Physiological Responses to Linear and Non-Linear Soccer-Specific Match Simulations and their Effects on Lower-limb Muscle Fatigue

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ABSTRACT

We investigated: i) the effects of linear and non-linear soccer simulations on lower-limb muscle function and physiological responses and ii) evaluated the relationship between match-running demands and changes in lower-limb muscle function. In a repeated measures crossover design, 8 participants completed either a linear or non-linear adapted Loughborough intermittent shuttle test (LIST) on two occasions. The movement of players was tracked with a global positioning system (GPS), while lower-limb muscle function tests and physiological measurements were performed before and every 15-min during the simulation. There was no differences in distance covered, yet high-speed running ($P = 0.007$), accelerations ($P = 0.008$) and decelerations ($P = 0.015$) were higher in the linear LIST. Mean heart rate ($P = 0.001$) and ratings of perceived exertion ($P = 0.013$) were higher in the non-linear LIST. Peak landing forces ($P = 0.017$) and jump height ($P = 0.001$) were reduced between baseline and 90-min but were not different between conditions. Changes in peak landing forces from baseline to half-time ($r = -0.57$, $n = 16$, $P = 0.022$) and full-time ($r = -0.58$, $n = 16$, $P = 0.019$) were related to high-speed running. Hamstring force was unaffected by time ($P = 0.448$) but was reduced in the linear LIST ($P = 0.044$). Protocols posing different external and internal demands elicited similar levels of fatigue across simulations. Hamstring function was not an effective indicator of fatigue but our results highlight the greater demands placed on this muscle group when higher-speed running is performed.

Key words: football; global positioning systems; change of direction; fatigue

INTRODUCTION

Soccer is characterised by prolonged low-intensity movement, interspersed by periods of high-intensity running, including both high and low-speed movements of varying energetic demand (25). In the context of team sports, fatigue can be identified by a reduction in performance (28), reflected by changes in distance covered, particularly at higher speeds, across progressive stages of a match (35). Recent advancements in player tracking technologies, such as global positioning systems (GPS), have facilitated the monitoring of fatigue during matches, which typically manifests during the end of the first half and during the second half of a match (1, 21, 29, 34).

Fatigue occurs in soccer matches owing to a combination of central and peripheral factors (7, 14, 21, 35). There are numerous ways to measure the effects of fatigue during or after matches, such as, invasive laboratory and non-invasive field-based tests (14, 27). Indeed, changes in physical function of the lower-limbs have been identified after soccer matches (19). However, due to the impracticality of laboratory-based assessments, it is common to simulate match-specific performance and adopt tests that can be reliably applied to more ecologically valid environments with greater ease. For example, assessments of muscle function, using dynamometry (10, 26) or portable force plate analysis (24), have identified reductions in strength and changes in landing kinetics after simulated treadmill-based soccer matches.

Whilst treadmill-based simulation protocols are commonly used for experimental control (10, 24, 26), they lack ecological validity. Consequently, field-based protocols such as the Loughborough Intermittent Shuttle Test (LIST) (23) or the Soccer-Specific Aerobic Field Test (SAFT^{90}) (16), have been used to simulate soccer match play and evaluate the effects of match-specific fatigue. For example, Small et al. (31) demonstrated reduced hip flexion and knee extension angles, as well as decreased stride length during a sprint at the end of each half of the SAFT^{90}. This was interpreted by Small and colleagues to place players at greater risk of hamstring strain. To further enhance ecological validity, adopting the use of a simulation protocol, such as the SAFT^{90}, that includes non-linear running patterns (changes of direction; COD) and high-intensity accelerating and decelerating movements is necessary. Non-linear running is frequently performed during soccer matches, with professional players completing 727 ± 203 swerves and turns within a single match (3). To successfully complete these actions in soccer, repetitive demanding muscle contractions are necessary (2), including those of an eccentric nature. The cumulative effect of performing these actions ultimately leads to fatigue, the adoption of less efficient movement patterns (31) and the potential for increased injury risk (10). Reports have suggested that Non-linear running induces greater heart rate, perceptual and metabolic responses than straight-line (linear) running (6) but this has been questioned in recent studies, where equal reductions in counter-movement jump and drop jump height were identified (11). However, the effect of non-linear activity has not been directly examined in a sports-specific scenario. Furthermore, there is limited understanding of the relationship between the demands of a soccer match and the degree of functional impairment in the lower-limbs.

The aims of this study were to: i) investigate the effects of linear and non-linear soccer simulations on acute lower-limb muscle fatigue and physiological responses and ii) evaluate the relationship between match-running demands and changes in lower-limb muscle function across different simulated match conditions. It was hypothesised that a protocol including more changes of direction would be more physiologically demanding and induce greater functional impairments than traditional simulations, characterised by greater periods of linear motion.

METHODS

Experimental Approach to the Problem

A repeated measures, counter-balanced crossover design was used, with participants completing either a linear (23) or non-linear adapted LIST protocol on two separate occasions, separated by one week. Field-based measurements of lower-limb muscle function were performed before, during (every 15-min) and immediately after each test. The participants were monitored with Global Positioning System (GPS) devices (FieldWiz, Advanced Sport Instrument Sarl, Switzerland) throughout each protocol, while physiological responses were measured via heart rate (HR) telemetry (Zephyr HxM BT, Medtronic, Annapolis, USA), rating of perceived exertion (RPE; 6-20) (4) and analysis of capillary blood lactate concentration (B[La]) (Biosen C Line, EKF diagnostic GmbH, Barleben, Germany). Including familiarisation, participants visited the testing facility on three occasions at the same time on each day. The participants were instructed to eat according to their normal diet and avoid caffeine and alcohol consumption in the 24-h prior to testing, as well as strenuous exercise in the 48-h before

Subjects

8 male university team sports players consented to take part in this study (Table 1). To be included in this study, the participants were screened for their readiness to perform physical exercise (PAR-Q) and were required to achieve a minimum level of nine on the multi stage fitness test (MSFT). Institutional ethical approval was given for this study, which was conducted in accordance with the 1964 Helsinki declaration.

*******Insert Table 1 here*******

Procedures

Initial pilot testing was conducted to develop the non-linear LIST, in an attempt to incorporate the 727 COD instances reported by Bloomfield et al. (3), without changing the duration of the test or intended total distance covered. The resulting design replaced the 55% and 95% $\dot{V}O_{2max}$ running sequences with a non-linear course (Figures 2 and 3). This meant that there were 120-144 COD per 15-min cycle and between 720 and 864 COD across the entire non-linear LIST, which ranged based on fitness levels. The traditional linear LIST has a total of 300-360 COD activities across the entire protocol. This design also ensured an equal total distance between courses, as well as an equal number of left and right-sided COD across the protocol. The intensity of the COD course during the non-linear LIST was calculated from the participants' maximal time-trial performance across one cycle of the non-linear course, which was previously determined during the familiarisation session. The maximal non-linear time trial was multiplied by 1.5 and used as the final intensity, which was determined via analysis of heart rate responses to this course compared to the linear protocol.

One week before testing, participants visited the testing facility for the first time. Each participant performed a standardised warm-up, followed by a maximal non-linear time trial. Their time was recorded for subsequent calculation of the COD intensity on the non-linear LIST. The maximal non-linear time-trial was based on the fastest time of two trials. The participants' were then tested for lower-limb muscle function, using a countermovement (CMJ) and isometric hamstring force (ISO), measured via a force plate (PASCO force plates, 1000 Hz, PASPORT PS-2141, PASCO, Roseville, CA, USA). After a 20-min period of rest, the MSFT was performed outdoors on a grass surface. The participants highest score (level) was used to determine their running intensity during the linear LIST, as described by

Nichloas et al. (23). After 60-min of rest, the participants performed three runs of a single 15-min cycle of the LIST protocol, based on their individualised intensities from the MSFT, followed by three runs of the adjusted LIST, based on their fastest agility time trial performance. Participants were reminded of the audio signals (instructions) used in the LIST and given time to listen to the audio file.

Testing was performed outdoors on a firm grass surface, in dry, calm conditions. The weather during the trial was recorded on a mobile weather station (Accuweather for Android, Accuweather Inc, USA). The mean temperature across all trials was 17.2°c and the mean humidity was 62%. The LIST protocols were all developed in audio software (Audacity Windows, Audacity 2.1.2, Boston, USA) and played through speakers connected to a laptop (Windows 10, Asus X55C). The participants wore the same shorts and t-shirt for both tests and their own studded football boots, which were only removed to perform the lower-limb muscle tests. They were permitted to drink water *ab-libitum* during the LIST and always performed the test on their own (rather than in pairs) and were given non-specific verbal encouragement throughout. The two lower-limb muscle field tests (CMJ and ISO), as well as physiological and perceptual measurements, were recorded immediately before each LIST condition, every 15-min during the test and immediately after.

Countermovement jump test

Countermovement jump (CMJ) tests were standardised, by the participants placing their hands on their hips and standing with their feet shoulder-width apart on the force plate. Participants were asked to descend into a quarter-squat and then jump as high as possible, without bending their legs in the air and without moving their hands. The jump was repeated twice with a 30-s rest between each jump. The highest jump height (cm) and subsequent peak force (N) was recorded on landing and had inter-day CVs of 2.2% and 3.2% respectively.

Isometric hamstring test

Isometric hamstring force of both legs was tested using the same force plate, following the protocol of McCall et al. (19). The test was performed on the right leg, with the participants lying supine on the floor. The hips and knees of the working leg were flexed to 90°, using a goniometer (Lafayette Instrument Company, USA), and rested on top of an elevated force plate. The force plate was fitted to an adjustable wooden plinth. The position of the participant was recorded for consistency between both conditions of the LIST. The contralateral leg was rested flat on the floor next to the plinth, with the knee remaining fully extended throughout the testing period. The participant pushed their heel into the force platform as hard as possible for 3-s, without lifting their buttocks, hands or head off the floor. The participants performed the tests barefooted. The contraction was repeated twice with 30-s rest between attempts. The highest peak force (N) was recorded. This test has a inter-day reliability of 6% CV, which is similar to that reported by McCall et al. (19).

Linear LIST

The linear LIST comprised 6 intervals and was performed for a total of 90-min, interspersed by 4-min recovery periods every 15-min cycle (Figure 1). During each 4 -min recovery period, the participants walked for 30-s from the field to the laboratory, where they performed a CMJ and isometric hamstring test. Whilst in the laboratory, the participants provided an RPE score and capillary blood was drawn from a finger for B[La], which was placed in an Eppendorf solution for later analysis. Heart rate was measured continuously throughout the trial reported as mean and peak per 15-min cycle of the LIST protocols.

******Insert Figure 1 here******

Adjusted non-linear LIST

The adapted non-linear LIST protocol (Figure 2) was based on the original version (i.e. linear LIST) but the 55% and 95% $\dot{V}O_{2max}$ sequences were replaced with two multidirectional runs at 1.5 × non-linear time trial (performed on the familiarization day) (Figure 3) for the whole protocol, without altering total simulation time or activity time during the simulation.

******Insert Figure 2 and 3 here******

Movement analysis

Global Positioning System (GPS) devices were fitted between the scapulae of the participants within a tightly fitting vest. The devices sampled at 10 Hz and an intra-unit reliability of between 1.0 %, 3.1 %, 4.7 % and 5.9 % CV for walking, jogging, sprinting and linear change of direction activities, respectively, which are all included in the LIST. The GPS devices were later attached to a laptop and data was extracted and imported into a customised excel spreadsheet, where analysis was conducted. Peak speed (km/h), mean speed (km/h), total distance (m), high-speed running distance (m) (> speed associated with final stage of the MSFT), low speed running distance (< speed associated with final stage of the MSFT), mean metabolic power (W/kg), number of accelerations and decelerations above 3 m/s^2 and the peak accelerations and decelerations were calculated.

Statistical Analyses

A-priori sample size estimations were conducted using G*Power (Version 3.0.10) (8). Based on the typical effect sizes (Cohen's $d > 0.3$) reported for changes in variables, such as jump height across a soccer match, with a statistical power of 0.80 and alpha level of 0.05, a sample size of 8 was estimated. A two-way repeated measures analysis of variance (ANOVA) was used to evaluate the main effects of time (Baseline, 15-min, 30-min, 45-min, 60-min, 75-min, 90-min) and condition (LIST, Adapted LIST) and their interactions on the dependent variables. If tests of Sphericity were violated, the Greenhouse-Giesser correction was used. In the event a statistical difference was identified, a *post-hoc* Bonferroni test was used to identify differences. Effect sizes (Cohen's *d*) were also performed on pairwise comparisons and defined as; trivial = 0.2; small = 0.21–0.6; moderate = 0.61–1.2; large = 1.21–1.99; very large > 2.0 (5). Where pairwise differences were apparent at baseline, the baseline values were added as a covariate (i.e. ANCOVA). Changes in peak landing forces were also evaluated with ANCOVA, using CMJ height as the covariate. Bivariate correlations (Pearson's *r*) were used to assess the relationships between physiological response and changes in force and movement (GPS) variables. The strength of the relationships was considered as: < 0.3 = weak, 0.3-0.5 = moderate; > 0.5 = strong (5). An alpha level of $P \leq 0.05$ was set for all analyses. Statistical analysis was conducted through IBM SPSS (Software V22.0, IBM, New York, USA).

RESULTS

Movement analysis

As presented in Figure 4, there were effects of condition ($F_{(1,7)} = 13.819$, $P = 0.007$) and time for high-speed running ($F_{(5,35)} = 4.531$, $P = 0.03$) but no interaction ($P = 0.438$). High-speed running (HSR) was different from baseline at 75-min ($P = 0.014$) and 90-min ($P < 0.001$). There were no effects of condition ($F_{(1,7)} = 0.027$, $P = 0.874$) or time ($F_{(5,35)} = 1.000$, $P = 0.230$) for total distance covered. There were condition ($F_{(1,7)} = 13.141$, $P = 0.008$) and time effects on the number of accelerations ($F_{(5,35)} = 14.517$, $P < 0.001$) as well as an interaction ($F_{(5,35)} = 8.874$, $P < 0.001$). *Post-hoc* tests showed that the number of accelerations were higher in the LIST compared to the adapted LIST at 15-min (162 ± 74 *vs.* 69 ± 22; $P = 0.041$, $d = -0.06$, 95% CI = -1.01 to 0.95) 30-min (136 ± 55 *vs.* 75 ± 34; $P = 0.010$, $d = -1.33$, 95% CI = -1.82 to 0.34), 45-min (118 ± 63 *vs.* 72 ± 31; $P = 0.015$, $d = -0.92$, 95% CI = -1.51 to 0.55) and 75-min (104 ± 49 *vs.* 69 ± 32; $P = 0.048$, $d = -0.85$, 95% CI = -1.47 to 0.58). Similarly, there was a condition ($F_{(1,7)} = 10.410$, $P = 0.015$) and time effect for the number of decelerations ($F_{(5,35)} = 4.690$, $P = 0.002$) but no interaction effect ($F_{(5,35)} = 1.209$, $P = 0.326$). There was an effect of condition only on average metabolic power ($F_{(1,7)} = 15.110$, $P = 0.008$), which was higher in the linear LIST (11.5 W/kg *vs.* 10.2 W/kg).

******Insert Figure 4 here******

Physiological and perceptual responses

As presented in Figure 5, there were effects of condition ($F_{(1,7)} = 32.218$, $P = 0.001$) and time for average heart rate ($F_{(6,42)} = 306.390$, $P = 0.001$) and interactions ($F_{(6,42)} = 3.313$, $P = 0.039$). *Post-hoc* tests showed that average HR was higher in the adapted LIST compared to the LIST at 15-min (165 ± 8 b/min *vs.* 161 ± 6 b/min; $P = 0.021$, $d = 0.57$, 95% CI = -0.71 to 1.29) and 60 min (163 ± 5 b/min *vs.* 157 ± 7 b/min; $P = 0.029$, $d = 0.99$, 95% CI = -0.51 to 1.56). Similarly, there were effects of condition ($F_{(1,7)} = 20.470$, $P = 0.003$) and time for peak heart rate ($F_{(6,42)} = 455.307$, $P = 0.001$) as well as an interaction effect ($F_{(6,42)} = 0.694$, $P = 0.046$). *Post-hoc* tests showed that peak HR was higher in the adapted LIST compared to the

LIST at 15 min (180 ± 6 b/min *vs.* 175 ± 7 b/min; $P = 0.039$, $d = 0.77$, 95% CI = -0.62 to 1.41), 60 min (178 ± 5 b/min *vs.* 171 ± 7 b/min; $P = 0.03$, $d = 1.15$, 95% CI = -0.43 to 1.24), 75 min (179 ± 7 b/min *vs*. 171 ± 7 b/min; $P = 0.017$, $d = 1.14$, 95% CI = -0.44 to 1.67) and 90 min (179 ± 6 b/min *vs.* 172 ± 8 b/min; $P = 0.016$, $d = 0.99$, 95% CI = -0.51 to 1.56).

There were effects of time for RPE ($F_{(6,42)} = 56.971$, $P = 0.001$) and interactions with condition ($F_{(6,42)} = 3.129$, $P = 0.013$), with *post-hoc* tests revealing higher RPE scores in the adapted LIST compared to the LIST at 15 min (15 ± 2.6 *vs.* 12 ± 2.9; $P = 0.018$, $d = 0.29$, 95% CI = -0.84 to 1.13) and 30 min (15 ± 2.6 *vs.* 14 ± 2.4; $P = 0.028$, $d = 0.4$, 95% CI = -0.79 to 1.19). There were only effects of time for blood lactate ($F_{(6,42)} = 7.580$, $P = 0.028$).

******Insert Figure 5 here******

Lower-limb muscle function

There were baseline differences in isometric hamstring force ($P = 0.033$). ANCOVA with control for baseline values revealed effects of condition for peak isometric hamstring force ($F_{(6,42)} = 2.342$, $P = 0.048$) but no effects of time ($P = 0.448$) (Figure 6). However, there were no effects of condition ($F_{(1,7)} = 5.678$, $P = 0.059$) but time effects for peak landing force ($F_{(6,42)} = 2.957$, $P = 0.017$) but no interactions ($P = 0.169$). Peak landing force was different at 90-min compared to baseline ($P = 0.003$). Only time affected peak jump height ($F_{(6,42)} = 10.616$, $P = 0.001$) with no condition interactions ($F_{(6,42)} = 0.709$, $P = 0.644$). Pairwise differences were found between 0-min and 45-min ($P = 0.025$), 60-min ($P = 0.011$), 75-min ($P = 0.002$) and 90-min ($P < 0.001$).

(Insert Figure 6 here)

Relationships between movement variables and changes in force production

There were significant relationships between HSR m/min and the change in peak landing force between baseline and half-time ($r = -0.57$, $n = 16$, $P = 0.022$) and baseline and full-time ($r = -0.58$, $n = 16$, $P = 0.019$) (Figures 7A and 7B). There were no other significant relationships ($P > 0.05$).

******Insert Figure 7 here******

DISCUSSION

We tested the hypothesis that non-linear simulated soccer performance would be more physiologically demanding and induce greater functional lower-limb muscle impairments compared to a linear simulated course. Accordingly, the non-linear course matched the total distance covered but elicited greater heart rate and perceptual demands, despite the linear course eliciting the greater HSR, accelerations, decelerations and metabolic power. Thus, the overall interpretation is that non-linear sports-specific running alters the internal:external load ratio, such that less external intensity is achieved, sometimes for a greater internal load. In contrast to our hypothesis, there were no effects of condition for peak jump height or peak landing forces, yet these did change between baseline and the end of the match. Conversely, there were no effects of time on hamstring isometric force but there was an overall effect of condition. Collectively, these findings suggest that peak jump height and landing forces can be attenuated by match simulations but that isometric hamstring function is not an indicator of fatigue. However, the lower hamstring force in the linear condition indicates that the type of locomotion will influence the locality of muscle fatigue. That is; accumulation of high-velocity running distance will influence hamstring force production but non-linear running performed during lower-velocity movements will induce equal lower-limb muscle fatigue but not alter hamstring function.

There were time effects for HSR by 75-min and 90-min of the match, thus indicating a match-like fatigue profile (35). Jump height and landing forces were concurrently reduced over the course of a match in both conditions, indicating the susceptibility of the lower-limbs to soccer-specific fatigue; however, this can be induced via different locomotor/physiological demands. These tests measure the capacity to generate propulsive forces (CMJ) and absorb landing forces (dropping from landing), which are both necessary components of high-intensity movement for a soccer player. The acute reduction in jump height is consistent with findings in simulated soccer (24) and after general fatiguing protocols (20, 30). These changes can be related to both peripheral and central mechanisms, as inferred by the induction of low-frequency fatigue and loss of voluntary activation after soccer matches (27).

The change in peak landing force is less well-researched but offers an indication that ‘softer’ landing strategies are adopted once fatigue has ensued. These changes could be related to structural alterations in the muscle-tendon complex or muscle activation patterns, resulting in leg-stiffness reductions. Our results somewhat contrast the findings of others (24), where increases in landing forces were identified after a treadmill-based soccer simulation. However, Oliver and colleagues investigated this in drop-jump landings and it is possible that jump landing fatigue manifests differently whilst landing from self-regulated heights. Given the statistical control for jump height in this study, this result might signify an interesting phenomenon, whereby the fatigued athlete reduces their jump height and adopts a different subsequent landing strategy to distribute the absorbed forces. In support of this, repetitive exhaustive isometric contractions have been shown to decrease tendon stiffness in the plantarflexors (12), which are partly responsible for force absorption during jump landing. Furthermore, reductions in vertical stiffness after repeated jumping have been attributed to reduced pre-activation of the triceps surae and knee extensor muscles, which are responsible for controlling the stiffness and the storage or elastic energy on landing (13, 15). Strategic changes in jump landing performance might also be adopted under soccer-specific fatigue. For example, male participants have been shown to land with increased hip external and knee internal rotation, as well as knee valgus, to help distribute the absorbed landing forces over different vectors and, thus, muscle fibres (33). Given the likelihood of muscle damage during and after the LIST protocol (18), such a strategy would provide a logical way of dealing with the imposed mechanical demands. Irrespective of the reasons for a reduced peak landing force after a simulated soccer match, the changes infer an alteration in jump landing kinetics, which might have potential implications for other parameters of soccer performance, such as reductions in running economy (9).

The traditional linear running LIST induced greater reductions in hamstring function, despite this not reducing as a function of time. The higher velocities achieved in the linear protocol are one potential explanation of this, although there was no direct correlation between these variables. During sprinting actions, substantial demand is placed on the hamstring muscle group to eccentrically control the rate of hip flexion and knee extension during the swing phase (22). At high velocity this demand is increased and, as such, a simulation with faster linear movements could feasibly reduce hamstring force. Whilst this partly explains the differences between conditions, it does not indicate why the hamstring force measurements included in this study lacked sensitivity for the identification of match-fatigue, which is not consistent with the reports of others (10, 17, 18, 31, 32). This could be related to the form of hamstring force test (19), which was shown to change in response to competitive matches. It is possible that the stress of soccer matches induced greater hamstring fatigue, given that the LIST does not involve any ball skills or sprints past ~ 15 m distance. Nevertheless, this finding has implications for practitioners in soccer and suggests that lower velocity sessions of equal volume, yet greater physiological load appear to place less demand on the hamstring muscle group.

The relationships found between HSR and peak landing force suggest that movements performed in higher speed categories make a partial contribution to the change in landing mechanics of players after soccer performance. Perhaps a more noteworthy finding is the non-significant relationships between any other match running variable and lower-limb muscle tests. This facilitates our understanding of the current data, since it removes the possibility that the relationship of HSR with peak force decrement is the product of covariation. For example, without a thorough analysis, the mandatory decelerations that follow each high-speed activity in the LIST might be expected to explain the changes in peak landing force. As HSR is registered on the GPS device when high-speed thresholds are surpassed, other GPS variables that register lower-speeds, yet are energetically demanding activities, such as metabolic power and accelerations can also be discounted. This finding highlights the importance of HSR as a marker of match-related lower-limb muscle fatigue and should be incorporated into the monitoring of soccer and the planning of training sessions.

PRACTICAL APPLICATIONS

These findings have implications for soccer practitioners in regard to the selection of training drills and monitoring of key metrics during training and matches. Soccer simulations with more frequent changes of direction may be used to induce higher physiological demands while a fixed-distance linear running alternative will permit greater external load (HSR and accelerations, decelerations) for a lower internal demand. Whilst the internal and external demands may vary, the lower-limb muscle responses across stages of the match are mostly similar, with peak jump height and landing forces reduced by the end of the match. This can allow coaches to tailor soccer training towards an internal/external demand focus while still eliciting all the lower-limb muscle responses of a typical game. When all simulated performances were considered, the relationship of HSR was identified as the only correlate of changes in peak landing forces. This also indicates HSR as an important marker of match-related lower-limb muscle fatigue and should be incorporated into the monitoring of soccer and the planning of training sessions. It should be recognised that the current findings relate, specifically, to the moderately trained, young, male subjects used in this study and should not be extrapolated to other populations until further research is conducted.

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Acknowledgements

We would like to thank Matthew Saunders for his help with data collection for this study.

Figures

Table 1. Participant characteristics (*n* = 8)

Participant characteristics	**Mean ± standard deviation**
Age (years)	24 ± 5
Stature (cm)	179.5 ± 5.3
Body mass (kg)	81.8 ± 6.9
Training age (years)	8 ± 4
$\dot{V}O_{2max}$ (ml.kg^{-1}.min^{-1})	51.4 ± 6.2

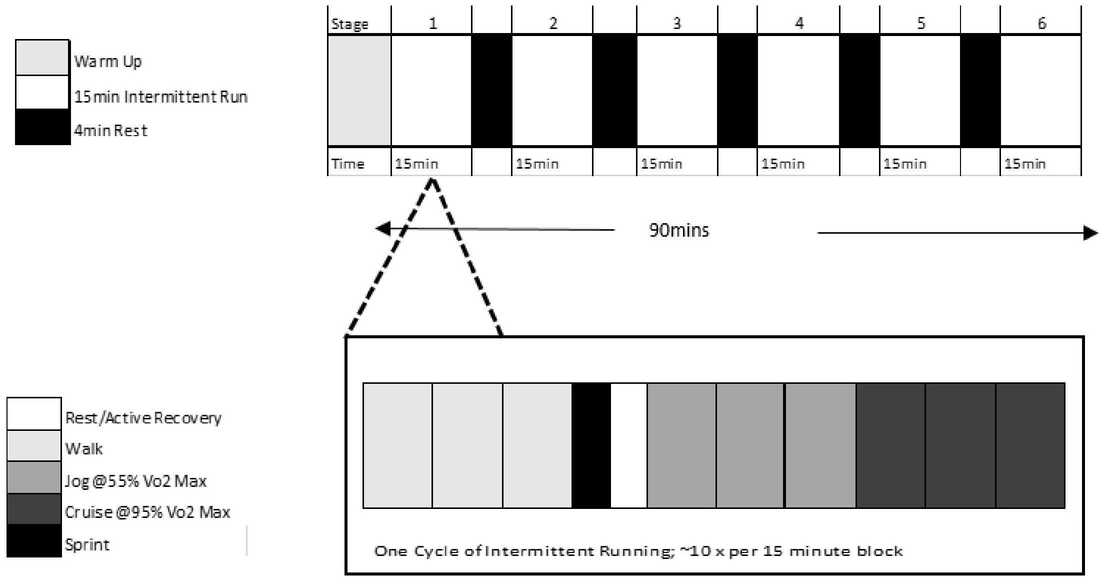

Figure 1. The Loughborough Intermittent Shuttle Test (LIST), based on Nicholas et al. (2000). Adjustments were made to the recovery period (4 min) and the 15 min blocks were repeated for a 90 min total duration.

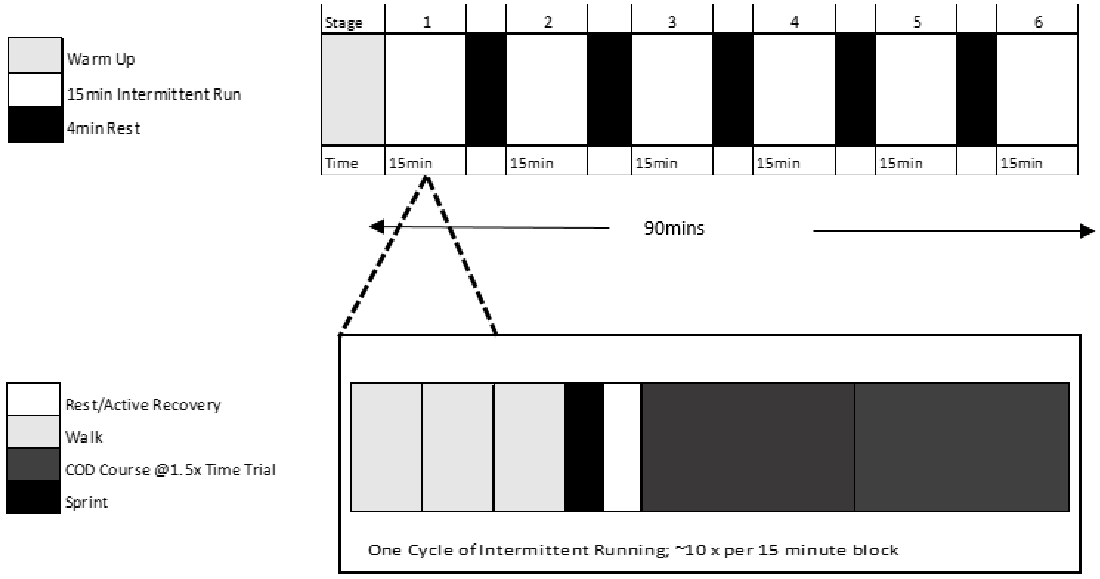

Figure 2. The adjusted, non-linear Loughborough Intermittent Shuttle Test (LIST), based on Nicholas et al. (23). A change of non-linear (denoted by change of direction; COD) segment was developed to replace the 55% and 95% $\dot{V}O_{2max}$ sequences. The same adjustments were made to the recovery period (4-min) and the 15-min blocks were repeated for a 90-min total duration.

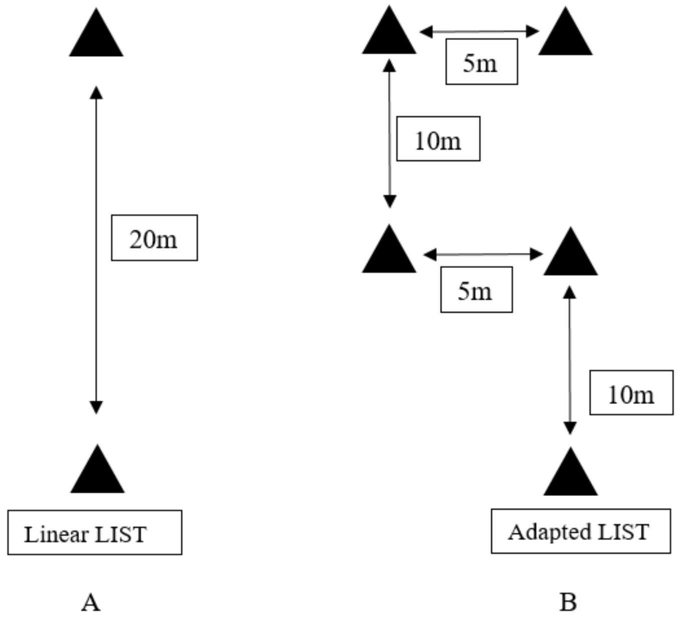

Figure 3. The Loughborough Intermittent Shuttle Test (LIST) 20 m linear configuration (A) and the adjusted, non-linear LIST configuration (B).

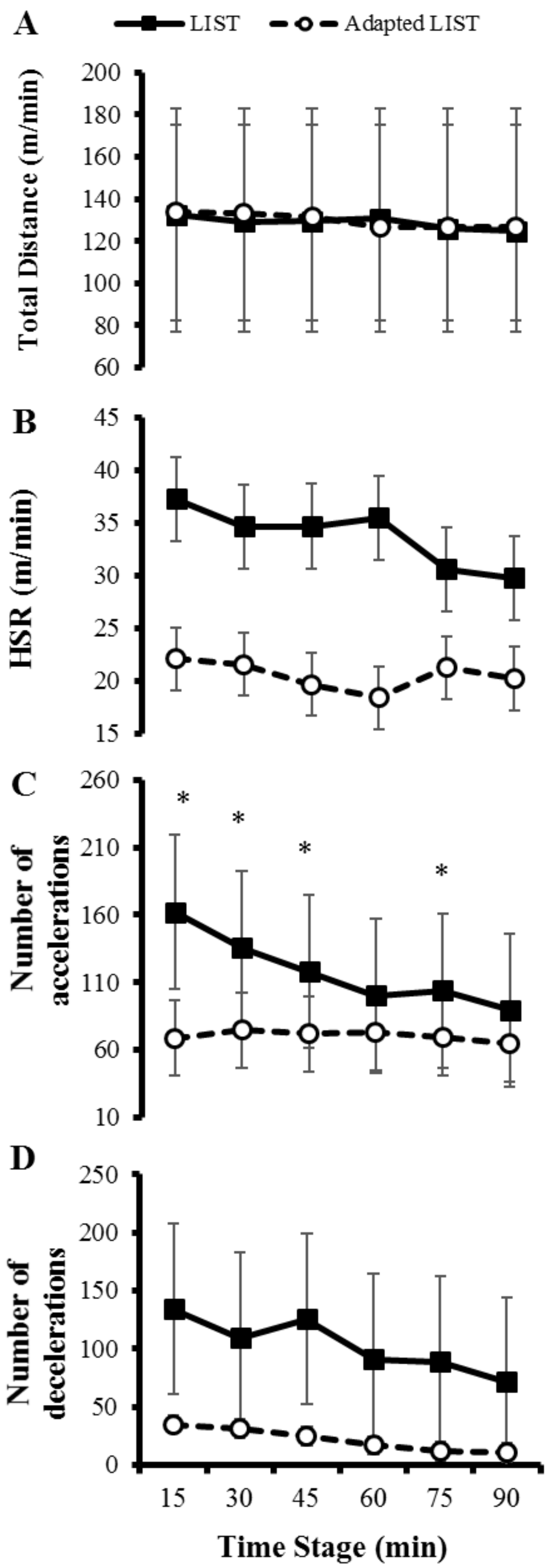

Figure 4. A) Total distance B) High-speed running distance C) Number of accelerations D) Number of decelerations during the Loughborough Intermittent Test (LIST) *vs.* the adapted

LIST across progressive match simulation periods (*n* = 8). * = sig. different ($P < 0.05$) to corresponding time point ($P < 0.05$).

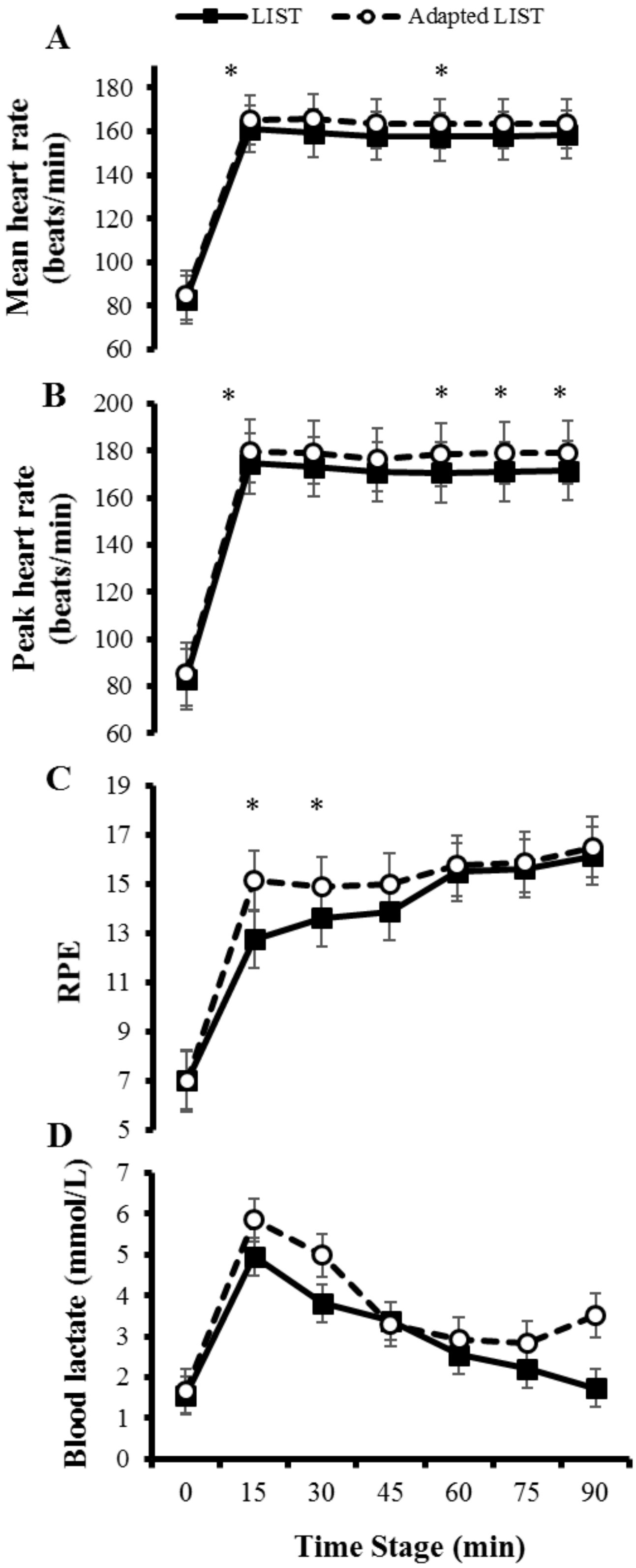

Figure 5. A) Mean heart rate B) Peak heart rate C) RPE D) Blood lactate during the Loughborough Intermittent Test (LIST) *vs.* the adapted LIST across progressive match

simulation periods (n = 8). * = sig. different ($P < 0.05$) to corresponding time point ($P < 0.05$).

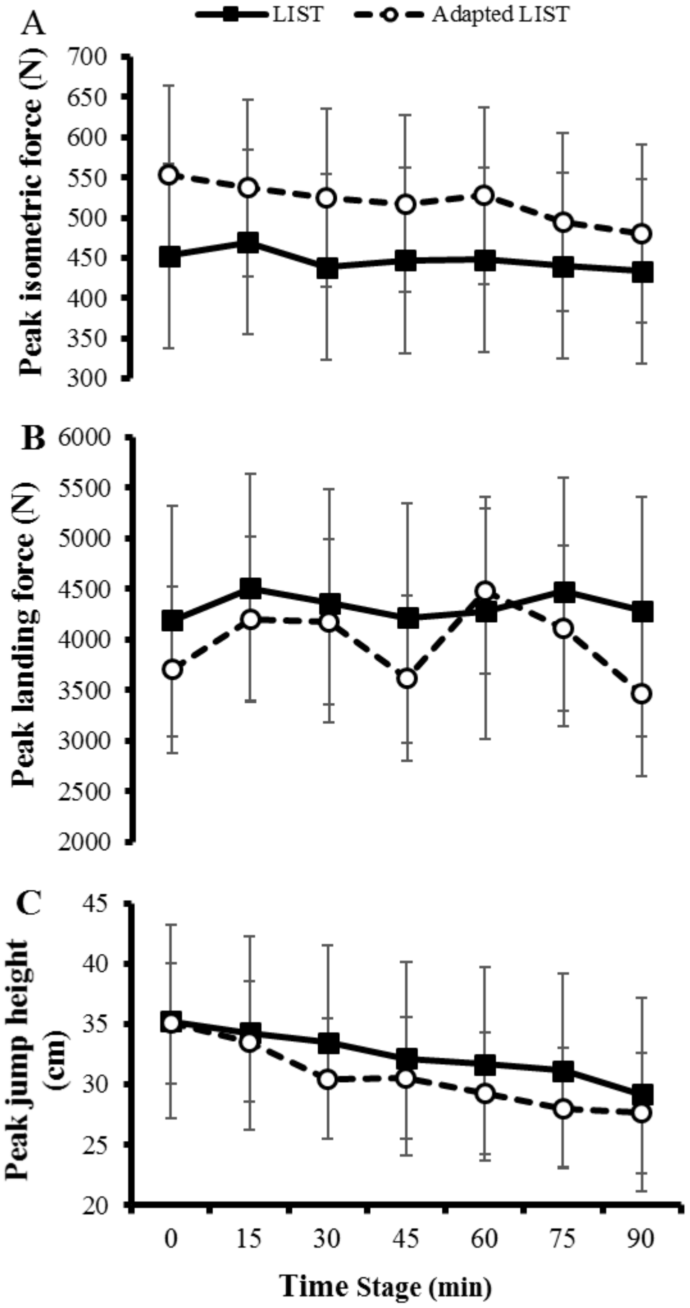

Figure 6. A) Peak unilateral isometric (iso) hamstring force B) Peak landing force C) Peak jump height during the Loughborough Intermittent Test (LIST) *vs.* the adapted LIST across progressive match simulation periods (*n* = 8).

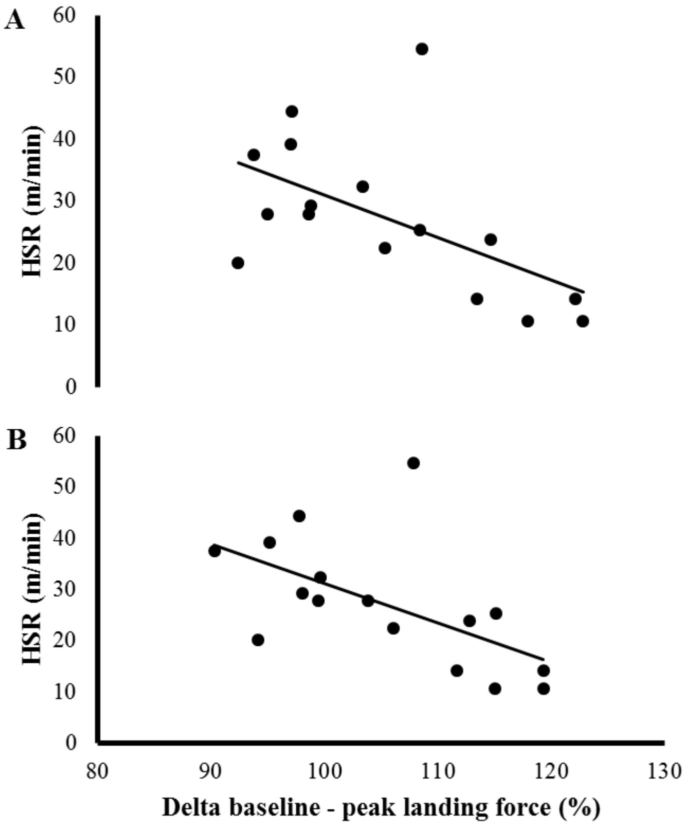

Figure 7. A) The relationship between the change in baseline – half-time peak landing force and HSR (*r* = -0.57, *P* = 0.022); B) The relationship between the change in baseline – full-time peak landing force and HSR (*r* = -0.58, *P* = 0.019).