Intermittent treadmill running induces kinematic compensations to maintain soccer kick foot speed despite no change in knee extensor strength

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Abstract

Kicking is a fundamental skill and a primary non-contact mechanism of injury in soccer, with injury incidence increasing during the latter stages of match-play. Ten male professional soccer players completed a 90min treadmill protocol based on the velocity profile of soccer match-play. Pre-exercise, and at 15 min intervals, players completed a maximal velocity kick subjected to kinematic analysis at 200 Hz. Pre-exercise, and at the end of each half, players also completed isokinetic concentric knee extensor repetitions at 180, 300 and 60 $°\cdot s^{-1}$. Kicking foot speed was maintained at ~19 $m\cdot s^{-1}$, with no main effect for exercise duration. In relation to proximal-distal sequencing during the kicking action, there was a significant increase in the duration (but not magnitude) of thigh rotation, with a compensatory decrease in the duration (but not magnitude) of shank rotation during the latter stages of the exercise protocol. In relation to long-axis rotation, pelvic orientation at ball contact was maintained at ~6°, representing a total pelvic rotation in the order of ~15 ° during the kicking action. Peak knee extensor torque at all speeds was also maintained throughout the protocol, such that kinematic modifications are not attributable to a decline in knee extensor strength.

***Keywords*:** soccer, kicking technique, injury, isokinetic strength

Word Count: 3475

Introduction

Despite the disproportionate increase in goals scored and injuries incurred during the last 15 minutes of soccer match-play, the influence of fatigue on technical performance is limited. Kicking represents both a fundamental movement skill and a primary non-contact injury mechanism in soccer, but few studies have considered kicking technique in relation to fatigue. Fatigue-induced changes in kicking precision [1] and kicking velocity [2] have been observed, but the authors measured only outcome and failed to discuss the associated changes in technique. Exhaustive protocols based on knee extension-flexion repetitions,[3] repeated counter movement jumps,[4] and treadmill running[5] fail to adequately reflect the activity profile of soccer match-play, and therefore interpretation in relation to injury epidemiology and aetiology is limited. In developing an experimental approach to the problem of replicating the activity profile of soccer, match-play represents the optimum in terms of ecological validity. However, the lack of experimental control limits opportunity for biomechanical analysis, and the influence of confounding variables such as playing position, opposition and score negate the opportunity to develop a standardized workload. Whilst free-running variants offer the opportunity to include utility movements such as changes in direction, treadmill models offer the greatest level of control in standardizing the activity profile. However, previous attempts to develop intermittent running protocols to simulate the demands of soccer match-play,[6] have failed to replicate the velocity profile and frequency of speed change observed during match-play.

Kicking is often cited in relation to the high incidence of muscle strains in the thigh.[7,8] Quadricep muscle strains frequently occur in kicking sports,[7-9] and lower extremity musculotendinous injuries are the most common type of injury in American football kickers.[10] Kicking performance has been positively correlated with concentric quadriceps strength,[11] and shown to improve following a resistance training program.[12] Previous research has demonstrated a fatigue-effect on muscular strength of the knee extensors,[13,14] which might subsequently affect kicking technique and performance. During the soccer kick, the foot rotates about both the medio-lateral and longitudinal axes of the body and several mechanisms contribute to foot speed.[15] A primary mechanism is due to the interaction of the thigh and shank in creating a proximal-to-distal sequencing pattern of segmental angular velocities. If the strength of the knee extensor musculature is compromised by fatigue, the proximal-distal mechanism acting to generate foot (and ultimately ball) speed might be inhibited. Such an alteration in technique would have implications for both performance and injury.

Despite the apparent links between fatigue, strength, and kicking performance, no study has previously employed a valid exercise protocol to examine both strength and kicking technique. In examining the influence of fatigue on soccer kicking technique, and the impact of muscular strength on performance, the choice of exercise protocol is fundamentally important. In the present study an intermittent treadmill protocol validated against notational analyses of soccer match-play is used,[16] which has previously been shown to induce changes in agility kinematics.[17] This same exercise protocol has been shown to influence the electromyographical response of the thigh musculature during running,[16] and impair eccentric knee flexor strength.[18] The purpose of the study was to investigate the temporal influence of a 90min intermittent treadmill protocol on knee extensor strength and kicking performance in soccer players. It was hypothesized that cumulative exposure to the exercise protocol would reduce peak knee extensor torque and kicking velocity.

Methods

Participants

Ten male professional soccer players were recruited (Mean ± SD; age 20.8 ± 1.7 yr, body mass 72.7 ± 4.7 kg). All players were recruited from a team playing in the Championship, reflecting the second tier of professional soccer in England. All players were free from injury over the previous season, and provided written informed consent in accordance with departmental and university ethical procedures at the host institution, and in the spirit of the Helsinki Declaration.

Experimental Design

Each participant completed the exercise protocol between 15:00 and 17:00 h to account for the effects of circadian variation and in accord with regular competition time. Each player completed the treadmill running protocol which has been previously validated against the velocity profile of soccer match-play in terms of the frequency and duration of each discrete bout of running at each speed.[16] The 15min activity profile (Figure 1) is repeated six times, with a 15 min half-time interval, and elicits a total distance covered of 9.72 km.[16] Pre-exercise and following each 15min activity bout, each player completed a single maximal velocity kick of a stationary ball. The kicking trials were completed in the immediate proximity to the treadmill location, minimizing the time spent away from the treadmill. Including any modifications required to the marker set-up as a result of prolonged exercise duration, the kicking trials were completed within 30sec before the player returned to the treadmill. The isokinetic testing was conducted pre-exercise and at the end of each 45min period, i.e. just before the half-time interval and at the end of the protocol. Given the greater time required to complete the isokinetic testing (compared with the kicking trials), this design ensured that disruption of the exercise protocol was reduced.

** Figure 1 near here **

Outcome Measures

The kicking trials comprised a single maximal velocity kick of a stationary ball, with no accuracy constraint. The approach was self-selected by the participant in each trial relative to a standardised ball placement. The movement volume was created to enable data collection of the final approach stride and the follow-through. 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 750 mm wand throughout the movement volume. A static standing model was created for each player with passive retro-reflective markers (Qualisys, Sweden) 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 (lateral knee, medial knee and a plate-mounted four marker cluster), each shank (lateral ankle, medial ankle and plate-mounted four-marker cluster) and each foot (calcaneus, fifth metatarsal head, fifth metatarsal base, and first metatarsal). This marker configuration was reduced to create the dynamic model. This reduction in marker set-up also reduced disruption in marker placement as a result of the prolonged exercise duration, minimizing any alterations required prior to each kicking trial. To enable tracking of each segment during the kicking trials the thigh and shank clusters remained, in addition to the posterior and anterior superior iliac spine markers to track the pelvis, and the calcaneus, fifth metatarsal head and base, and the lateral ankle markers to define each foot segment. Given the prolonged exercise duration, marker placement was supplemented with additional fixation where appropriate. 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 where a model template was created for each player.

The performance measure of the kicking action was defined as the mass centre velocity of the kicking foot at ball contact, given its high correlation with ball speed.[19] Temporal phases were used to define the kicking action:[20] Stage 1 refers to the withdrawal of the thigh and shank during the backswing and was defined as the time between maximum knee flexion and the initiation of forward rotation of the thigh; Stage 2 until the instant when the thigh angular velocity is reduced and the shank angular velocity increases; Stage 3 to the instant of ball contact. The segmentation process to define the discrete kicking stages was completed manually, reflecting individual nuances in kicking technique which limited automated identification in some cases. The manual identification of stage initiation/termination was completed using time histories of the segmental and joint angles and angular velocities. Intra-class correlation coefficients of ≥ 0.87 were obtained for this segmentation process across all kicking phases.

Thigh and shank angle time histories were quantified at the start of each temporal stage, to examine the contribution of the proximal-distal sequencing kicking mechanism

(Figure 2). The long-axis rotation kicking mechanism was first considered with respect to the self-selected approach angle, defined relative to the direction of the kick over the final approach stride. The length, angle relative to the kicking direction, and duration of this final approach stride were quantified using metatarsal coordinate data between final and penultimate foot contacts. The final foot contact represents planting of the support foot prior to the kicking action, and the lateral displacement of the support foot relative to the ball was also calculated. The orientation of the pelvis relative to the frontal plane was also quantified for each stage, given the contribution of pelvic rotation to kicking performance.[15,21] Coordinate data of the anterior superior iliac spine, posterior superior iliac spine, and each greater trochanter were used to define the pelvis, with orientation defined relative to the axial plane (Figure 2).

** Figure 2 near here **

Pre-exercise and at the end of each half, each player completed five dominant limb (defined as the kicking leg) maximal effort knee extensor repetitions at isokinetic speeds of 180, 300 and 60°·s^{-1} (System 3, Biodex Medical Systems, New York). There was a rest period of 60 seconds between each set, and passive concentric knee flexion at 30°·s^{-1} was used between each rep. Dynamometer set-up was specific to each player and based on previous applications,[22] with range of motion preset from full extension to a 90° range of motion. Gravity-corrected peak torque was calculated at each test speed across the five reps, with data considered only during the isokinetic phase of the movement.

Statistical Analysis

In subsequent sections the kinematic and isokinetic measures are classified according to the time during the protocol, with testing conducted every 15min through the simulated game. The pre-testing score would therefore be allocated the time subscript “00”. The time classification is cumulative and includes the passive half-time interval. The end of the first half would be specified as “45”, the start of the second half as “60”, and the end of the game as “105”.

One-way repeated measures ANOVA was used to investigate the influence of time on peak knee extensor torque, kicking foot velocity at ball contact, and the kinematics (angle, length, duration, lateral displacement of the support foot relative to the ball) of the final approach stride. For kicking stage duration, segmental displacement and pelvic orientation, a two-way repeated measures ANOVA was used to investigate a within factors main effect for time, and for kicking stage. Interaction effects between time and kicking stage were subsequently examined, where a significant interaction would infer a change in kinematics across the kicking stages and over the duration of the exercise protocol. The assumptions associated with each statistical model were assessed to ensure model adequacy. To assess residual normality for each dependant variable, q-q plots were generated using stacked standardised residuals. Scatterplots of the stacked unstandardized and standardised residuals were also utilised to assess the error of variance associated with the residuals. Mauchly's test of sphericity was also completed for all dependent variables, with a Greenhouse Geisser correction applied if the test was significant. Where significant main effects were observed, post hoc pairwise comparisons with a Bonferonni correction factor were applied. The GLM was supplemented with partial eta squared (η^2) values calculated to estimate effect sizes for each dependant variable, and provide a measure of meaningfulness. Where the GLM post hoc comparisons identified a significant difference, this was supplemented with a calculation of effect size (ES) quantified using Cohen's d formula as the standardized difference between means. All statistical analysis was completed using PASW Statistics Editor 22.0 for windows (SPSS Inc, Chicago, USA). Statistical significance was set at $p \leq 0.05$, and all data are presented as mean ± standard deviation.

Results

Kicking performance was not affected by time ($F = 1.15$; $p = .352$; $\eta^2 = .14$), with kicking foot velocity at ball contact maintained between 18.2 ± 1.2 - 19.7 ± 1.3 $m \cdot s^{-1}$.

Kinematics of the final approach stride were also unaffected by time. The angle of approach at ~13 ^{o} ($F = 0.28$; $p = .961$; $\eta^2 = .04$), the length of the final stride at ~1.60 m ($F = 0.18$; $p = .976$; $\eta^2 = .03$), and the duration of this stride at ~0.12 s ($F = 0.30$; $p = .948$; $\eta^2 = .14$) were maintained throughout the protocol. The lateral displacement of the support foot relative to the ball was maintained at ~ 0.27 m ($F = 1.05$; $p = .413$; $\eta^2 = .13$).

Kicking stage duration (Figure 3) was not influenced by time ($F = 1.09$; $p = .375$; $\eta^2 = .05$), but there was a main effect for stage ($F = 982.21$; $p < .001$; $\eta^2 = .93$). The duration of Stage 1 was significantly shorter than both Stage 2 and Stage 3 ($p < 0.001$), which were themselves not different ($p = .144$). Stage 1, the stretch-reflex action, is assigned a negative duration as the thigh started to rotate (initiating Stage 2) while the knee was still flexing. There was also a significant time x stage interaction ($F = 2.47$; $p = .004$; $\eta^2 = .19$). Stage 1 (p = 0=.013; ES = 1.13) and Stage 2 ($p = .025$; ES = 1.25) duration was greater at t_{105} than at t_{00}, whilst Stage 3 duration ($p = .013$; ES = 1.86) was significantly reduced. Thus during the latter stages of the exercise protocol, the relative duration of each stage had changed.

** Figure 3 near here **

Time did not affect either thigh (F = 0.31; $p = .946$; $\eta^2 = .02$) or shank (F = 0.53; $p = .810$; $\eta^2 = .04$) angular displacement relative to the vertical axis (Figure 4). Thigh displacement was consistent across the kicking stages (F = 0.75; $p = .388$; $\eta^2 = .01$). In contrast, shank displacement did elicit a main effect for stage (F = 316.78; $p < .001$; $\eta^2 = .77$), with angular displacement significantly lower in Stage 2 than in Stage 3 ($p < .001$) at all time points. There was no stage x time interaction effect for thigh (F = 0.50; $p = .830$; $\eta^2 = .04$) or shank (F = 0.48; $p = .848$; $\eta^2 = .03$) displacement.

** Figure 4 near here **

Pelvis orientation (Figure 5) was unaffected by time (F = 0.49; $p = .844$; $\eta^2 = .02$), but did reveal a main effect for stage (F = 52.96; $p < .001$; $\eta^2 = .46$). Pelvis orientation was significantly greater at foot plant than at the start of Stage 2 ($p = .078$), the start of Stage 3 ($p < 0.001$) and ball contact ($p < 0.001$). Pelvic orientation at the start of Stage 2 was significantly higher than at the start of Stage 3 and ball contact ($p < 0.001$), and this continued with significantly reduced pelvic orientation at ball contact relative to Stage 3 ($p = 0.003$). The pelvic orientation at ball contact was maintained at ~6°, representing a total pelvic rotation in the order of ~15 ° during the kicking action. There was no interaction effect between stage and time (F = 0.12; p = .999; η^2 = .01).

** Figure 5 near here **

Peak knee extensor torque was not affected by time (F = 0.25; p = 0=.97; η^2 = .01) at any testing speed (Figure 6). There was a main effect for testing speed (F = 67.48; p < =.001; η^2 = .39), with peak torque significantly lower ($p < 0.001$) with each increase in isokinetic speed. The force-velocity curve is therefore as expected with $T_{60} > T_{180} > T_{300}$. There was no interaction effect between isokinetic speed and time (F = 0.14; p =.999; η^2 =.01).

** Figure 6 near here **

Discussion

The aim of the present study was to investigate the temporal pattern of kicking kinematics and knee extensor strength throughout an intermittent treadmill protocol based on the activity profile of match-play.[16] Performance of the kick, quantified as foot velocity at ball contact was maintained between 18 - 20 $m \cdot s^{-1}$ throughout the exercise protocol and in accord with previous observations.[23] This is in contrast to the findings of previous studies,[3-6] however direct comparison is difficult due to methodological differences, particularly in relation to the exercise protocol used. Soccer match-play is self-paced and sub-maximal, with a typical distance covered eliciting an average velocity of ~ 6.5 $km \cdot h^{-1}$

over the duration of a 90 min game. The activity profile is intermittent in nature, with periods of low intensity interspersed with high intensity efforts.[16] In comparison to the present study, previous exercise models used prior to kicking trials have comprised exhaustive knee extension-flexion repetitions,[3] counter movement jumps,[4] and treadmill running protocols that do not replicate the intermittent nature of soccer.[5,6] The relatively greater intensity of these exercise models, in comparison to the present study, most likely creates the decrease in kicking performance. The influence of the chosen exercise model is also likely to impact upon factors such as muscle type recruitment, mode of contraction, and metabolic demands with implications on performance. The maintenance of kicking speed parallels the lack of a fatigue effect in knee extensor strength, these parameters having been shown to be highly correlated.[11] There was no change in maximal knee extensor torque, even at the higher testing speeds, with peak torque decreasing with increased isokinetic velocity as expected. There was also no change in the characteristics of the self-selected approach to the kick.

Despite the maintenance of strength and kicking speed, there were temporal patterns in kinematic markers of kicking technique. During the kick the thigh segment starts to rotate forward while the knee is still flexing, which stretches the extensor muscles of the thigh before they shorten.[20] This stretch-shortening component has previously been shown to be beneficial in developing distal point velocity,[24] but has also been highlighted as a potential mechanism of quadriceps strain injury.[8] The duration of Stage 1 increased during each half, suggesting a fatigue effect, although maximum knee flexion of the kicking leg was unaffected and maintained between 99 – 103°. To initiate the forward swing of the thigh and start Stage 2 of the kicking action, the knee extensor musculature must reverse the direction of the limb by powerfully concentrically contracting.[25] With the increased duration of Stage 1, if the pre-stretch placed upon the muscle becomes so great that the succeeding concentric contraction of the muscle is weakened, then injury might result. The biarticular nature of rectus femoris and its role in knee extension, hip flexion and pelvic stabilization has been associated with an increased risk of injury.[8] Kicking is commonly identified as the most common mechanism of rectus femoris injury,[7-10] but a focus on a specific muscle is not possible with isokinetic dynamometry generating a net torque for the knee extensors. In a study of injuries sustained by American football kickers, lower extremity musculotendinous injury represented 49% of all injuries.[10] In this study the injury pattern of the punting technique was different to place kicking, with place kicking more representative of the technique adopted in this study. The two most common injuries sustained by kickers were adductor strains and hamstring strains.[10] A second potential implication of the extended pre-stretch is an increase in the passive elastic recoil of the rectus femoris tendon, increasing the load which must be counteracted by the eccentrically contracting hamstrings. The decrease in eccentric hamstring strength elicited in previous studies using this same exercise protocol[18] may further impair the ability of the hamstrings to effectively decelerate the limb and avoid injury.

A compensatory change was observed in Stages 2 and 3 during the kicking action, with Stage 2 increasing and Stage 3 decreasing in duration during the final 30mins of the exercise protocol. These observations suggest a change in the proximal-distal nature of the kicking action that places greater emphasis on the second stage of the kicking action and rotation of the thigh as a result of hip flexion.[20] Kinetic analyses of kicking have consistently reported that the joint contribution from the hip is greater than that from the knee.[26] Stage 2 of the kick, driven by the musculature of the hip and thigh, has been reported to contribute about half of the shank angular velocity at contact.[20] The remaining contribution is derived from a transfer of energy from the thigh to the shank during Stage 3. The temporal pattern of kinematic modifications during the latter stages of the second half therefore places greater emphasis on the musculature driving hip flexion. The bi-articular function of the hamstrings musculature is then problematic, with the same exercise protocol having been shown to increase the EMG response to the activity profile,[16] and decreasing values of peak eccentric hamstring torque.[18] Practical implications highlight a need for eccentric hamstring strength development, since the fatigue of the hamstring musculature during this exercise protocol might underpin the compensatory change in kicking technique. Kicking mechanics changed following a muscle strengthening program,[12] and the lack of change in quadriceps strength in comparison with a decrease in hamstrings strength in our study might elicit the same technical adaptations.

The observed changes in the proximal-distal mechanisms are supported by the mechanism of long axis rotation, as greater pelvic displacement in the initiation of the kick serves to promote the greater contribution made by the thigh segment.[21] By ‘opening’ the pelvis during Stage 1 of the kick, a potentiation effect is achieved to pre-empt the thigh rotation. This is analogous to ‘opening’ the shoulders during a tennis serve or golf swing. Rotation about the longitudinal axis operates as a second mechanism contributing to end-point velocity of the lower-limb kinetic chain.[27,28] The mechanisms of increasing foot speed during the kicking action do not occur in isolation and might be complimentary, as observed in upper-body movements.[29-31] In soccer, substantial forces act through the anterior pelvis, and the cumulative affect with repetitive kicking actions has been implicated in the pathogenesis of osteitis pubis and chronic adductor strains.[32]

It must be acknowledged that the interpretation of data should not be generalized beyond the experimental design choices of the present study. The use of professional players was considered fundamentally important given the relevance to both the notational analyses used to develop the exercise protocol, and the epidemiological data used to generate the research hypotheses. The use of professional players to complete an additional 'match', in addition to exclusion criteria relating to injury history, inevitably limited the sample size. In addition, gender and playing level are likely to be confounding factors, but opportunity is limited currently in valid exercise protocols and epidemiological data. The use of a treadmill protocol inevitably limits the opportunity to consider the multi-directional nature of soccer, and whilst real match-play lacks ecological validity, free-running alternatives might be considered, particularly where there is less demand on the attachment of micro-technologies. The isokinetic profiling was restricted to concentric knee extensor strength, and the order and magnitude of testing speeds is an important consideration. Based on the mechanism of eccentric rectus femoris injury,[8] and the associated risk of adductor and hamstring injury in kickers,[10] a more comprehensive isokinetic evaluation is advocated. The kicking trial was completed with no accuracy constraint, so as to focus on maximal velocity of the kicking action. The speed-accuracy trade-off with prolonged exercise would be an interesting opportunity for future research.

In conclusion, completion of a 90min intermittent running protocol based on the activity profile of match-play induced no change in knee extensor strength or kicking foot velocity. However, there was evidence of kinematic compensations which will alter musculo-skeletal loading and may increase the risk of ligamentous and muscular injury across multiple sites, supporting epidemiological data. Specifically, elongated duration of the pre-stretch during the backswing, increased pelvic orientation at the start of the forward kicking motion, and greater reliance on thigh rotation during the forward kicking motion were observed. These changes suggest greater mechanical effort, or at least perceived effort, to maintain performance in the fatigued state. Kicking is a primary mechanism for muscle strain injury, the incidence of which is higher in training than in competition,[33] as a result of greater exposure. The common practice of concluding training sessions with shooting drills should be given consideration. The epidemiological observations of increased thigh muscle strain injury during the latter stages of match-play[7,33] suggest that consideration of the biomechanical demands of match-play be considered in strength training regimes.

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References

1. Russell M, Benton D, Kingsley M. The effects of fatigue on soccer skills performed during a soccer match simulation. *Int J Sports Physiol Perf.* 2011;6:221-233.
2. Ferraz R., van den Tillar R., Marques M.C. The effect of fatigue on kicking velocity in soccer players. *J Hum Kinet.* 2012;35:97-107.

3. Apriantono T, Nunome H, Ikegami Y, et al. The effect of muscle fatigue on instep kicking kinetics and kinematics in association football. *J Sports Sci.* 2006;24(9):951-960.
4. Torreblanca-Martinez V, Otero-Saborido FM, Gonzalez-Jurado JA. Effects of muscle fatigue induced by CMJ on efficacy parameters of instep ball kicking in soccer. *J Appl Biomech.* In press.
5. Katis A, Amiridis I, Kellis E, et al. Recovery of powerful kick biomechanics after intense running fatigue in male and female soccer players. *Asian J Sports Med.* 2014;5(4):e24013.
6. Kellis E, Katis A, Vrabas IS. Effects of an intermittent exercise fatigue protocol on biomechanics of soccer kick performance. *Scand J Med Sci Sports.* 2006;16:334-344.
7. Hagglund M, Walden M, Ekstrand J. Risk factors for lower extremity muscle injury in professional soccer. The UEFA injury study. *Am J Sports Med.* 2013;41(2):327-335.
8. Mendiguchia J, Alentorn-Geli E, Idoate F, et al. Rectus femoris muscle injuries in football: a clinically relevant review of mechanisms of injury, risk factors and preventive strategies. *Br J Sports Med.* 2013;47:359-366.
9. Orchard J, Seward H. Epidemiology of injuries in the Australian Football League seasons 1997-2000. *Br J Sports Med*. 2002;36:39-44.
10. Brophy RH, Wright RW, Powell JW, et al. Injuries to kickers in American football: the National Football League experience. *Am J Sports Med*. 2010;38:1166-1173.

11. Cabri J, De Proft E, Dufour W, et al. The relation between muscular strength and kick performance. In: Reilly T, Lees A, Davids K, Murphy WJ eds. *Science and Football*. London: E & FN Spon; 1998.

12. Manolopoulos E, Katis A, Manolopoulos K, et al. Effects of a 10-Week Resistance Exercise Program on Soccer Kick Biomechanics and Muscle Strength. *J Strength Cond Res*. 2013;27(12):3391–3401.

13. Gleeson NP, Reilly T, Mercer H, et al. Influence of acute endurance activity on leg neuromuscular and musculoskeletal performance. *Med Sci Sports Exerc*. 1998;30:596-608.

14. Rahnama N, Reilly T, Lees A, et al. Muscle fatigue induced by exercise simulating the work rate of competitive soccer. *J Sports Sci.,* 2003;21:933-942.

15. Lees A. Technique analysis in sports: a critical review. *J Sports Sci*. 2002;20:813-828.

16. Greig MP, McNaughton L, Lovell RJ. Physiological and mechanical response to soccer-specific intermittent activity and steady-state activity. *Res Sports Med*. 2006;14:29-52.

17. Greig MP. The influence of soccer-specific activity on the kinematics of an agility sprint. *Eur J Sports Sci*. 2009;9(1):23-33.

18. Greig MP, Siegler J. Soccer specific fatigue decreases eccentric hamstring strength. *J Athl Train*. 2009;44(2):180-184.

19. Bull Andersen T, Dorge HC, Thomsen FI. Collisions in soccer kicking. *Sports Eng*. 1999;2:121-125.

20. Lees A, Nolan L. The biomechanics of soccer: A review. *J Sports Sci.* 1998;16:211-234.

21. Inoue K, Nunome H, Sterzing T, et al. Dynamics of the support leg in soccer instep kicking. *J Sports Sci.* 2014;32(11):1023-1032.

22. Greig, M. The influence of soccer-specific fatigue on peak isokinetic torque production of the knee flexors and extensors. *Am J Sports Med.* 2008;36(7)1403-1409.

23. Isokawa M, Lees A. A biomechanical analysis of the instep kick motion in soccer. In: Reilly T, Lees A, Davids K, Murphy WJ, eds. *Science and Football*. London: E & FN Spon; 1998.

24. Bober T, Putnam C, Woodworth GC. Factors influencing the angular velocity of a human limb segment. *J Biomech*. 1987;20:511-521.

25. Hsu JC, Fischer DA, Wright RW. Proximal rectus femoris avulsions in national football league kickers. *Am J Sports Med.* 2005;33(7):1085-1087.

26. Luhtanen P. Biomechanical aspects. In: Ekblom B, ed. *Football (Soccer)*. Oxford: Blackwell Scientific; 1994

27. Rodano R, Tavana R. Three dimensional analysis of the instep kick in professional soccer players. In: Reilly T, Clarys J, Stibbe A, eds. *Science and Football II*. London: E & FN Spon; 1993.

28. Browder KD, Tant CL, Wilkerson JD. A three dimensional kinematic analysis of three kicking techniques in female players. In: Tant CL, Patterson PE, and York SL, eds. *Biomechanics in Sport IX*. Ames, Iowa: Iowa State University Press; 1991.

29. Marshall RN, and Elliott BC. Long-axis rotation: The missing link in proximal-to-distal segmental sequencing. *J Sports Sci.* 2000;18:247-254.

30. Bahamonde RE. Changes in angular momentum during the tennis serve. *J Sports Sci.* 2000;18:579-592.

31. Hirashima M, Kadota H, Sakurai S, et al. Sequential muscle activity and its functional role in the upper extremity and trunk during overarm throwing. *J Sports Sci.* 2002;20:301-310.

32. Rodriguez C, Echegoyen S, Miguel A, et al. Soccer injuries: study in three seasons. *J Athl Train.* 1998;33:S21.

33. Hawkins RD, Hulse MA, Wilkinson C, et al. The association football medical research programme: an audit of injuries in professional football. *Br J Sports Med.* 2001;35:43-47.

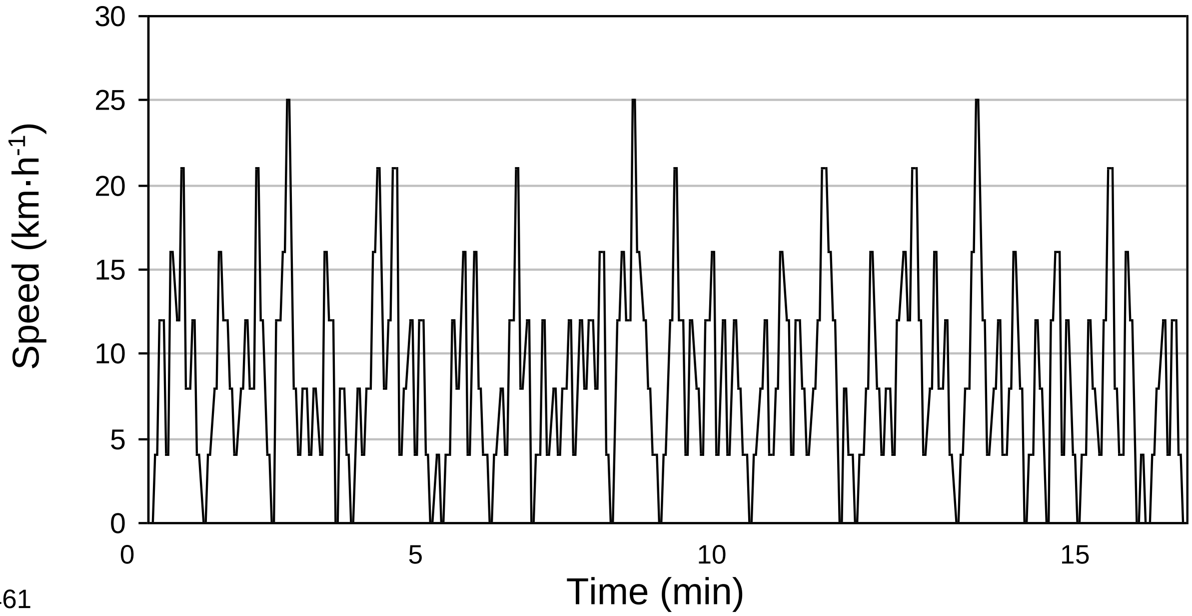

Figure 1. The 15 minute intermittent exercise bout.[16]

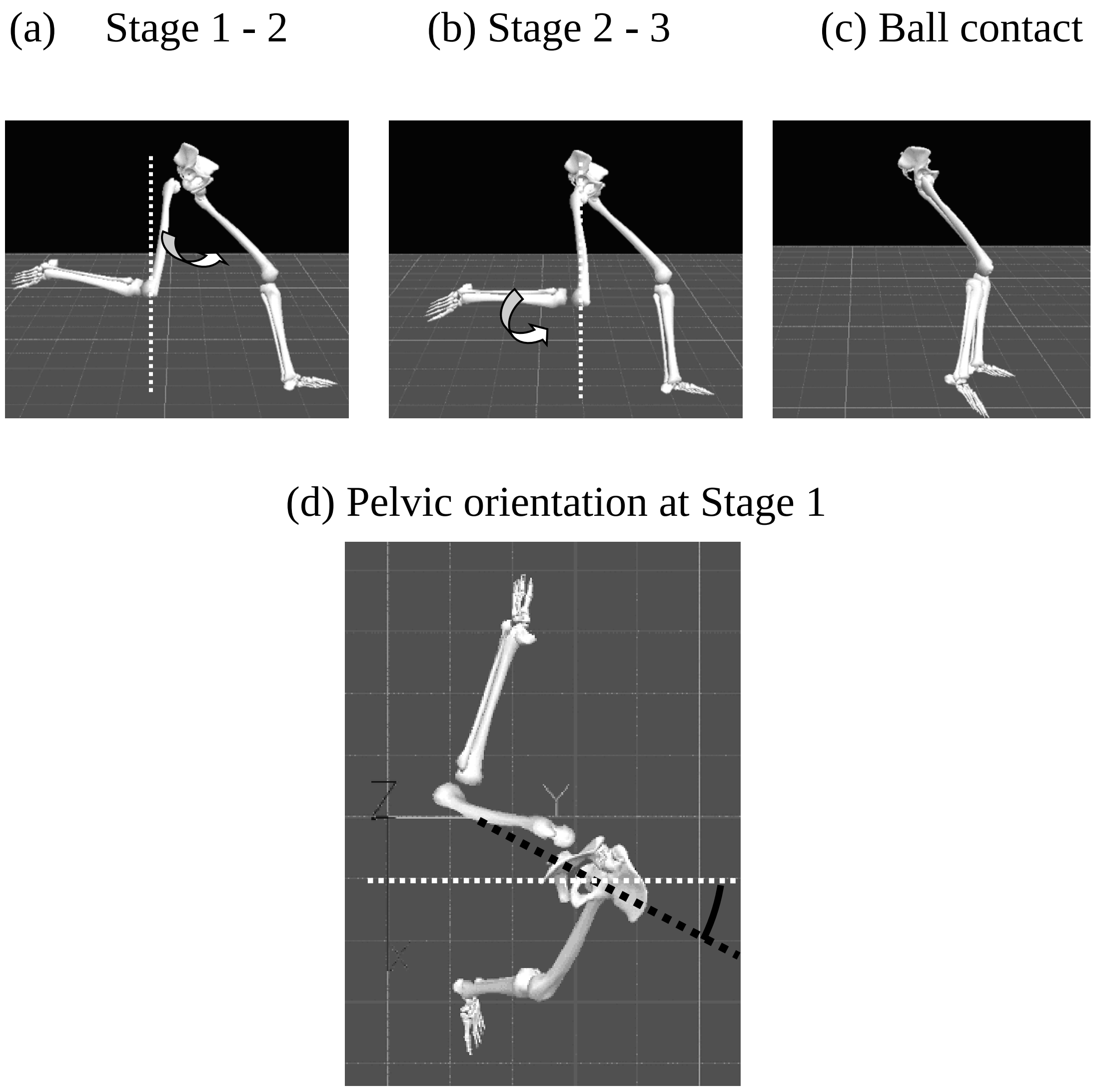

Figure 2. (a) Forward thigh rotation to start Stage 2, (b) Forward shank rotation to start Stage 3, (c) Ball contact, (d) Calculating orientation of the pelvis relative to the axial plane.

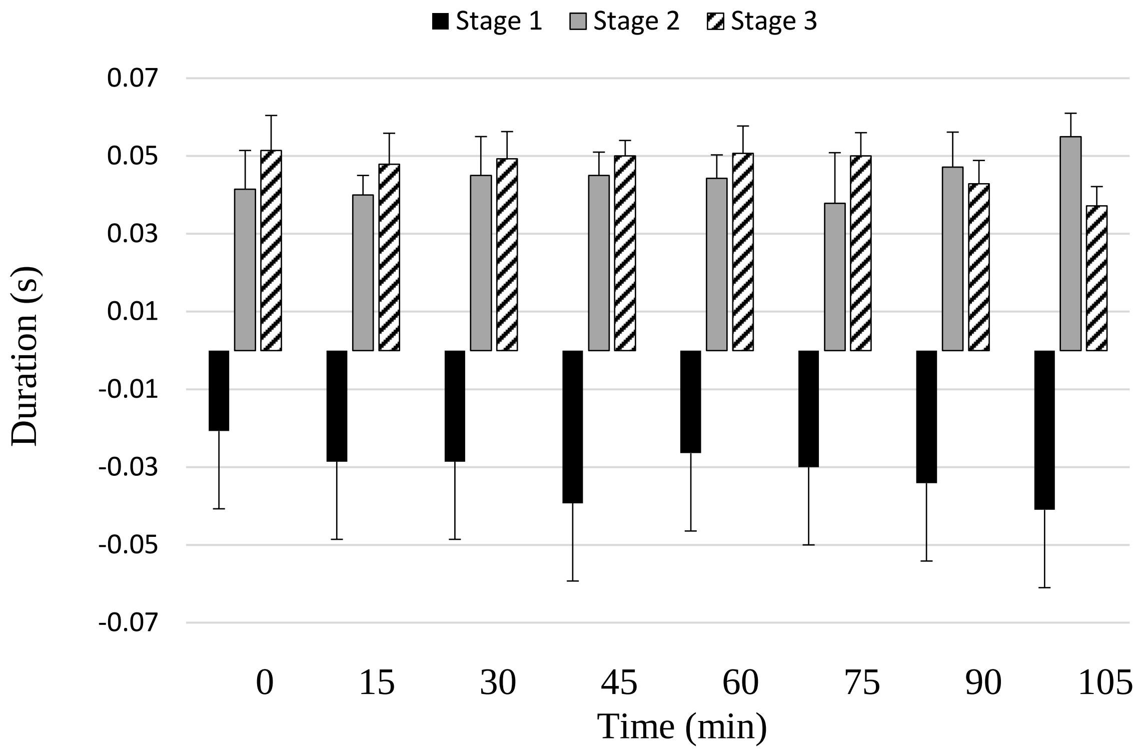

Figure 3. The temporal pattern of changes in Stage duration during the exercise protocol. * signifies significantly greater than t_{00}, & signifies significantly greater than t_{00}-t_{75}, # signifies significantly less than t_{00}-t_{75}.

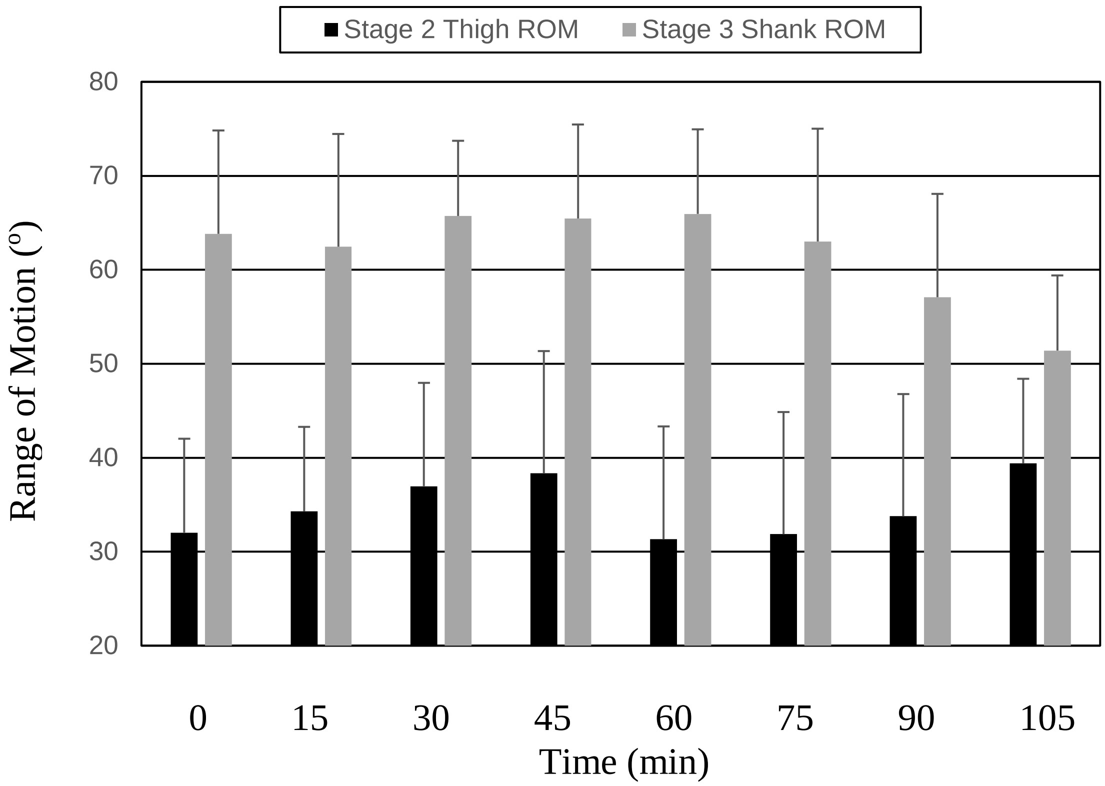

Figure 4. The temporal pattern of changes in thigh (Stage 2) and shank (Stage 3) rotation.

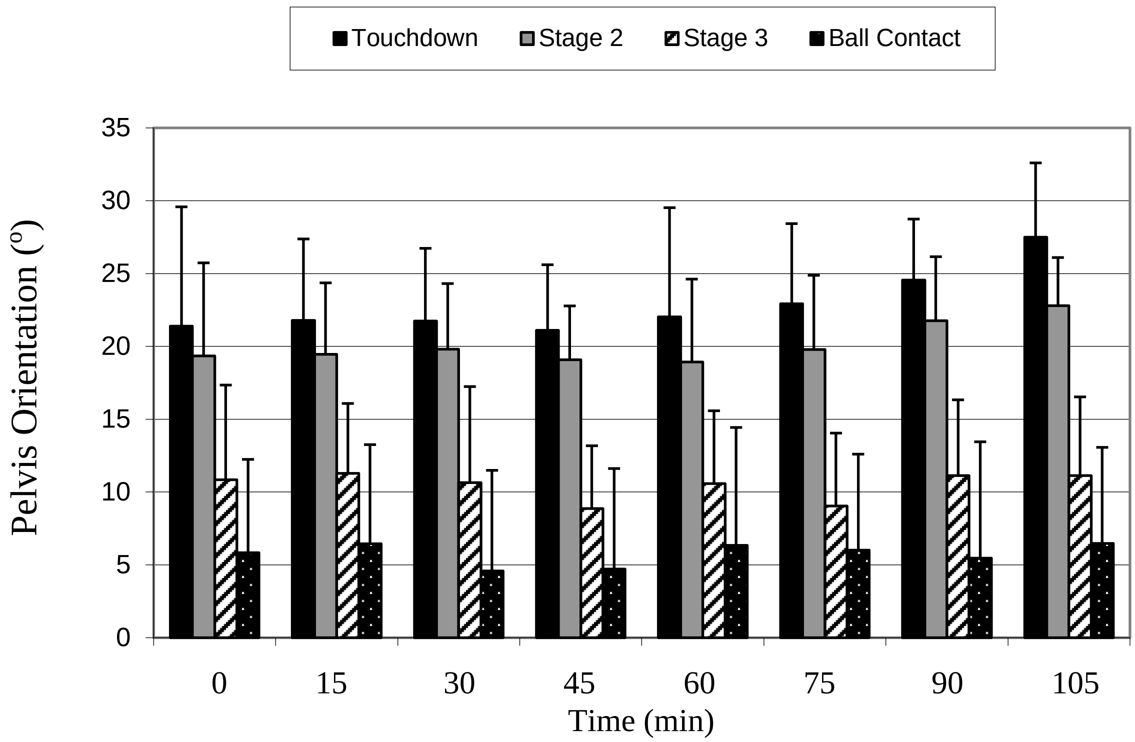

Figure 5. The temporal pattern of changes in pelvic orientation during the exercise protocol.

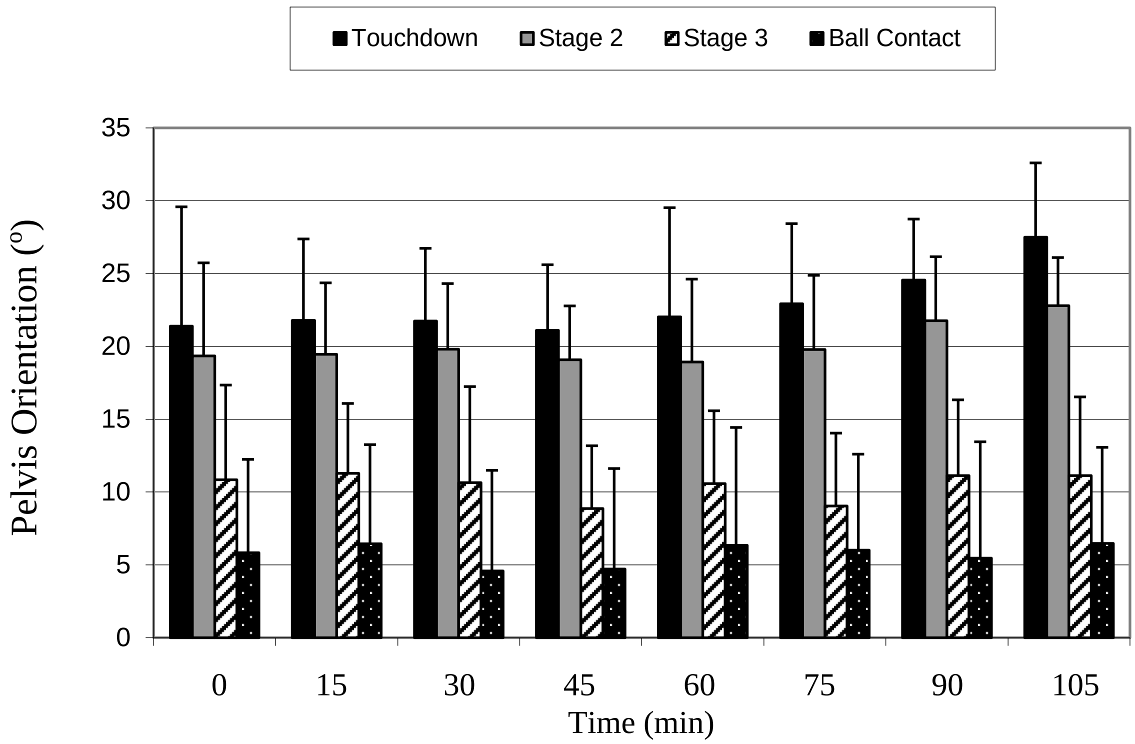

Figure 6. The temporal pattern of changes in peak knee extensor torque at each testing speed.