168-173 beats·min⁻¹[considered equivalent approximately to 70% of \·VO_{2max}^3]) was similar to the upper level of mean heart rates ([almost equal to]170 beats·min⁻¹) observed in competitive match play, although higher heart rates (>92% age-related heart rate maximum) have been observed for extended periods of play in some players (40). Similarly, blood lactate concentrations at the start of PHISR trials and the pattern of decrease across sections are comparable with that of competitive match-play in which lactate values have been shown to be lower during second half compared with that in first half performances (4).

Despite exercise intensities among trials having been matched experimentally to elicit similar overall heart rates, differences in blood lactate profiles associated with PHISR, SR, and TR trials illustrated different metabolic stresses among the exercise trials. The PHISR trial, involving sprinting and other intermittent periods of rapid movement, appears to be associated with the greatest metabolic stress and the TR trial with the least metabolic stress. The specific blood lactate profiles, reflecting rates of lactate production, release and removal (4), are likely to have been influenced by several factors. These would include rate of muscle glycogen depletion and initial status (45), the intermittent nature of the PHISR trial compared with the continuous nature of the SR and TR trials (4,7), the frequency of sampling, and the nature and timing of the rest intervals during intermittent activities (4,10).

Despite the even distribution of stress across the sections of the exercise trials, central and peripheral (leg) markers of perceptual strain showed a significant increase across PHISR, SR, and TR trials. The latter findings may be indicative of the cumulative nature of the metabolic, neuromuscular, and mechanical stresses associated with the exercise trials.

Leg strength changes associated with PHISR, SR, and TR activities. The significant progressive decreases in PT in the PHISR, SR, and TR trials for both knee extension and flexion movements support the notion that prior acute endurance activity impaired the potential for tension development in subsequent resistance activity. This extent of this effect may be specific to the involved muscle group since the decrease in strength was greater in the knee flexors than the extensors and also was related to the degree of neuromuscular, mechanical, and metabolic stresses imposed on the musculature. The latter notion was supported in this study in that the PHISR and SR trials, which involve additional intermittent high intensity and shuttle running compared with the unidirectional endurance running of the TR trial, showed the most pronounced strength impairment responses. The parity of scores across the CON trial excludes the possibility that the assessment trials contributed to the strength impairment.
Evidence of strength impairment following functionally-relevant endurance tasks in the present study, together with other corroborating findings from other studies involving laboratory-based interventions, illustrate the potential for differential duration and mode-specific strength responses to acute endurance exercise. In a study of six active males (1), knee extension torque at 0.52 rad below the horizontal and measured at a movement velocity of 1.05 rad·s⁻¹, showed significant decreases of 14% and 2% compared with baseline levels following both 150 min of continuous cycle ergometry at 35% ·VO₂max and 50 min of higher intensity interval-type cycle ergometry, respectively. Other researchers (13) reported inhibition of strength during isokinetic evaluations of the effects of interval-type endurance activities at test movement velocities of greater than 1.68 rad·s⁻¹ only. More work is required to assess the robustness of these observations.

Several processes involved in the conversion of excitation into a muscle fiber force have the potential to contribute to the strength decrement process linked with endurance activity. These include impairment of neuromuscular propagation (17) and changes within the intracellular milieu reducing the amount of Ca²⁺ released and increasing the intracellular binding of Ca²⁺ (14). In general, the relative importance of such mechanisms to the decline in force remains to be determined (14).

Ultrastructural changes within skeletal muscle fibers may have contributed to the strength impairment noted. Prolonged eccentric activation of the musculature is associated with immediate and prolonged strength loss. For example, a substantial (>50%) decrease in strength was observed immediately after a 40-min exercise trial involving downhill running at 80% of the maximum heart rate (15). It is likely that the 480 reversals of direction and concomitant arresting of momentum required only in the PHISR and SR trials presented a substantial eccentric mechanical stress loading in comparison with that in the unidirectional TR trial. In animal models, ultrastructural damage during level running may have a metabolic etiology related to the depletion of glycogen (2). The latter may have occurred to some degree during all exercise trials in the present study according to depressed blood lactate responses and elevated self-reports of perceived exertion across sections 1-4. It is possible, therefore, that metabolic factors may have contributed in the strength impairment process in all types of exercise stress used in the present study. The greater PT impairment response observed for PHISR and SR trials compared with that in the TR trial is consistent with both the contribution from processes provoking ultrastructural damage and the interaction of differential mechanical and metabolic stressors within the exercise trials. Further, although not addressed formally in the present study, the pattern of self-reports of muscle soreness on days following the exercise trials is consistent with the latter interpretation of findings.

Angle-specific torque reflects strength performance of the dynamic muscular stabilizers of the knee close to full knee extension where the ACL is challenged by increasing levels of mechanical stress (16,24). It is noteworthy that despite impairment to PT indices of isokinetic leg strength, results suggest that strength levels close to full knee extension during both knee extension and flexion movements were not influenced by the metabolic and mechanical stresses associated with the exercise trials. It is possible to induce a substantial transient impairment of strength in both PT and AST close to full knee
extension (up to 60% reduction compared with pre-exercise strength) by means of an acute isokinetic endurance exercise task (22). By contrast, functionally-relevant activities, such as the PHISR, SR, and TR trials, do not appear to provoke impairment to strength close to full knee extension and associated dynamic stabilization. It may be that under these functional stresses the characteristics of the joint angle-torque relationship is preserved in such a way as to minimize the potential threat to knee joint stability in positions close to full knee extension.

In both PT and AST close to full knee extension, measured torque in any given movement direction reflects the net contributions from functional co-activation patterns of agonist and antagonist muscle groups (5). Any potential changes in these patterns as a result of the endurance activities may be implicated in changes in strength. Further, there is evidence that antagonist co-activation may impair by reciprocal inhibition, the ability to activate agonists fully (48). However, minimal co-activation has been observed during electromyographic evaluations of the knee extensor (m. rectus femoris; m. vastus lateralis) and flexor (m. biceps femoris; m. semitendinosus) muscle groups (Gleeson and Mercer, unpublished observation) during a standardized isokinetic fatigue task at 3.14 rad·s⁻¹ (22). Thus, co-activation factors may not have contributed substantively to the isokinetic torque observations in this study.

**Electromechanical delay and knee laxity associated with PHISR, SR and TR activities.** The mean EMD for the biceps femoris muscle across pre-exercise trial assessments in the present study (100 ms) was similar to the EMD observed for the knee extensors during static muscle actions (106 ms (49); 118 ms (26), and isokinetic actions (95 ms (32)). Results suggests that the EMD was influenced substantially (up to 19% increase compared with that in pre-exercise task scores) by the acute repetitive stress loading associated with soccer match-play and training.

There are conflicting reports in the literature about the influence of fatiguing exercise on EMD. Some reports suggest that EMD during voluntary movements in the knee extensors is influenced by exercise (26,32), other reports suggest the opposite (28,49). The study by Vos et al. (49) described EMD responses of the knee extensors during a fatigue task consisting of 100 s of repetitive static muscle actions at 1.57 rad of knee flexion and 50% MVC. The EMD scores at 10, 40, and 90 s of[almost equal to]113, [almost equal to]116, and [almost equal to]123 ms (N = 7), respectively, which are similar to the range of performance observed in the present study, did not reach significance at an alpha level of 0.05, possibly because of low experimental design sensitivity.

The impairment of EMD in the present study may be attributed to a complex interaction of neuromuscular and biomechanical factors. The rate of shortening of the series elastic component of muscle may be the primary cause of EMD in a given muscle (33). The limb segment orientation and moment of inertia and unfavorable joint position for muscle torque development associated with the testing configuration in the present study may have presented a substantive challenge to the whole musculotendinous unit before the commencement of limb movement. Thus, any increases in compliance of the musculotendinous unit associated with the exercise trials would tend to have increased the EMD. Muscle temperature may be an important moderator in the latter process. The
prolonged activities associated with soccer match-play and training simulated in the present study would be expected to increase core and intramuscular temperature (4,40). Such changes are associated with an increase in neural propagation and an increase in compliance in the connective tissue. Since the time to shorten the series elastic component of muscle exceeds substantially the time for the activation of cross-bridges during concentric muscle actions (33), the influence of increased compliance during the exercise trials may have prevailed and contributed to the observed increase in EMD.

The physiological and metabolic responses of subjects to simulations of match-play and training in the present study reflect a combination of aerobic and anaerobic demands. It seems reasonable therefore to assume that a range of motor unit types (fast contracting, fast-to-fatigue; fast contracting, fatigue-resistant; slow contracting, fatigue-resistant) would have contributed to work demands of the PHISR and SR exercise trials. These units would be susceptible to impaired functioning and fatigue-related processes. The protocol for EMD used in the present study would not have been able to discriminate contributions of the various types of motor units. It is possible that the time-to-movement determination of EMD reflects principally contributions from slow contracting, fatigue-resistant since these motor units are recruited first according to the “size-principle.” However, recruitment order may be violated under some conditions (14). Larger high-threshold, fast contracting motor units are recruited preferentially over slow contracting units in tasks demanding rapid ballistic muscle actions (43), and it is unclear how well orderly recruitment is preserved under conditions of fatigue (14). Irrespective of mechanism, the results suggest that the EMD was impaired by the acute repetitive stress loading associated with soccer match-play and training.

The SR trial provoked the greatest impairment in EMD compared with the PHISR and TR trials. It may be that the sustained greater velocity and concomitant arresting of greater momentum during the regular reversals of direction associated with the SR trial provoked increased neuromuscular and musculoskeletal stress.

Anterior TFD was increased following PHISR, SR, and TR exercise trials. The increase (44%) in anterior TFD associated with the PHISR trial was comparable with a 52% increase in this parameter after 90 min of basketball match-play practice (42). The 24% increase in anterior TFD after the TR trial was similar to that reported after distance running (20%) (46). The largest increase in knee laxity associated with the exercise trials (PHISR) was less than that reported following ACL injury and was considered to be within physiological limits (25).

The increase in anterior TFD associated with acute endurance exercise may be attributed principally to property changes within the ACL. It may be indicative of transient impairment to knee musculoskeletal robustness. This ligament demonstrates visco-elastic behavior during extended periods of repetitive mechanical stress caused by a high collagen content (50). Concomitant changes in other supporting fibrous tissues may contribute to the changes in knee laxity but probably to a much lesser extent.

The increase in anterior TFD across the standardized applied load range (0 N to 200 N) following acute endurance activity demonstrated that substantial increases in compliance are possible in major fibrous
knee structures. Even greater changes may be expected during physiological loading (8). The latter would tend to give some support to the notion, alluded to earlier, that increased compliance in the musculotendinous unit may have contributed to the observed increase in EMD. Furthermore, it has been postulated that increased knee laxity and compliance in females compared with that in males (27) accounts for increased EMD in the former population (51).

**Functional implications.** This study offers partial support for the hypothesis that acute prior endurance activity impairs the ability to develop isokinetic torque during subsequent muscle actions (11). While impairment of PT was observed, the ability to develop torque close to full knee extension appears to be resistant to adverse influences of acute functionally-relevant endurance activities. The latter angle-specific response may reflect a normal functional adaptation to preserve joint stability during mechanically stressful phases of training and match-play.

These findings have implications for the physical preparation of soccer players. The optimum adaptive response to strength training in soccer players may be impaired. In those aspects of strength performance that have demonstrated the impairment process, the culmination of systematic exposure to extended periods of endurance activities within the training macrocycle which are similar to those used in this study may be to impair regularly the capacity to develop tension and to deflate systematically the levels of tension experienced by the neuromuscular system. As a consequence, the stimulus for strength development would be reduced (3). In the absence of appropriate compensatory strength conditioning regimens, this process would tend to reduce leg strength performance in soccer players and potentially reduce the ability to resist unfavorable musculoskeletal stresses. This proposition requires further investigation. Furthermore, the findings from the present study suggest that strength development may be impaired at intermediate joint positions rather than at those that are close to full knee extension.

Although the time-course of restoration of pre-intervention strength levels following functionally-relevant endurance activities has received limited scrutiny, isokinetic PT performance across a range of velocities (1.05 rad·s\(^{-1}\) to 5.24 rad·s\(^{-1}\)) may be reduced for up to 7 d after a marathon run (44). The volume and intensity of training associated with the 4-5 wk preseason period for both senior and youth squads during contemporary training practice in English professional soccer and the prominence of endurance activity during this period (31) suggest strongly that this phase of the training macrocycle would be most likely influenced adversely by regular episodes of impairment in strength performance. Any potential strength deficiencies at this stage may persevere throughout the subsequent competitive season. Given the concerns for injury prevention relating to the failure to improve strength performance across the preseason and competitive season, the present findings under-score the need for major strength training program to precede the preseason and competitive season (4). In general, continuous endurance running activity elicited less adverse adaptive strength responses than PHISR-type activity and so may be preferred on the basis that it reflects a lesser threat to cumulative inhibition of strength function.

The reduction of strength performance associated with acute functionally-relevant endurance activities
may constitute a threat to knee stability during critical phases of play within match-play or training activities and appears to correlate with emerging patterns of injury occurrence (18). Despite strength impairment in PT (and presumably in other indices of strength at intermediate knee joint positions) only, the risk of ligamentous injury may still increase if the player is unable or reluctant to sustain correct technique and knee-flexed positions in episodes of fatiguing play due to reduced strength at intermediate knee joint positions. The latter techniques have been proposed to offer favorable mechanical advantage for increased dynamic joint stabilization from the knee flexors and thus greater protection for the ACL (52).

In the present study variables reasoned to be related substantively to knee joint stability were evaluated simultaneously during acute functionally-relevant endurance activities. The observed increases to EMD and anterior TFD at joint angles considered to be most threatening to ACL integrity suggest that despite preservation of strength performance at this joint angle, the period over which unrestrained forces may build up and the degree of joint excursion before restraint takes effect is increased by up to 19% and 44%, respectively. The functional significance and potential for interactive effects of these levels of performance impairment are not yet established and require further experimental scrutiny. However, these factors represent potentially increased injury threats to ligamentous tissue. The increased EMD and overall impairment to PT may be reflected in the observed increases in 15-m sprint performance in the PHISR trial because of to impaired muscle activation times and reduced ability to accelerate limb segments. The increased EMD associated with acute functionally-relevant endurance activities and chronic exposure to such activities may contribute also to compromised neuromuscular adaptation to strength training (12).

The intermittent and acyclical nature of activity during match-play means that it is difficult to reflect fully the demands of game-related activities in laboratory experiments (40). The critical phases of match-play may demand greater functional capacities in the musculature of the knee joint than have been experienced by participants in the present study. The potential for increased threat to knee joint stability may be amplified substantially in the latter more hostile environment.

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