Concurrent changes in eccentric hamstring strength and knee joint kinematics during a soccer-specific treadmill protocol

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ABSTRACT

Objectives: To investigate the influence of soccer-specific fatigue on concurrent changes in knee joint kinematics and hamstring strength, given the increased risk of injury during the latter stages of match-play and the prevalence of knee joint and hamstring muscular injury. **Design:** Repeated measures, randomized order trials. **Setting:** Laboratory. **Participants:** Ten male professional soccer players. **Main Outcome Measures:** Reactive inversion, eversion and neutral hop tasks were completed at 15 min intervals during a soccer-specific protocol, with touchdown knee joint kinematics in the frontal and sagittal planes calculated at 200Hz. In a separate trial, players completed maximal eccentric knee flexions at $160°\cdot s^{-1}$ (reflecting average knee angular velocity in the functional task) at 15 min intervals, quantifying peak torque. **Results:** All trials were characterized by knee varus at touchdown, with ~4° greater mal-alignment elicited over the final 15 mins of the protocol ($P \leq 0.05$). Peak eccentric hamstring strength was significantly ($P = 0.045$) reduced throughout the 2^{nd} half. **Conclusions:** The coincident impairment of eccentric hamstring strength and increased knee varus at touchdown predisposes the player to injury, supporting epidemiological observations. Knee varus in these elite male players is in marked contrast to the valgus associated with ACL injury risk in female players.

Keywords: fatigue, soccer, eccentric hamstring strength, knee varus

INTRODUCTION

The epidemiology of hamstring strains in soccer is well considered (Ekstrand et al., 2011, 2013) but despite advancements in sports medicine the UEFA Elite Club injury study recently reported a 4% annual increase in hamstring injuries (Ekstrand et al., 2016). Incidence increases during the latter stages of match-play (Woods et al., 2004; Ekstrand et al., 2011) and isokinetic dynamometry studies have highlighted reductions in peak knee flexor torque during the latter stages of simulated match-play (Greig, 2008; Small et al., 2010). The bi-articular function of the hamstring is such that fatigue induced changes in strength are also likely to impact on knee joint stabilisation. Reduced eccentric hamstring strength has been associated with a reduced capacity to control frontal plane knee kinematics in a single leg squat (Claiborne et al., 2006) and during single leg landing tasks (Wild et al., 2013; Dewig, 2016).

The knee joint is the most common site for a severe injury in soccer (Ekstrand et al., 2011), with a lack of knee flexion and increased knee valgus displacement often cited as predictors of injury in soccer players (e.g. Hewett, Myer, Ford, Heidt, Colosimo, McLean, et al., 2005). Fatigue has been shown to impair frontal and sagittal plane knee joint kinematics during landing tasks (Kernozek et al., 2008; Gehring et al., 2009). Soccer-specific fatigue has also been shown to influence frontal plane knee joint kinematics during an agility task (Greig, 2009) and sagittal plane hip and knee joint angles during sprinting (Small et al., 2009). Small et al. (2010) used the same SAFT^{90} exercise protocol to highlight changes in eccentric hamstring strength metrics at 120°·s^{-1}, but this angular velocity is not a functionally valid representation of the sprinting task previously analysed

(Small et al., 2009). The aim of this study is therefore to consider concurrent changes in eccentric hamstring strength and knee joint kinematics, with the isokinetic testing speed matched to the kinematic demands of the task.

In selecting an appropriate functional task, jump landings and hopping tasks are commonly used as they replicate the mechanism of knee ligamentous injury (Garrett, 2005). Soccer is characterised by a reactive and multi-directional activity profile which is likely to increase loading at the knee joint (Besier, Cochrane & Ackland, 2001). Therefore, the aim of the present study is to examine the influence of soccer-specific activity on concurrent changes in knee joint kinematics during multi-directional, reactive, single legged jumping tasks and speed-matched eccentric hamstring strength.

MATERIALS AND METHOD

Participants

Ten male professional players completed the present study (Mean ± SD: age 24.7 ± 4.4 yr, body mass 77.1 ± 8.3 kg, VO_{2max} 63.0 ± 4.8 ml·kg·min^{-1}). Male professional soccer players were recruited so as to be specific to the epidemiology data (Woods et al., 2004; Ekstrand et al., 2011) and the notational analyses used to develop the soccer-specific exercise protocol (Greig, McNaughton, & Lovell, 2006). Further inclusion criteria stated that each player was completing a minimum of four training sessions and one match per week, and reported as having been injury free for 3 months prior to data collection. Testing was completed during the competitive season to avoid the effects of detraining, and thus participants were recruited on the understanding that they would not be selected for competitive matches in the 72hrs pre or post-testing. This combination of inclusion criteria inevitably reduced the sample of eligible players, but an *a priori* power calculation identified that a maximum of ten participants were required to establish a main effect across all primary outcome measures. All participants provided written informed consent in accordance with the departmental and university ethical procedures, and in accordance with the Helsinki Declaration.

Experimental design

Each participant performed all exercise periods between 15:00 and 17:00 h to account for the effects of circadian variation and in line with regular competition time. Each player completed two counter-balanced experimental trials (isokinetic strength testing, or kinematic analysis of hopping trials), separated by 96 hrs. A familiarization trial was completed in the week prior to experimental testing which included two 15 min bouts of the exercise protocol and completion of the hopping tasks. This trial also served to ensure players were acquainted with marker attachment for kinematic analysis. Completion of the hopping trials facilitated calculation of sagittal plane knee angular velocity time histories upon which the isokinetic testing velocity was determined. Following completion of the hopping trials, each player also completed three sets of five repetitions of the experimental isokinetic dynamometry trial by way of familiarization. This single familiarization trial was completed ≥ 96 hrs prior to the first experimental trial.

Soccer-specific fatigue protocol

The soccer-specific intermittent treadmill (LOKO S55, Woodway GmbH, Steinackerstraße, Germany) protocol (Greig et al., 2006) is represented as a 15 min activity profile (Figure 1) which is repeated 6 times in the test (i.e. 90 min), with a 15 min passive half-time interval. The protocol elicits a standardized total distance covered of 9.72 km.

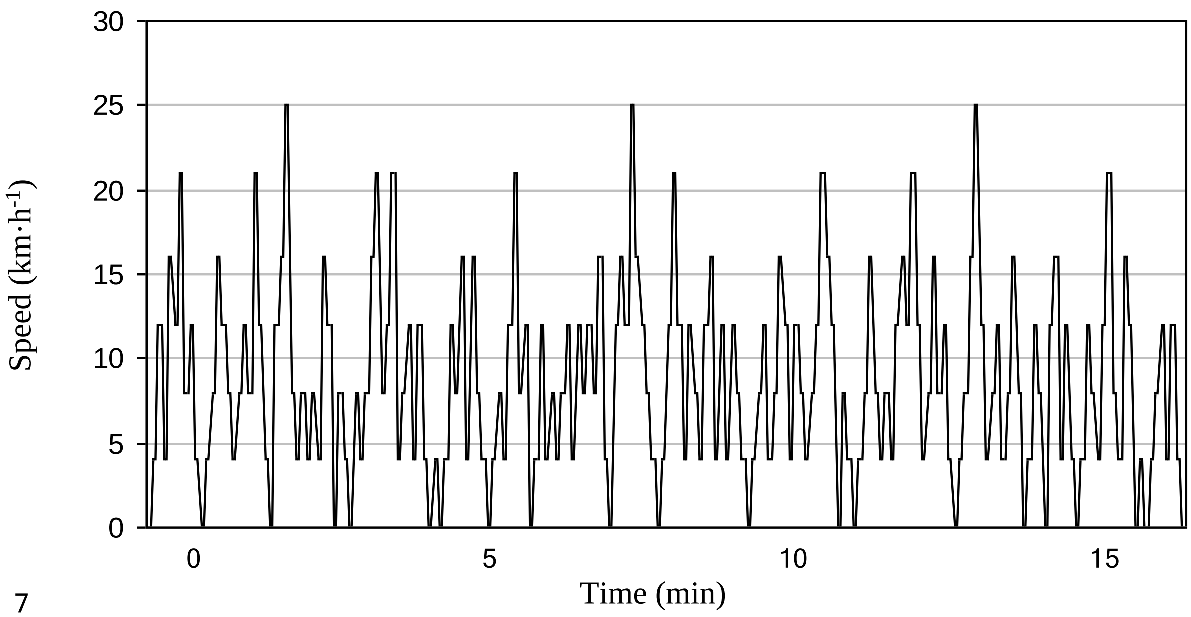

Figure 1. The soccer-specific intermittent treadmill protocol.

Isokinetic Dynamometer Trial

In the isokinetic trial (System 3, Biodex Medical Systems, New York), each player completed three maximal eccentric knee flexor repetitions pre-exercise, at 15 min intervals during the fatigue protocol, and immediately post-exercise. The dynamometer was located immediately adjacent to the treadmill, minimizing time spent in transitions.

With the dynamometer already set-up for each participant, the three-repetition assessment was completed in < 2mins. Familiarization repetitions were completed only prior to the pre-exercise trial, further minimizing time spent off the treadmill once exercise had started. Dynamometer set-up was specific to each player and based on previous applications (Greig, 2008), with the crank axis aligned with the axis of rotation of the knee and the lever arm cuff secured around the ankle at approximately 5 cm proximal to the malleoli. Repetitions were performed maximally at $160^{o} \cdot s^{-1}$, replicating the average knee flexion angular velocity across the different hopping tasks. This velocity was established from familiarization trials of the hopping tasks performed 72hrs prior to the first experimental trial, and using the same methodological approach detailed in the following section. Passive concentric knee flexion repetitions at $30^{o} \cdot s^{-1}$ were used to return the limb to the starting position between reps, and requiring no exertion from the player.

Hopping Trial

Each player completed a series of single-legged hopping tasks pre-exercise and following each 15 minute activity bout. Three hopping tasks were completed: an inversion hop, an eversion hop, and a neutral hop. All players used their dominant (defined as preferred kicking) leg for all trials. For all trials the player started from a stationary and upright position and on command hopped over two 15 cm hurdles placed 35 cm apart into a target landing zone. For the inversion hop the player then hopped laterally over a 15 cm hurdle, and medially for the eversion hop. For the neutral hop the standardized approach was followed by a hop along the continued line of travel. After the penultimate foot contact, i.e. during the flight phase, the researcher (stood beyond the neutral task hurdle) outstretched an arm to the left (or right) to signify an inversion (or eversion) hop, or placed both arms in front of the body to signify a neutral hop for height. This process was used to ensure each trial was reactive in nature (Garrett, 2005). Furthermore, trials were performed in random order and to ensure the final trial was also reactive (rather than prescribed by a process of elimination) four trials were often used. In such a case the first trial of each 'type' of hop was selected for analysis.

The movement volume was created to enable data collection of the entire movement including the takeoff and landing phases. Data was collected using nine high-speed ProReflex MCU1000 digital cameras (Qualisys, Sweden) operating at 200 Hz for real-time three-dimensional optical motion capture. The movement volume was calibrated by moving a 750mm wand throughout the movement volume. A static standing model was created for each player with passive retro-reflective markers of 20 mm diameter placed so as to define the pelvis (anterior superior iliac spine, posterior superior iliac spine, and each greater trochanter), each thigh (medial and lateral epicondyles of the femur, and a plate-mounted four marker cluster), and each shank (medial and lateral malleoli, and plate-mounted four-marker cluster). The marker configuration was reduced for the dynamic model, retaining the segmental clusters to enable tracking of each segment during the running trials. Data was captured and tracked using Qualisys Track manager software (Qualisys, Sweden), and exported in c3d format to Visual3D software (C-Motion, MD, USA) for analysis.

Data Processing

Torque-angle curves were used to determine gravity corrected peak torque, with data analysis restricted to the isokinetic phase. The average peak torque was calculated across the three repetitions. Peak torque was recorded pre-exercise and subsequently at each 15min interval.

For the kinematic data, a model template was created for each player in Visual3D (C-Motion, MD, USA). For each hopping trial (inversion, eversion, neutral), knee joint kinematics were calculated at touchdown given the injury risk associated with this event (Hewett et al., 2005). The touchdown event was identified using the displacement time history of an additional retro-reflective marker placed at the fifth metatarsal. Knee joint angle was defined as the orientation of the shank segment relative to the thigh segment, and quantified in both the sagittal plane to calculate the degree of flexion-extension, and in the frontal plane to determine the degree of knee varus-valgus. Knee joint kinematics were recorded pre-exercise and subsequently at each 15min interval during the soccer-specific exercise protocol.

In subsequent sections the performance measures are classified according to the time during the protocol, with testing conducted every 15 min through the simulated game. The pre-testing score would therefore be allocated the time subscript "t_{00}". The time classification is cumulative and includes the passive half-time interval. The end of the first half would be specified as "t_{45}", and the end of the game as "t_{105}". There are a total of eight time points across the protocol.

Statistical Analysis

The assumptions associated with a repeated measures and multi-variate General Linear Model were assessed to ensure model adequacy. To assess the residual normality for each kinematic variable, q-q plots were generated, and Mauchly's test of sphericity was completed for all variables with a Greenhouse Geisser correction where appropriate. Subsequently, inferential analyses were performed using a mixed method two-way (hop trial *x* time) repeated measures GLM to examine differences in knee joint kinematics between the three hop trials, and over the protocol duration. For eccentric hamstring torque, a univariate model was employed to investigate the influence of exercise duration, comparing data at each 15 min interval. Where significant main effects or interactions were observed, post-hoc pairwise comparisons with a Bonferonni correction factor were used. As a measure of meaningfulness, partial eta-squared (η^2) values were calculated to estimate effect sizes for main effects and interactions. All data are reported as the mean ± standard deviation, with significance accepted at $P<0.05$.

RESULTS

Figure 2 summarizes the temporal pattern of changes in peak eccentric hamstring torque. There was a significant main effect for exercise duration ($P = 0.045$, $\eta^2 = 0.167$), and post-hoc testing revealed that the peak torque was significantly reduced throughout the 2nd half ($t_{60} – t_{105}$) in comparison to pre-exercise values (t_{00}).

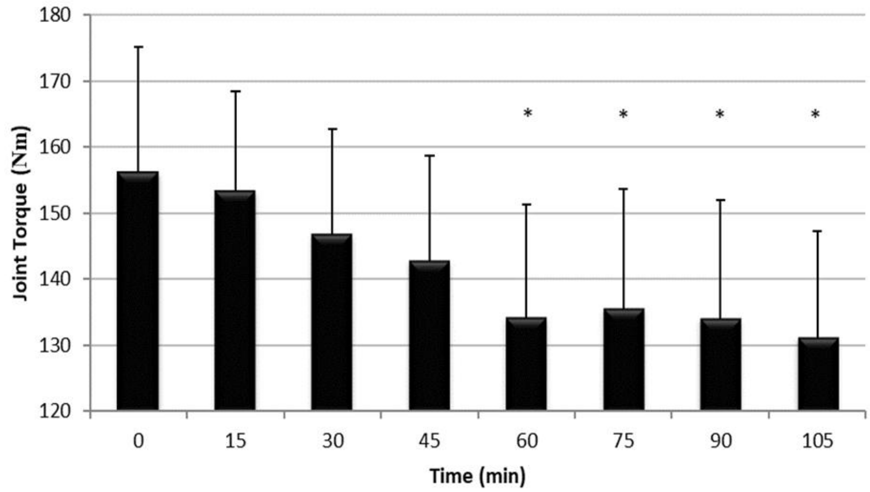

Figure 2. Time history of changes in eccentric knee flexor strength. * Significantly different to pre-exercise.

The temporal pattern of changes in knee flexion at touchdown is shown in Figure 3. There was a main effect for hop trial with the Inversion trial demonstrating significantly greater knee flexion at touchdown (P = 0.008, η^2 = 0.064) than the Eversion or Neutral trials, which were themselves no different (P = 0.963). There was no main effect for exercise time (P = 0.408, η^2 = 0.048), and no time *x* trial interaction (P = 0.877, η^2 = 0.053).

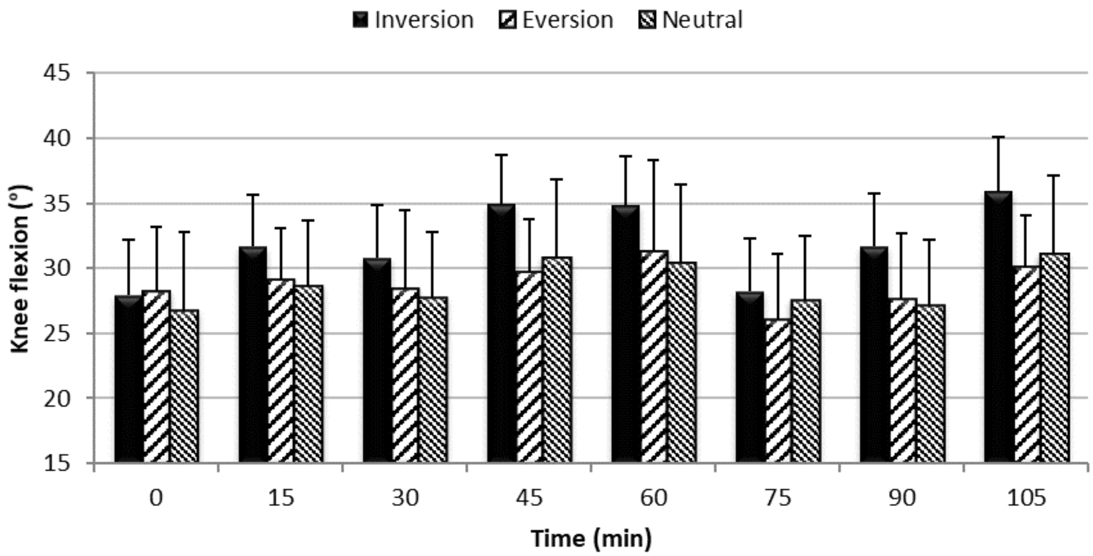

Figure 3. Time history of changes in knee flexion at touchdown.

All trials were characterized by varus knee displacement at touchdown (Figure 4). There was no significant main effect for trial (P = 0.520, η^2 = 0.009), and no interaction between time *x* trial (P = 0.999, η^2 = 0.013). Post-hoc analysis in time revealed significantly greater values at t_{90} (P = 0.050) and t_{105} (P = 0.046) compared with pre-exercise t_{00}.

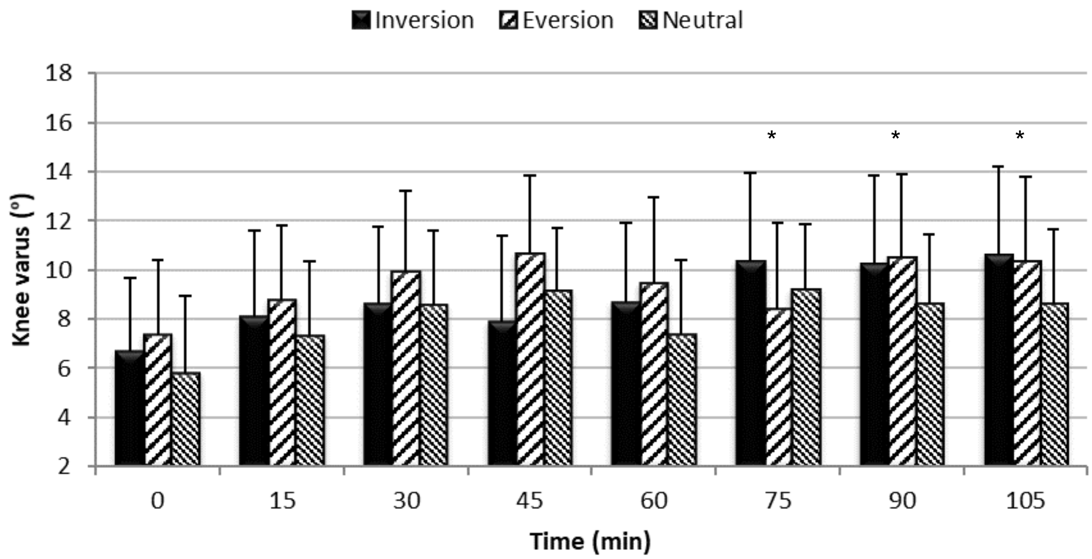

Figure 4. Time history of changes in knee varus at touchdown. * Significantly different to pre-exercise.

DISCUSSION

The aim of the current study was to investigate the temporal pattern of changes in eccentric hamstring strength and knee joint kinematics during soccer-specific intermittent activity, in light of epidemiological observations spanning more than a decade (Woods et al. 2004; Ekstrand et al. 2016).

In this cohort of elite male players, landing during all trials was characterised by a flexed knee in varus malalignment. Whilst the varus displacement of the knee might be a risk factor for ligamentous injury (Wind, Bergfeld, & Parker, 2004), the knee flexion at touchdown serves as a protective mechanism (e.g. Hewett et al., 2005). These elite male players maintained a knee flexion angle of approximately 30^{o} at touchdown, indicative of a 'soft' landing which can reduce injury risk. The degree of knee flexion at touchdown was significantly greater during the inversion trial, most likely indicative of the greater mechanical challenge imposed by this task with inversion movements incurring a greater risk of ligamentous injury (Woods, Hawkins, Hulse, & Hodson, 2003).

Knee varus alignment at touchdown was evident across all hopping tasks, but the degree of knee varus increased significantly during the final stages ($t_{90} – t_{105}$) of the simulation in comparison to pre-exercise values. A concurrent change was observed in eccentric hamstring strength, which was suppressed throughout the 2nd half of the protocol, supporting previous observations at up to $300^{o}\cdot s^{-1}$ (Greig, 2008). The decrease in eccentric hamstring strength might provide the mechanism for the increased varus displacement, as the hamstring musculature acts to stabilize the knee joint during such functional tasks. Conversely, the knee in varus would increase tension on the biceps femoris, creating an increased risk of hamstring strain injury with fatigue, supporting epidemiological observations (Woods et al., 2004). Garrett (2005) stated that during a perturbed landing the body might not have sufficient time to go through the process of selecting and executing an appropriate movement pattern, increasing the risk of ligamentous injury. The reactive movement may subsequently not be the optimal movement strategy and will be further impaired if the eccentric hamstring control required to stabilize the knee is decreased.

The observation of knee varus in this elite male sample is markedly different to the vast body of literature on the presence of knee valgus in female athletes, and worthy of discussion. Besier et al. (2001) showed that varus stress increases during cutting tasks compared to linear running, and that the stress is exacerbated further when these cutting movements are reactive (rather than prescriptive). Reactive, multi-directional movements are inherent in soccer, and thus continued exposure to soccer might produce the varus displacement observed in soccer players (Witvrouw, Danneels, Thijs, Cambier, & Bellemans, 2009; Yu, McClure, Onate, Guskiewicz, Kirkendall, & Garrett, 2005). Furthermore, in the mature form of the kicking action the angled approach to the ball and lateral hip displacement of the support limb enable long-axis rotation and increase foot (and thus ball) speed. The adduction inherent in the kicking action might also create an adductor/abductor strength imbalance with repeated exposure to kicking, which might increase the risk of knee varus. Prolonged exposure to soccer-specific activities might therefore explain the evidence of a maturation toward knee varus in soccer players (Yu et al., 2005; Witvrouw et al., 2009). Witvrouw et al. reported a significant increase in degree of genu varum in males after the age of 14, and from 16-18 years a significantly higher degree of genu varum in soccer players compared to non-football players.

The implications of a varus malalignment to injury risk is multi-factorial. Genu varum predisposes the player to injuries as the line of force at the knee is shifted medially creating a compartment load that is nearly 3.5 times that of the lateral compartment (Lewek, Rudolph, & Snyder-Mackler, 2004). Genu varum has also been identified as a risk factor for the development of patellofemoral pain syndrome (Messier, Davis, Curl, Lowery, & Pack, 1991). Hagglund, Zwerver, & Ekstrand (2011) reported that patellar tendinopathy is a fairly common condition in elite soccer, with a high recurrence rate, and exposure identified as a risk factor. Genu varum has also been associated with the deterioration of the articular cartilage in the knee's medial tibiofemoral compartment, and as a risk factor for osteoarthritis (Brouwer, van Tol, Bergink, Belo, Bernsen, Reijman, et al., 2007). Ligament and cartilage damage are the most commonly reported types of career-ending injury, with a prevalence of osteoarthritis in the knee joints of retired professional players (Drawer & Fuller, 2001; Kuijt, Inklaar, Gouttebarge, & Frings-Dresen, 2012). The knee is the most common site of both acute and chronic injuries which lead to early retirement. Chantraine (1985) reported a varus angulation in 81% of all knees in veteran soccer players and suggested that the high amount of load and torque imposed on the knee during growth and adolescence through intensive exposure may contribute to a growth deformity.

Generalizing beyond the specific research design elements of this study should be treated with caution. An elite male population was used based on the availability of injury epidemiology and notational analysis data, but the influence of gender and playing age warrant investigation. Furthermore the changes observed in hamstring strength and knee joint motion are likely to be specific to the exercise protocol used, and a treadmill protocol has some inherent limitations in replicating the demands of soccer match-play, and specifically the reactive and multi-directional characteristics of the hopping tasks. Whilst free running protocols such as the $SAFT^{90}$ have been shown to elicit a similar reduction in peak hamstring strength (Small et al., 2009), the impact of this activity profile on multi-directional tasks warrants consideration. The impact of repeated isokinetic repetitions at 15 min intervals over a total exercise trial duration of 105 mins should also be considered. Whilst not a homogeneous population, a 'control' trial replicating the volume of isokinetic testing without completion of the treadmill task elicited no deterioration in strength of a semi-professional cohort. The interaction of the treadmill and isokinetic exertions should be considered however.

CONCLUSION

Fatigue induced concurrent changes in eccentric hamstring strength and knee varus displacement, such that injury risk was greatest towards the latter stages of the 2nd half. These concurrent changes support epidemiological observations of a fatigue effect in ligamentous and muscular injury risk during match-play. The greater injury risk during inversion movements also supports previous research and epidemiological observations. The observation of knee varus malalignment in elite male soccer players is likely due to prolonged exposure to soccer-specific activities, with implications for (acute and chronic) injury risk. This is in contrast to the vast body of literature on female athletes which has related the valgus knee to injury risk.

Isokinetic dynamometry might therefore have clinical value in identifying those individuals most susceptible to fatigue-induced changes in strength, rather than simply less eccentric hamstring strength. This fatigue analysis would have implications for conditioning and prehabilitation interventions, more specifically than simply increasing strength. The association between strength and joint kinematics implicated in injury risk provides further clinical merit for isokinetic assessments, provided the isokinetic assessment has functional relevance to the demands of the sport and/or mechanism of injury. In this study functional relevance was aligned to speed matched analyses of strength and knee joint motion.

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LEGENDS TO FIGURES

Figure 1. The soccer-specific intermittent treadmill protocol.

Figure 2. Time history of changes in eccentric knee flexor strength. * Significantly different to pre-exercise.

Figure 3. Time history of changes in knee flexion at touchdown.

Figure 4. Time history of changes in knee varus at touchdown. * Significantly different to pre-exercise.