Effects of an Individualized Soccer Match Simulation on Vertical Stiffness and Impedance

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Abstract:

An observed relationship between soccer match duration and injury has led to research examining the changes in lower extremity mechanics and performance with fatiguing exercise. Because many fatigue protocols are designed to result in substantial muscular deficits, they may not reflect the fatigue associated with sport-specific demands that have been associated with the increasing incidence of injury as the match progresses. Thus, the aim of this study was to systematically analyze the progressive changes in lower extremity mechanics and performance during an individualized exercise protocol designed to simulate a 90-minute soccer match. Previous match analysis data were used to systematically develop a simulated soccer match exercise protocol that was individualized to the participant's fitness level. Twenty-four National Collegiate Athletic Association Division I soccer players (12 men, 12 women) participated in 2 testing sessions. In the first session, the participants completed the Yo-Yo Intermittent Recovery Test Level 1 to assess their fitness level and determine the 5 submaximal running intensities for their soccer match simulation. In the second test session, progressive changes in the rating of perceived exertion (RPE), lower extremity performance (vertical jump height, sprint speed, and cutting speed), and movement mechanics (jumping vertical stiffness and terminal landing impedance) were measured during the soccer match simulation. The average match simulation running distance was 10,165 ± 1,001 m, consistent with soccer match analysis research. Time-related increases in RPE, and decrements in sprinting, and cutting speed were observed, suggesting that fatigue increased as the simulation progressed. However, there were no time-related decreases in vertical jump height, changes in lower extremity vertical stiffness in jumping, or vertical impedance during landing. Secondary analyses indicated that the coordinative changes responsible for the maintenance of stiffness and impedance differed between the dominant and nondominant limbs. Despite an increase in RPE to near exhaustive levels, and decrements in sprint and cutting performance, the participants were able to maintain jump performance and movement mechanics. Interestingly, the coordinative changes that allowed for the maintenance of vertical stiffness and impedance varied between limbs. Thus, suggesting that unilateral training for performance and injury prevention in soccer-specific populations should be considered.

Keywords: intermittent exercise | prescription | Yo-Yo | performance | fitness

Article:

INTRODUCTION

Time loss injury in soccer occurs at a rate >1one injury per player per season (16–18), with injury rates being 5-fold (16) to 12-fold (33) higher in competition than in training. Noncontact mechanisms are responsible for 55% (22) and 59% (17) of the injuries in youth and professionals, respectively, and result in greater time loss than do contact injuries (23). The primary actions at the time of noncontact injury are running, twisting or turning, jumping, and landing (17,18). The rate at which injuries occur during competition increases steadily with soccer match duration, peaking in the final 15 minutes of a match (18,39). Consistent with an increased rate of injury with match duration are observed decreases in physical performance (3,32). Together, these findings lead to speculation that fatigue associated with soccer match duration may compromise movement mechanics (15), thus contributing to the rise in injury rates during the latter stages of a match (18).

Because of the practical and extraneous challenges of analyzing movement mechanics during a competitive soccer match, exercise protocols have been developed that simulate the demands of a soccer match. These protocols have predominantly used treadmill (11,15,36,41,42) and shuttle running (11) and have demonstrated changes in strength (15,42), jump performance (35), surface muscle activation (15,35,41), and cutting mechanics (14). However, the effectiveness of these exercise protocols in adequately replicating the physiological and biomechanical demands of a soccer match remains questionable. For example, previous protocols have not accounted for the variability in a participant's fitness levels that have been shown to contribute to match performance, that is, players having greater fitness levels perform to a higher physical standard (i.e., greater total distance run and distance run at sprint and high intensities) during competitive matches (27,32). Because previous match simulation studies have reported variations in fitness levels ranging from 7.6 (15) to 15% (11), the observed decreases in thigh muscle strength (15,41,42) and dynamic hamstring to quadriceps ratio (eccentric hamstring torque to concentric quadriceps torque) that are proposed to compromise the ability to stabilize the knee joint effectively (13,42) may be potentially overestimated or underestimated if an individual's fitness level is inconsistent with the exercise protocol demands. Thus, accounting for an individual's fitness level may result in changes in performance and biomechanical outcomes better reflecting the actual response to prolonged sport-specific exercise.

The highly intermittent nature of soccer and accompanying 1,100 changes in activity observed in a match (2,27) result in a large amount of stretch-shortening cycle (SSC) work that may not be fully accounted for by previous soccer match simulation protocols. The need to account for an appropriate amount of SSC work is supported by findings that (a) soccer-simulated exercise containing the largest amount of SSC work resulted in greater decrements in performance and movement mechanics (11) and (b) soccer-specific exercise precipitated greater decrements in thigh strength ratios (13) and muscle activation (35,41) during higher compared with lower velocity movements. For these reasons, replicating the full spectrum of intensities examined in match analyses research and including an appropriate amount of SSC work while examining high velocity actions (e.g., sprinting, cutting, and jumping) is integral to more effectively simulating and examining soccer-specific demands.

Previous examinations of exercise effects on lower extremity biomechanics have used vertical and joint stiffness to quantify change during SSC actions such as a vertical drop jump task (9,20,28,43). Stiffness (or alternatively impedance when examining a terminal action such as drop landing) is defined as the body's resistance to deformation (5) and consists of a passive component (provided by bones, ligaments, and tendons) and an active muscular component (1). Within a single joint, stiffness is calculated as the joint moment relative to its angular displacement (6), while lower extremity stiffness (representing the combined stiffness of lower extremity joints) is calculated as the peak vertical ground reaction force relative to the displacement of the body's center of mass (COM) (31). Because modulation of lower extremity stiffness during exercise has been shown to occur through a combination of muscle and stretch-reflex activation (12,24,25,29), an exercise-induced decrease in lower extremity vertical stiffness is the result of a decrease in neuromuscular control at one or more joints of the lower extremity (1). In this way, decreasing vertical stiffness reflects a decrease in dynamic joint stability (19) and a subsequent reduction in movement control (9,28,43) that results in increased stress being placed on the body's passive structures and an increased likelihood of injury (9). Given the increasing rate of injury with soccer match duration, there is a need to understand how lower extremity vertical stiffness is affected during prolonged intermittent exercise that is reflective of sport-specific demands. This may provide important insights into more effective performance and injury prevention training.

The purpose of this study was to examine the progressive changes in indices of fatigue (sprinting and cutting performance, SSC jump performance, and rating of perceived exertion [RPE]), and corresponding changes in lower extremity biomechanics (vertical stiffness during an SSC jump and vertical impedance in terminal landing) during an individually prescribed soccer match simulation. We hypothesized that as the soccer match simulation progressed (a) RPE would increase, (b) sprint, cutting, and SSC jump performance would decrease, (c) squat jump (SJ) height (incorporating only concentric muscle action) would remain stable based on previous research findings (15,35,41,42), and (d) vertical stiffness (during an SSC jump) and vertical impedance (during a terminal landing) would decrease. We further hypothesized that a greater change in performance and movement mechanics would be observed in the second half as compared with that in the first half. Finally, we hypothesized that the rate of decline in performance and movement mechanics would peak toward the end of the second half.

METHODS

Experimental Approach to the Problem

The soccer match simulation was structured in a manner consistent with an actual soccer match and consisted of two 45-minute halves and a 15-minute half-time. Seven individualized running intensities were incorporated: (a) standing, (b) walking, (c) jogging, (d) low-intensity running, (e) moderate intensity running, (f) high-intensity running, and (g) sprinting, with the duration and mean frequency of time spent at each intensity corresponding to previously published soccer match analyses (32) (Table 1). A slightly higher amount of moderate intensity running was incorporated to account for the lack of multidirectional movement, whereas the slightly higher amount of sprinting was designed to account for the lack of high-intensity actions incorporating a ball. All submaximal running speeds (27,32) were prescribed via the subject's performance on the Yo-Yo Intermittent Recovery Level 1 (YYIR1), which has been previously shown to be highly correlated to physical soccer match performance (total distance run, distance run at high and sprint intensities, and distance run during the final 15 minutes of a soccer match) (26,27). Specifically, using the maximal running speed achieved during the YYIR1 (YYIR1max), defined as the mean speed of the final 8 shuttles performed, 5 submaximal running intensities were defined: (a) walk = 20–39%, (b) jog = 40–59%, (c) low = 60–83%, (d) moderate = 84–94%, (e) high = 105–109%. This resulted in the close replication of the running speeds and total distances run during an actual soccer match (Table 2). Comparison of the predicted total distance for the match simulation using these methods with published match analyses data (26,27) showed close agreement (0.9–6.2% difference) that was well within the intraindividual variability (5.2–8.9%) reported between matches (7).

Table 1. Comparison of time spent across all intensities in match simulation vs. match analysis.

	Percentage of time relative to 90-min match duration	
Intensity	Match simulation	Match analysis (Bangsbo et al. [3])
Standing	23.33	14–22
Walk	23.33	38–45
Jog	12.44	14–18
Low	21.78	11–21
Moderate	9.33	5–6
High	3.11	2–3
Sprint	~2.07	0.6–0.8

Table 2. Comparison of submaximal running speeds and distance run of actual match analysis, predicted match simulation distance for male and female professionals, and match simulation distance run by participants.*

Running intensity ($\%YYIR1_{max}$)	Match analysis running speed ($m \cdot s^{-1}$) (23,27)	Match simulation running speeds ($m \cdot s^{-1}m$): Male professionals								
		Male professionals				Male subjects	Female professionals (predicted)			Female subjects
		Midfielders	Full backs	Attackers	Defenders	Mean (±*SD*)	Mean	Low	High	Mean (±*SD*)
Walk (20–39%)	1.66	1.38	1.37	1.35	1.33	1.38 ± 0.05	1.27	1.17	1.34	1.25 ± 0.04
Jog (40–59%)	2.22	2.31	2.30	2.26	2.23	2.32 ± 0.08	2.12	1.96	2.25	2.11 ± 0.07
Low intensity (60–83%)	3.33	3.34	3.33	3.26	3.23	3.35 ± 0.12	3.07	2.83	3.25	3.04 ± 0.10
Moderate (84–94%)	4.17	4.15	4.14	4.06	4.01	4.17 ± 0.15	3.82	3.52	4.05	3.78 ± 0.12
High intensity (105–109%)	4.99	4.99	4.98	4.88	4.83	5.01 ± 0.18	4.59	4.23	4.86	4.55 ± 0.14
Match simulation distance run (km)										
Match analysis distance (km)		10.9	10.8	10.6	10.5		10.0	9.3	10.6	
Match simulation distance (km)		11.0 ± 0.21	10.98 ± 0.23	10.48 ± 0.22	9.74 ± 0.22	10,185.81 ± 3 74.70	10.5	9.7	11.3	9,237.78 ± 288.98

*All running speeds are expressed in meters per second. Match analyses and simulation running speeds are derived from the findings of Mohr and co-workers (32) and Krustrup et al. (27).

The match simulation was structured to be performed in a gymnasium as an intermittent shuttle run dictated by a web-based metronome (www.webmetronome.com). To allow for progressive analyses and between half comparisons of lower extremity performance and biomechanics, each half consisted of 6 identical 7.5-minute segments, comprising 6 minutes of submaximal intermittent running and 1.5 minutes of testing. Each 6-minute submaximal running segment included 15 randomized intermittent running bouts of 6 seconds of submaximal running (at the varying intensities), followed by 6 seconds of combined walking and standing, in proportions consistent with what has been previously described in actual match analyses (Table 1). This resulted in 1,100 changes in locomotion, which compares well with the 1,179 changes in activity and mean duration of 4.5 seconds previously reported via match analyses (3). Each 1.5-minute testing interval consisted of 2 tasks: an integrated jump task (Figure 1) and the 5-0-5 agility test, which is a combined sprint and cutting task (8). These tasks were chosen because they are consistent with the specific SSC actions and demands during actual match play (3,32) and the primary actions at the time of noncontact injury (e.g., running, twisting or turning, jumping, and landing) (17,18). The 30 integrated jumps completed by each participant during the match simulation reflects a slightly higher demand than the range of 16–24 observed in match analyses (3), whereas the number of sprints reflects a slightly lower demand than the peak number of 36 that was observed in match analyses (3).

Subjects

Twenty-four highly trained National Collegiate Athletic Association division I soccer players (12 men, 12 women: age = 19.5 ± 1.4 years, height = 170.2 ± 8.5 cm, weight = 66.5 ± 6.5 kg) with an average of 14.38 ± 2.22 years' playing experience participated in this study. The player positions represented were forwards (*n* = 4), defenders (*n* = 6), and midfielders (*n* = 14). Goalkeepers were excluded from the analysis because the match simulation was designed to emulate the physical demands of field players. All the subjects were free of prior lower extremity surgery, free from lower extremity injury currently and for the past 6 months, and had a minimum of 8 years competitive playing experience. Before performing any testing, all the methods were approved by the University institutional review board (IRB) for the protection of human subjects. Before participating in testing, all the subjects were informed of the study risks and provided their informed consent by signing a consent form approved by the University's IRB for the protection of human subjects. Each subject completed 2 testing sessions, conducted at the same time of the day, 3–10 days apart (i.e., to ensure adequate recovery while minimizing the changes in fitness level between sessions). Although we did not specifically monitor dietary intake and hydration status, the participants were instructed to maintain the same dietary, hydration, and exercise habits in the days preceding the test sessions as they would before a competitive match. They were also told to refrain from alcohol for the 72 hours before testing and to not perform moderate or high-intensity exercise during the 48 hours preceding each testing session. All testing occurred within 3 weeks of the start of the college preseason, a time when it was anticipated that the players would be at a high level of fitness.

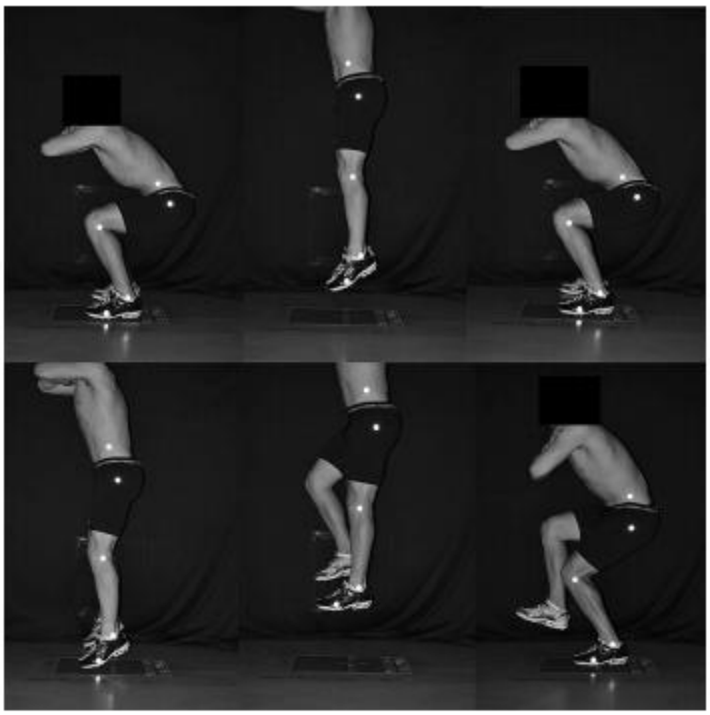


Figure 1. Integrated jump task.

Procedures

Test session 1 consisted of a 15-minute progressive dynamic warm-up, followed by the YYIR1 (26). The subjects were first familiarized with the structure of the YYIR1 test and were accompanied by 1 of the testers on the first 3 levels of the YYIR1 to ensure adequate familiarization and appropriate pacing. Upon completion of the test, maximal performance was recorded as the distance run ($YYIR1_{max}$) and entered into Excel software (Microsoft Corporation) to calculate each individual's submaximal running speeds. The subjects were then familiarized with all components of the match simulation to be performed during test session 2; this included the integrated jump task, the 505 test for agility (8), and the match simulation structure incorporating their individualized intermittent running speeds.

The 505 agility test consists of a 15-m shuttle run performed around a single horizontal cut performed with either the dominant or nondominant limb (8). The subjects began the run 0.5 m behind the 15-m line at their own volition (to ensure that subject reaction did not affect performance). Infrared light meters (Brower timing systems Salt Lake City, UT, USA) positioned 5 and 15 m from the cutting point allowed for assessment of both sprint and cut speed via a single performance task. Cutting speed was defined as the time to complete the 10 m surrounding the cutting task and sprint speed was defined as the time to complete the final 10 m of the shuttle run. During the familiarization period, the subjects performed a minimum of 2 submaximal trials, followed by 7 maximal trials for each limb. The trials were performed alternately between the dominant (preferred limb in kicking) and nondominant limbs with a 60- to 90-second active recovery (walking) between each trial. Pilot testing indicated that 7 trials per limb were required for performance stability; however, if cutting speed continued to increase during the final 3 trials for the respective cutting limb, familiarization continued until performance stabilized for that limb.

The integrated jump task is a 3 phase jump task (Figure 1) performed with the dominant or nondominant limb in a manner similar to that reported by Impellizeri et al. (21). The subject began by standing with feet shoulders width apart, one foot on the force plate and the other foot next to the force plate, and the arms placed across the chest. The subject began the integrated jump task in a squat position with the knees flexed to approximately 90°, paused for approximately 3 seconds, then initiated a maximal SJ on the "go" command of the tester (phase 1). The subject absorbed the landing from the previous jump with both limbs (one landing in the center of the force plate and the other next to it) and immediately performing a second maximal jump (phase 2: SSC jump). The subjects then landed on the force plate with a single limb and maintained their balance for approximately 2 seconds (phase 3: terminal landing). Familiarization comprised 4–6 submaximal jump trials followed by 24 (12 each limb) successful maximal trials of the integrated jump task randomly assigned to the dominant or nondominant limb. Forty-five seconds of passive recovery was provided between each jump to limit fatigue. After the completion of task familiarization, the subjects were familiarized with their individualized running speeds and the structure of the individualized soccer match simulation.

The second test session began with 5 minutes of refamiliarization to the individualized submaximal running speeds at the walk, jog, and low-intensity running speeds followed by the same progressive dynamic flexibility warm-up performed during the first test session. Thereafter, the subjects were refamiliarized with the 505 agility test and the integrated jump tasks, and they completed a total of 4 submaximal trials, followed by 4 maximal trials of each task (2 performed on each limb to establish preexercise values). After 3–5 minutes of active recovery, the subjects began the individualized soccer match simulation as previously described. During the 15-minute half-time interval, the participants were given 9 minutes of passive recovery followed by 4 minutes of progressive rewarming and asked to consume 8–12 oz. of a glucose-electrolyte solution (Gatorade®, Chicago, IL, USA). Upon completion of testing, the subjects were asked to rate how well the match simulation replicated the physical demands of their actual soccer matches, based on their response to the following standardized question: "From 0 to 10, zero being nothing like a match to 10 being exactly like a match, how closely do you feel the simulation replicated an actual competitive game?"

During each 1.5-minute testing interval, sprint, cutting performance, and RPE were recorded manually, and 3-dimensional kinetic data were collected (sampling rate 1,000 Hz) during the integrated jump task using a piezoelectric Kistler force plate (Kistler North America, Amherst, NY, USA) and Datapac 2K2 laboratory application software (Version 3.13, Run Technologies, Mission Viejo, CA, USA). The kinetic data were subsequently filtered at 60 Hz with a fourth-order low pass Butterworth filter and exported to Excel software (Microsoft Corporation). Thereafter, each trial was divided into its constituent phases and the following calculations made using Rgui version 2.9.2 software (R Foundation for Statistical Computing). During phase 1 (SJ) and 2 (SSC Jump), total jump impulse ($J_{impulse}$) was defined as the peak center of mass displacement (as calculated via the double integration of vertical ground reaction force [vGRF]) to toe off allowing for the calculation of SJ and SSC jump height. The mean of 2 trials at each time interval and for each limb was used for analysis. Vertical stiffness (during the SSC jump phase) and impedance (during the single-leg landing phase) (newtons per meter) were calculated as the maximal vGRF (newtons) relative to the maximal vertical displacement of the body's center of mass (meters), normalized to the subject's body mass in kilograms (kilonewton·per meter·per kilogram). During pilot testing, intraclass correlation coefficients (ICC) and standard error of the measurement (*SEM*) confirmed strong day-to-day consistency in normalized vertical stiffness (ICC = 0.94, *SEM* = 0.014 $kN \cdot m^{-1} \cdot kg^{-1}$) and impedance (ICC = 0.94, *SEM* = 0.010 $kN \cdot m^{-1} \cdot kg^{-1}$) during the integrated jump.

Statistical Analyses

A univariate piecewise quadratic growth model was used to analyze the progressive changes in all dependent variables (RPE, sprint and cutting speed, squat and SSC jump height, and vertical stiffness and impedance). The model, expressed below, was developed via hierarchical linear modeling (HLM) software 6.08 (Scientific Software International, Lincolnwood, IL, USA). The piecewise component allowed for comparisons between the first and second halves, whereas the quadratic component allowed for the analysis of the rate of change in dependent variables over time within each half.

Before the HLM analysis, assumptions of normality and homogeneity of the statistical model residuals were assessed for each dependent variable using PASW 18.0. The RPE and dominant limb cutting appeared to violate these assumptions. Subsequently, sprint and nondominant limb cutting were assessed using random effects with statistical significance set at $p < 0.05$, whereas statistical analysis of RPE and dominant limb cutting was assessed using fixed effects with robust standard errors with statistical significance set at $p < 0.05$.

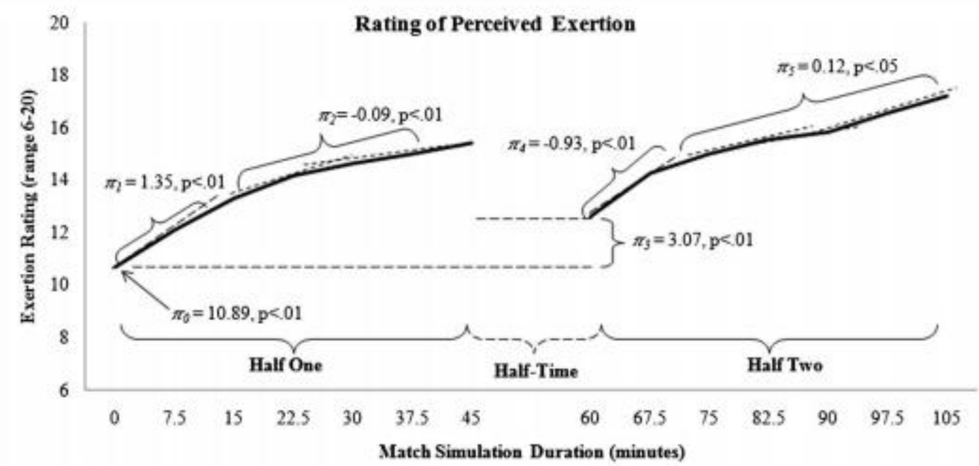
RESULTS

Paired *t*-tests revealed no significant differences in the exercise environment between session 1 and session 2 in the mean temperature (23.7 ± 0.2 vs. 23.9 ± 0.4°C, $p = 0.142$), humidity (57.7 ± 4.3 vs. 59.5 ± 4.8%, $p = 0.151$), and barometric pressure (29.2 ± 0.4 vs. 29.2 ± 0.1 mm Hg, $p = 0.400$). The mean performance on the YYIR1 test was 1,780 ± 619.2 m (women: 1,276.7 ± 306.3, men: 2,283.3 ± 393.9), resulting in a mean YYIR1 maximal running speed of 4.48 $m \cdot s^{-1}$ (women: 4.25, men: 4.69). This resulted in a mean match simulation distance run of 10,165.5 ± 1001.7 m (women: 9,237.8 ± 289.0, men: 11,093.3 ± 369.5). Table 2 displays the resulting activity profile across all submaximal running intensities for the soccer match simulation. Subjective ratings of the soccer match simulation ability to effectively replicate the physical demands of an actual match were 8.7 ± 0.6.

Analysis of performance measures revealed significant decrements in sprint and cutting performance, with no significant differences observed in SJ or SSC jump height. The subjects began at a mean initial sprint speed of 6.20 $m \cdot s^{-1}$ at the start of the first half and decreased 0.105 $m \cdot s^{-1}$ each 7.5 minutes ($p < 0.01$) at the beginning of the first half. The rate of decrement in sprint performance slowed minimally during the first half at a rate of 0.011 $m \cdot s^{-1}$ each 7.5 minutes ($p < 0.05$). Between half comparisons revealed that sprint speed at the start of the second half was 0.278 $m \cdot s^{-1}$ slower ($p < 0.01$) relative to the start of the first half (half 1: 6.20 vs. half 2: 5.92 $m \cdot s^{-1}$). No significant between half differences in change or the rate of change in sprint performance were observed. Cutting speed similarly decreased during the match simulation; however, these decrements differed between limbs. Cut speed at the start of the match simulation was 4.41 $m \cdot s^{-1}$ with the dominant limb and 4.34 $m \cdot s^{-1}$ with the nondominant limb. During the first half, cut speed decreased in both limbs every 7.5-minute interval (dominant limb: 0.090 $m \cdot s^{-1}$ [$p < 0.01$] and nondominant limb: 0.059 $m \cdot s^{-1}$ [$p<.01$]). Cutting speed was decreased at the start of the second half compared with that of the first (dominant limb: 0.121 $m \cdot s^{-1}$ [$p< 0.01$] and nondominant limb: 0.104 $m \cdot s^{-1}$ [$p < 0.01$]). Although the rate of decrease in dominant limb cutting speed accelerated during the first and second halves (half one: 0.011 $m \cdot s^{-1}$each 7.5 minutes $p < 0.05$, half 2: 0.054 $m \cdot s^{-1}$ each 7.5 minutes $p < 0.05$), there was no change in the rate of decrease in nondominant limb cutting speed.

Analysis of RPE revealed significant changes across the match simulation (Figure 2). At the start of the first half, the subjects reported a mean RPE of 10.89 (±1.90). The RPE initially increased during the first half at a rate of 1.35 exertion units (EUs) each 7.5 minutes ($p = 0.00$) and then slowed down as the first half progressed (0.09 EUs each 7.5 minutes [$p = 0.00$]). Between half comparisons revealed that RPE at the start of the second half was greater than that at the start of the first half (10.89 ± 1.90 vs. 13.96 ± 1.21 [$p = 0.00$]), increased at a slower rate at the start of the second half relative to the first (half one: 1.35 vs. half 2: 0.42 EUs each 7.5 minutes [$p = 0.008$]) and was attenuated to a greater extent during the second half relative to the first (half one: 0.09 vs. half 2: 0.03 EUs each 7.5 minutes [$p = 0.018$]).

Analysis of movement mechanics during jumping and landing revealed no significant change in vertical stiffness (Figure 3) or vertical impedance (Figure 4) as the match simulation progressed. To better elucidate how stiffness and impedance were effectively maintained, a secondary analysis was performed to determine if the peak vGRF and peak COM displacement (the 2 components used to compute vertical stiffness and impedance) were differentially modulated. Analysis of these subcomponents for vertical stiffness revealed no change in the COM for either limb, but vGRF of the dominant limb increased at the start of the first half ($p = 0.016$), with the rate of increase slowing as the first half progressed (-0.17 $N \cdot kg^{-1}$ each 7.5 minutes of exercise [$p = 0.038$]). Analysis of these subcomponents of vertical impedance revealed that COM displacement of the dominant limb was significantly greater at the start of the second half (0.035 m, $p = 0.026$) than at the start of the first half, was less at the start of the second half than the first (half one: 0.005 vs. half 2: 0.026, $p = 0.015$), and showed a slower rate of decline during the second half than the first (half one: 0.001 vs. half 2: 0.004, $p = 0.031$).



	Half One								Half Two						
	0	**7.5**	**15**	**22.5**	**30**	**37.5**	**45**		**60**	**67.5**	**75**	**82.5**	**90**	**97.5**	**105**
RPEave	10.89	12.23	13.29	14.17	14.63	15.00	15.42		13.96	14.25	15.00	15.54	15.83	16.54	17.21
RPEsd	1.90	1.77	1.73	1.66	1.84	2.00	2.00		1.21	1.48	1.82	1.84	2.14	1.82	1.67

Figure 2. Time-related changes in rating of perceived exertion. (Note: All values are expressed as mean ± *SD*. Borg rating of perceived exertion (6–20) scale used.)

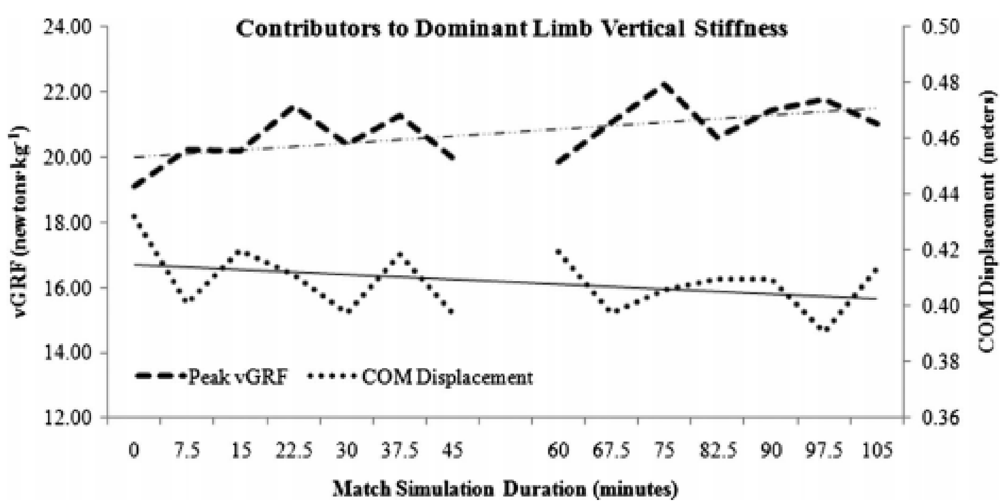


Figure 3. Time-related changes in dominant limb vertical stiffness, peak vertical ground reaction force, and COM displacement.

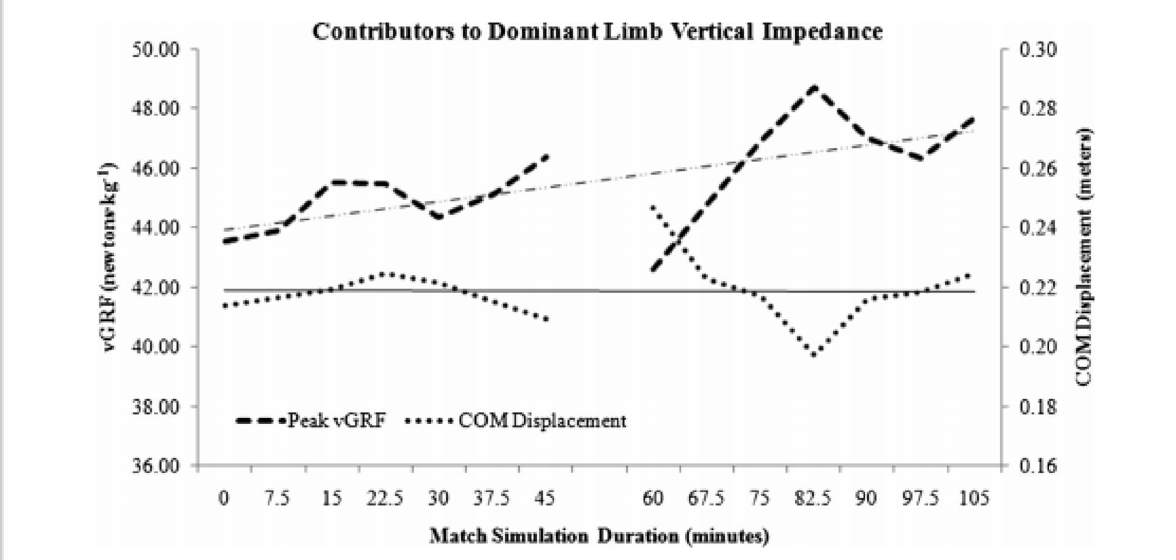


Figure 4. Time-related changes in dominant limb vertical impedance, peak vertical ground reaction force, and COM displacement.

DISCUSSION

The primary findings of this study were that, despite decrements in cutting and running speed, and substantial increases in RPE that were consistent with exhaustive running (18.2 ± 1.7) (10), we observed no changes in lower extremity vertical stiffness and impedance with match duration. The lack of change in vertical stiffness and impedance was in contrast to our hypotheses and reflects an apparent maintenance of neuromuscular coordination despite apparent fatigue. Subjective analysis of the subcomponents used to calculate vertical stiffness and impedance (peak vGRF and COM displacement) revealed an increase in vGRF and a decrease in COM displacement with match duration (Figures 3 and 4) resulting in the observed maintenance of vertical stiffness and impedance with match duration. These secondary analyses also demonstrated that the maintenance of stiffness and impedance was inconsistent between limbs (dominant vs. nondominant), and actions (jumping vs. landing). Specifically, dominant limb stiffness (SSC jump) was maintained primarily by changes in peak vGRF, whereas dominant limb impedance (landing) was maintained primarily by changes in COM displacement. Although our analyses did not allow for direct comparisons between limbs or tasks, these findings infer that the coordination between the 2 limbs differs and that coordination changes may be specific to the type of muscle action being performed. This differential response may be an important finding as previous soccer-specific research has demonstrated a high prevalence of limb asymmetry (40), which is thought to contribute to an increased rate of injury (38). The practical implications of these findings are that both performance training and injury prevention training for soccer should focus on unilateral training.

There were several other novel findings in this study relative to previous match simulation research. First, the increase in RPE we observed suggests that the current match simulation caused greater physical stress compared with previous match simulations (11,15). Second, the decrement in sprint speed observed in this study was not observed during a nonmotorized treadmill match simulation (35), which supports previous findings that intermittent running incorporating SSC work is of a higher physical demand than is treadmill running (11). Third, previous research analyzing movement kinematics in cutting demonstrated significant increases in total knee flexion and knee valgus range of motion during dominant limb cutting (13) without addressing potential performance changes or nondominant limb cutting. To our knowledge, this study is the first to demonstrate a significant decrement in cutting speed and the development of cutting limb performance asymmetry in response to soccer-specific exercise. Given the asymmetrical response to exercise observed in jumping, landing, and cutting, it may be important for future research to analyze potential exercise-induced limb asymmetries, coordinative differences, and task-related variability.

The maintenance of jump performance and movement mechanics was unexpected and contrasts previous research where changes in jump mechanics and performance were documented while sprint speed was maintained during a treadmill soccer match simulation (35). However, although some have observed *decrements* in vertical stiffness and impedance during exhaustive treadmill running (9) and repeated sprint bouts (34) (thus precipitating our proposed hypotheses), others have observed *maintenance* of vertical stiffness and impedance after fatigue induced submaximal squatting (37) and maximal drop jumps (28). When considered together, these disparate findings may indicate an exercise-dependent response, thus supporting the need to more closely replicate the demands of sport during competition and training (30).

It is also possible that the maintenance of jump height and vertical stiffness and impedance reflects the complexity of the task, or alternatively, a lack of sensitivity of the measures used. The integrated jump task was chosen because it required movements consistent with the types of muscle action observed in sport; specifically, it incorporates and allows for subsequent analysis of concentric, SSC, and eccentric muscle work within a single task. However, the need to perform these sequential movements may have contributed to increased variability in task performance and subsequently made it more difficult to observe meaningful changes across time. Assuming this were the case, increasing task familiarity would likely have been observed and reflected in either an increase in jump height performance and vertical stiffness and impedance; however, this was not observed. Because previous research has observed interindividual coordinative changes accompanying fatiguing exercise (4), it is possible that this additional variability obscured mean changes across time. Finally, it should be noted that vertical stiffness and impedance represent a composite measure of lower extremity joint stiffness (the sum of joint stiffness or impedance of the hip, knee, and ankle) (5,19). This is a limitation of this study, which, because of the extensive nature of the exercise protocol and laboratory constraints made 3-dimensional instrumentation not feasible. This shortcoming is highlighted by the coordinative changes implied by our secondary analyses and subjective observations regarding peak COM displacement and peak vGRF (Figures 3 and 4). Given the limitations of the current research, future research should consider more sensitive measures of movement biomechanics by examining: (a) the potential interlimb and intralimb and interjoint coordinative changes that may accompany soccer match demands, (b) intersubject variability in these coordinative changes, and (c) the potential contributors to compensatory strategies such as limb, muscle, and joint asymmetries.

PRACTICAL APPLICATIONS

In summary, lower extremity biomechanics during a fatiguing soccer match simulation were effectively modulated (albeit differently for the nondominant and dominant limbs), allowing for the maintenance of global lower extremity vertical stiffness and impedance. The apparent differential response between limbs to the type of muscle action performed (SSC vs. eccentric) highlights the potential role and characteristics of limb asymmetries. A better understanding of dominant and nondominant limb differences in soccer players, and more specifically, their potential differential response to fatigue will allow for more effective performance and injury prevention training in soccer-specific athletes. Although more work needs to be done, the asymmetrical responses to fatiguing exercise emphasize the need to consider including unilateral exercises in soccer-specific strength training to effectively address potential limb asymmetries. A secondary contribution of this study is that the exercise protocol successfully diminishes the gap between the field and laboratory settings and more effectively replicates the actual demands of a competitive soccer match in a controlled laboratory setting. By better accounting for the demands of an actual match, this analysis draws the laboratory closer to the field and allows for the development of research directed at better understanding how sport demands effect movement and performance.

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REFERENCES

1. Arampatzis A, Schade F, Walsh M, Bruggemann GP. Influence of leg stiffness and its effect on myodynamic jumping performance. J Electromyogr Kinesiol 11: 355–364, 2001.

2. Bangsbo J. The physiology of soccer—With special reference to intense intermittent exercise. Acta Physiol Scand 619: 1–155, 1994.

3. Bangsbo J, Norregaard L, Thorso F. Activity profile of competition soccer. Can J Sport Sci 16: 110–116, 1991.

4. Bonnard M, Sirin AV, Oddsson L, Thorstensson A. Different strategies to compensate for the effects of fatigue revealed by neuromuscular adaptation processes in humans. Neurosci Lett 166: 101–105, 1994.

5. Brughelli M, Cronin J. Influence of running velocity on vertical, leg and joint stiffness. Sports Med 38: 648, 2008.

6. Brughelli M, Cronin J. A review of research on the mechanical stiffness in running and jumping: Methodology and implications. Scand J Med Sci Sports 18: 417–426, 2008.

7. Di Salvo V, Baron R, Tschan H, Calderon Montero FJ, Bachl N, Pigozzi F. Performance characteristics according to playing position in elite soccer. Int J Sports Med 3: 222–227, 2007.

8. Draper JA, Lancaster MG. The 505 test: A test for agility in the horizontal plane. Austr J Sci Med Sport 17: 15–18, 1985.

9. Dutto DJ, Smith GA. Changes in spring-mass characteristics during treadmill running to exhaustion. Med Sci Sports Exer 34: 1324–1331, 2002.

10. Garcin M, Mille-Hamard L, Billat V. Influence of aerobic fitness level on measured and estimated perceived exertion during exhausting runs. Int J Sports Med 25: 270–277, 2004.

11. Gleeson NP, Reilly T, Mercer TH, Rakowski S, Rees D. Influence of acute endurance activity on leg neuromuscular and musculoskeletal performance. Med Sci Sports Exer 30: 596–608, 1998.

12. Gollhofer A, Schmidtbleicher D, Dietz V. Regulation of muscle stiffness in human locomotion. Int J Sports Med 5: 19–22, 1984.

13. Greig M. The influence of soccer-specific fatigue on peak isokinetic torque production of the knee flexors and extensors. Am J Sports Med 36: 1403–1409, 2008.

14. Greig MP. The influence of soccer-specific activity on the kinematics of an agility sprint. Eur J Sport Sci 9: 23, 2009.

15. Greig MP, McNaughton LR, Lovell RJ. Physiological and mechanical response to soccer-specific intermittent activity and steady-state activity. Res Sports Med 14: 29–52, 2006.

16. Hagglund M, Walden M, Ekstrand J. Exposure and injury risk in Swedish elite football: A comparison between seasons 1982 and 2001. Scand J Med Sci Sports 13: 364–370, 2003.

17. Hawkins RD, Fuller CW. A prospective epidemiological study of injuries in four English professional football clubs. Br J Sports Med 33: 196–203, 1999.

18. Hawkins RD, Hulse MA, Wilkinson C, Hodson A, Gibson M. The association football medical research programme: An audit of injuries in professional football. Br J Sports Med 35: 43–47, 2001.

19. Hughes G, Watkins J. Lower limb coordination and stiffness during landing from volleyball block jumps. Res Sports Med 16: 138, 2008.

20. Hunter I, Smith GA. Preferred and optimal stride frequency, stiffness and economy: Changes with fatigue during a 1-h high-intensity run. Eur J Appl Physiol 100: 653, 2007.

21. Impellizzeri FM, Rampinini E, Maffiuletti N, Marcora SM. A vertical jump force test for assessing bilateral strength asymmetry in athletes. Med Sci Sports Exerc 39: 2044–2050, 2007.

22. Junge A, Chomiak J, Dvorak J. Incidence of football injuries in youth players. Comparison of players from two European regions. Am J Sports Med 28: S47–S50, 2000.

23. Junge A, Dvorak J, Graf-Baumann T. Football injuries during the World Cup 2002. Am J Sports Med 32: 23S–S27S, 2004.

24. Komi PV. Stretch-shortening cycle: A powerful model to study normal and fatigued muscle. J Biomech 33: 1197–1206, 2000.

25. Komi PV, Gollhofer A. Stretch reflexes can have an important role in force enhancement during SSC exercise. J Appl Biomech 13: 451, 1997.

26. Krustrup P, Mohr M, Amstrup T, Rysgaard T, Johansen J, Steensberg A, Pedersen PK, Bangsbo J. The yo-yo intermittent recovery test: physiological response, reliability, and validity. Med Sci Sports Exerc 35: 697–705, 2003.

27. Krustrup P, Mohr M, Ellingsgaard H, Bangsbo J. Physical demands during an elite female soccer game: Importance of training status. Med Sci Sports Exerc 37: 1242–1248, 2005.

28. Kuitunen S, Kyrolainen H, Avela J, Komi PV. Leg stiffness modulation during exhaustive stretch-shortening cycle exercise. Scand J Med Sci Sports 17: 67–75, 2007.

29. Kyrolainen H, Avela J, McBride JM, Koskinen S, Andersen JL, Sipila S, Takala TE, Komi PV. Effects of power training on muscle structure and neuromuscular performance. Scand J Med Sci Sports 15: 58–64, 2005.

30. McLean SG. The ACL injury enigma: We can't prevent what we don't understand. J Athl Train 43: 538–540, 2008.

31. McMahon TA, Cheng GC. The mechanics of running: how does stiffness couple with speed? J Biomech 23(Suppl.)1: 65–78, 1990.

32. Mohr M, Krustrup P, Bangsbo J. Match performance of high-standard soccer players with special reference to development of fatigue. J Sports Sci 21: 519–528, 2003.

33. Morgan BE, Oberlander MA. An examination of injuries in major league soccer. The inaugural season. Am J Sports Med 29: 426–430, 2001.

34. Morin JB, Jeannin T, Chevallier B, Belli A. Spring-mass model characteristics during sprint running: Correlation with performance and fatigue-induced changes. Int J Sports Med 27: 158–165, 2006.

35. Oliver J, Armstrong N, Williams C. Changes in jump performance and muscle activity following soccer-specific exercise. J Sports Sci 26: 141, 2008.

36. Oliver JL, Armstrong N, Williams CA. Reliability and validity of a soccer-specific test of prolonged repeated-sprint ability. Int J Sports Physiol Perform 2: 137, 2007.

37. Padua DA, Arnold BL, Perrin DH, Gansneders BM, Carcia CR, Granata KP. Fatigue, vertical leg stiffness, and stiffness control strategies in males and females. J Athl Train 41: 294, 2006.

38. Plisky PJ, Rauh MJ, Kaminski TW, Underwood FB. Star excursion balance test as a predictor of lower extremity injury in high school basketball players. J Orthop Sports Phys Ther 36: 911–919, 2006.

39. Price RJ, Hawkins RD, Hulse MA, Hodson A. The Football Association medical research programme: An audit of injuries in academy youth football. Br J Sports Med 38: 466–471, 2004.

40. Rahnama N, Lees A, Bambaecichi E. Comparison of muscle strength and flexibility between the preferred and non-preferred leg in English soccer players. Ergonomics 48: 1568–1575, 2005.

41. Rahnama N, Lees A, Reilly T. Electromyography of selected lower-limb muscles fatigued by exercise at the intensity of soccer match-play. J Electromyogr Kinesiol 16: 257–263, 2006.

42. Rahnama N, Reilly T, Lees A, Graham-Smith P. Muscle fatigue induced by exercise simulating the work rate of competitive soccer. J Sports Sci 21: 933–942, 2003.

43. Toumi H, Poumarat G, Best TM, Martin A, Fairclough J, Benjamin M. Fatigue and muscle-tendon stiffness after stretch-shortening cycle and isometric exercise. Appl Physiol Nutr Metab 31: 565–572, 2006.