SCANDINAVIAN JOURNAL OF
MEDICINE & SCIENCE
IN SPORTS

Lower extremity dexterity is associated with agility in adolescent soccer athletes

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Agility is important for sport performance and potentially injury risk; however, factors affecting this motor skill remain unclear. Here, we evaluated the extent to which lower extremity dexterity (LED) and muscle performance were associated with agility. Fourteen male and 14 female soccer athletes participated. Agility was evaluated using a hopping sequence separately with both limbs and with the dominant limb only. The LED test evaluated the athletes' ability to dynamically regulate foot–ground interactions by compressing a spring prone to buckling with the lower limb. Muscle performance included hip and knee isometric strength and vertical jump height. Correlation analyses were used to assess the associations between muscle performance, LED, and agility. Multiple regression models were used to determine whether linear associations differed between sexes. On average, the female athletes took longer to complete the agility tasks than the male athletes. This difference could not be explained by muscle performance. Conversely, LED was found to be the primary determinant of agility (double limb: $R^2 = 0.61$, $P < 0.001$; single limb: $R^2 = 0.63$, $P < 0.001$). Our findings suggest that the sensorimotor ability to dynamically regulate foot–ground interactions as assessed by the LED test is predictive of agility in soccer athletes. We propose that LED may have implications for sport performance, injury risk, and rehabilitation.

The ability to rapidly change the velocity and direction of whole body center-of-mass is a fundamental locomotor skill in most sports. It is not surprising, therefore, that this ability, typically referred to as agility, has been shown to discriminate among skill levels in soccer (Reilly et al., 2000; Kaplan et al., 2009; Mujika et al., 2009; Vescovi et al., 2011), American football (Sierer et al., 2008), and rugby (Gabbett, 2009). In fact, Reilly et al. (2000) identified agility as the best variable to discriminate between a group of elite and sub-elite soccer players. Thus, identifying factors that influence proficiency of this motor skill could be useful for the development of training programs aimed at improving sports performance.

Currently, little is known regarding definitive factors that influence agility. Sprint speed, strength, and vertical jump height have been evaluated as potential indicators, but no consistent relationships have been reported. One potential reason may be due to the use of agility tests with varying physical demands (Brughelli et al., 2008). For example, agility tests that include running as a component (e.g., t-test, 5-0-5) have been shown to correlate moderately with sprint speed ($r = 0.55$–0.77; Pauole et al., 2000; Vescovi & McGuigan, 2008; Jones et al.,

2009; Mujika et al., 2009) and poorly to moderately with vertical jump height and strength ($r = 0.03$–0.69; Pauole et al., 2000; Barnes et al., 2007; Markovic, 2007; Vescovi & McGuigan, 2008; Jones et al., 2009; Meylan et al., 2009; Salaj & Markovic, 2011). In contrast, physical function tests that evaluate agility with hopping sequences (e.g., hexagon test) have been shown to correlate modestly at best with sprint speed and vertical jump height ($r = 0.22$–0.40; Pauole et al., 2000).

Studies evaluating the influence of exercise interventions on agility may provide the best available evidence concerning potential factors underlying agility. For example, exercise interventions shown to improve agility have included jumping and landing in multiple directions and sequences (Miller, 2006; Meylan & Malatesta, 2009) and change-of-direction sprints over short distances (Young et al., 2001). In contrast, athletes who practiced straight-ahead sprints (Young et al., 2001) or performed vertical jump and/or strength training in isolation did not improve performance on agility tests (Tricoli et al., 2005; Brughelli et al., 2008; Maio Alves et al., 2010). Taken together, these findings suggest that maximal running speed, lower extremity strength, and the ability to accelerate the body vertically are not

critical for success (at least when considered in isolation) when performing agility tests that emphasize the ability to rapidly change direction. Rather, a common element shared by exercise interventions shown to improve agility is motor tasks that challenge athletes to dynamically regulate foot–ground interactions in multiple planes. We propose, therefore, that the ability to control the magnitude and direction of limb endpoint force, previously referred to as *lower extremity dexterity* (Lyle et al., 2013a), may be a fundamental attribute of agility.

We recently described a test designed to quantify lower extremity dexterity. We have shown that the lower extremity dexterity test (LED-test) is poorly correlated with body mass, height, and maximal isometric strength of the knee extensors, knee flexors, and hip extensors (Lyle et al., 2013a). Moreover, LED-test scores have been shown to be lower in female soccer athletes when compared to males (Lyle et al., 2013b). Here, we examine the extent to which lower extremity dexterity, as opposed to strength and power, is associated with agility in female and male soccer athletes. We hypothesized that lower limb dexterity (as assessed by the LED-test) would be correlated with agility but not lower limb strength and power in both male and female soccer athletes. Based on previous literature (Lyle et al., 2013b; Pauole et al., 2000; Peterson et al., 2006; Meylan et al., 2009; Mujika et al., 2009; Munro & Herrington, 2011), it was further hypothesized that female athletes would exhibit slower times to complete the agility task as a result of reduced dexterity.

Materials and methods

Fourteen female and 15 male high school soccer athletes participated in this study [mean ± standard deviation (SD); age: 16.1 ± 0.8 vs 15.9 ± 0.7 years; body mass: 63.9 ± 11.6 vs 67.8 ± 8.9 kg; height: 1.67 ± 0.06 vs 1.79 ± 0.07 m]. To control for the potential confound of experience, the female and male soccer athletes enrolled in this study were matched by age and skill level. This was achieved by recruiting players from the same competitive club or high school soccer division (i.e., varsity vs junior varsity). Total years of soccer experience and club experience were similar between female and male soccer athletes (mean ± SD; 10.9 ± 1.8 vs 10.3 ± 2.1 and 5.4 ± 1.9 vs 4.5 ± 1.8 years, respectively). We excluded participants if they reported any of the following: (a) history of previous anterior cruciate ligament injury; (b) previous knee surgery; or (c) recent injury that had prevented them from participating fully in soccer for greater than 3 weeks within the last 6 months. Prior to participation, subjects and their parent/guardian provided written informed assent and/or consent as approved by the Institutional Review Board of the University of Southern California Health Sciences Campus.

Procedures

Participants attended a single session that included completing the LED-test, hip and knee strength testing, double- and single-limb agility tests, and vertical jump testing. They were fitted with the same style of athletic shoe (New Balance, X700, Boston, Massachusetts, USA) and their body mass was recorded prior to testing. Each athlete performed a dynamic warm-up, which consisted of the hopping sequence for the agility tests (see below for task description). Testing was performed on the dominant limb for the LED-test and single-limb agility as determined by the preferred foot used to kick a ball.

LED-test

The LED-test is a dynamic contact–control task based on the ability of participants to compress a slender spring that is prone to buckling with the lower limb (Valero-Cuevas et al., 2003; Venkadesan et al., 2007; Lyle et al., 2013a). For a detailed description, see Lyle et al. (2013a). Briefly, the LED-test device consists of a 25.4 cm helical compression spring mounted on a 30.5 × 30.5-cm base with a 20 × 30-cm platform affixed to the free end (i.e., top). The spring had the following specifications: mean diameter: 3.08 cm; wire diameter: 0.04 cm; spring rate: 36.8 N/cm; total coils: 28.7; hard-drawn wire (#850, Century Spring Corp., Los Angeles, California, USA). The spring stiffness and slenderness was chosen such that spring instability occurred at low force magnitude (i.e., minimize fatigue and influence of strength). The test device was positioned on a force platform and the vertical ground reaction force component recorded at 1500 Hz (AMTI, Watertown, Massachusetts, USA). Vertical reaction forces were low-pass filtered with a fourth-order zero-lag Butterworth filter at 15 Hz and displayed for participants as force feedback on a computer monitor using LabVIEW (National Instruments Corp., Austin, Texas, USA).

Participants performed the LED-test in an upright partially supported posture with weight equally distributed on a bike saddle and the non-test limb. The non-test limb rested on a step with the height adjusted so that the hip and knee were extended and the pelvis was level. The trunk was supported by leaning forward approximately 20° against a strap at the level of the xiphoid process. The forearms rested on a crossbar adjusted to the level of the xiphoid process. At the beginning of each trial, the test limb was positioned with the foot on the device platform in a standardized posture (i.e., 75–80° of hip and knee flexion).

Participants were instructed to slowly compress the spring with their foot with the goal to raise the force feedback line as high as possible and keep it there without losing control. Participants were informed that it is natural for the spring to bend and become unsteady. Despite the inherent instability, the goal was to sustain the highest vertical force possible during each 16-s trial. Importantly, the reaction force recorded by the force platform at the base of the spring quantified the level of spring compression with the highest sustained force a surrogate for the greatest level of instability that could be controlled (Lyle et al., 2013a). The force magnitudes achieved during the LED-test are on the order of approximately 16% body weight, and therefore well below the subject's maximal voluntary force capability with the leg. Throughout testing, subjects were instructed to avoid using the contralateral limb or arms to help direct the movement of the test limb.

Participants were allowed five practice trials to become familiar with the test and visual feedback. We provided a real-time plot of the vertical compression force to encourage the subjects to compress the spring as far as possible, and therefore achieve their greatest level of instability. Subjects then completed between 21 and 25 trials. Consistent with our previous study, testing was stopped after trial 21 if performance on this trial was not among the best three of the previous 20 trials. Additional trials were completed up to 25 if performance on the 21st trial was one of the top three achieved (Lyle et al., 2013a). Thirty-second rest periods were provided between trials and 2 min of rest were provided after every fifth trial. Verbal encouragement was provided to facilitate maximum performance.

The dependent variable for the LED-test was the highest average vertical force over a 10-s period during the sustained-hold phase of each trial. Maximal values were identified for each trial using a point-by-point 10-s moving average calculated from the

raw vertical reaction force (Lyle et al., 2013a). Maximum values were considered for analysis if the coefficient of variation was ≤10% for each moving window time step. This criterion was chosen as an indicator that the dynamic interactions between the foot and spring platform system (i.e., vertical ground reaction forces) were controlled (Venkadesan et al., 2007; Lyle et al., 2013a). Participants had to complete at least 15 trials that met the coefficient of variation criterion to assure that performance had stabilized. Failure to meet this criterion resulted in the subject being excluded from the analysis. The average of the best three trials was used for analysis. The LED-test, performed as described earlier, has been shown to exhibit excellent test–retest reliability (intraclass correlation coefficient$_{(2,3)}$ = 0.94; minimal detectable difference = 5.5 N; Lyle et al., 2013a).

Lower extremity strength and power

Peak isometric torque was obtained for the knee extensors, knee flexors, and hip extensors using a Humac Norm Dynamometer (CSMi, Stoughton, Massachusetts, USA). For knee extensor and flexor strength, subjects were seated with the hip at 90° and the knee flexed to 60°. The thigh was secured to the dynamometer seat with a strap. The resistance pad was placed just proximal to the ankle. Hip extension strength was evaluated in the prone position with the pelvis supported at the edge of the dynamometer testing table and the hip in 60° of flexion. Participants were asked to extend their hip into a resistance pad positioned against the posterior thigh with the knee flexed to 90°. To facilitate a maximum effort, real-time torque was displayed as feedback during each trial and verbal encouragement was provided. One practice trial was provided for each testing position. Three maximal effort repetitions consisting of 5-s holds were then recorded. A rest period of ≥30 s was provided between repetitions. The maximal torque value obtained from each muscle group was divided by body mass for statistical analyses.

Lower extremity power was quantified using countermovement jump height recorded by a Vertec measuring device (Perform Better, Cranston, Rhode Island, USA). First, participants reached as high as possible with their dominant arm while keeping their feet flat on the ground. Countermovement jump height was recorded as the difference between reach height and the highest point reached with the fingertip during the jump in centimeters. Athletes were allowed to swing their arms during the countermovement jump. The best of three trials was used for statistical analysis.

Change-of-direction ability

Most measures of agility require running as part of the test. However, moderate correlations between agility measures that involve running and sprint speed suggest the domain of function evaluated by such tests favors running speed over the ability to change direction quickly (Pauole et al., 2000; Vescovi & McGuigan, 2008; Jones et al., 2009; Mujika et al., 2009). Therefore, the task chosen for the current study involved a hopping sequence that focused on quick change of directions we refer to as the cross-agility test, which is similar in principle to the hexagon test (Beekhuizen et al., 2009) and a test described by Miller (2006). For the cross-agility test, four target positions were marked on the floor anterior, posterior, right, and left of a center position on a 1.2 × 1.2 m force platform (AMTI; Fig. 1). Starting from the central position and maintaining a forward-facing body orientation (i.e., toward anterior target), participants were instructed to hop sequentially to the target positions and back to the center as fast and as accurate as possible. Participants moved in a clockwise direction if they were right-foot dominant and counterclockwise if they were left-foot dominant. Two clockwise cycles (or counterclockwise cycles if left-foot dominant) starting
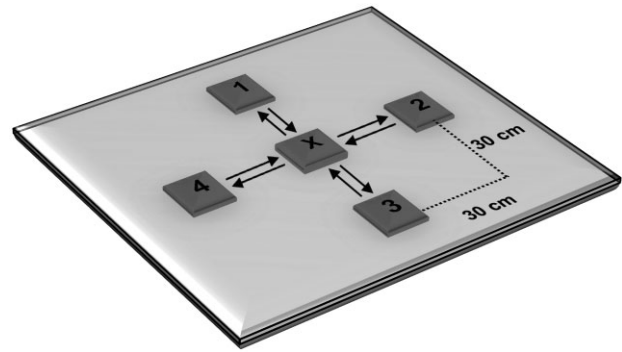

Fig. 1. Schematic depicting force plate and target positions for the cross-agility test. The targets were spaced 30 cm apart for the single-limb (shown here) and 40 cm apart for the double-limb hopping sequence. Starting in the center (X) and maintaining a forward-facing body orientation (i.e., toward target 1), participants hopped sequentially in a clockwise direction for two cycles if right-foot dominant as follows: X (start)→ 1 → X → 2 → X → 3 → X → 4 → X → 1 → X → 2 → X → 3 → X → 4 → X → 1 → X (end). Two counter-clockwise cycles were completed if left-foot dominant.

and ending with the anterior target were completed per trial (i.e., 18 foot–ground interactions per trial). Participants kept their hands on their hips while performing the hopping sequence to mitigate the potential influence of arm posture. Each athlete first completed the hopping sequence using both lower limbs. Following the double-limb trials, subjects completed the hopping sequence with their dominant limb. The hop distances were 40 cm when using both limbs and 30 cm during single-limb hopping.

In an effort to capture the best possible performance, at least six trials were recorded for both the double-limb and single-limb agility conditions. Subjects were allowed additional trials up to 10 if they felt they could improve or a clear trend of improvement was observed. The number of trials attempted was similar for the female athletes and the male athletes, for both the double-limb and single-limb agility tests (mean ± SD; double-limb: 6.9 ± 0.7 vs 7.3 ± 1.3; single-limb: 6.8 ± 0.8 vs 7.1 ± 0.8). A trial was considered for analysis if at least 15 of the 18 foot touches contacted the targets on the floor. The time to complete the task was determined by the vertical ground reaction force, which was sampled at 1500 Hz. The test time started at toe off (<20 N) of the first hop and ended upon foot contact (>20 N) on the force platform of the last hop. The average of the best three trials was used for statistical analysis.

Statistical analysis

Pearson product–moment correlation coefficients were used to examine the relation between agility performance and LED-test performance, strength, and vertical jump height. Correlation analyses were evaluated separately for male and female soccer players. For independent variables that had a significant correlation with agility across sexes, the data were pooled and a series of multiple linear regression models was used to determine whether the regression lines were statistically different between sexes. Specifically, this was done by fitting full- and reduced-regression models and computing an *F*-test (Kutner et al., 2005). The full-model equation was as follows: agility = β_0 + β_1(independent variable) + β_2(sex) + β_3(independent variable) × (sex). The reduced-model equation was absent the grouping variable sex as follows: agility = β_0 + β_1(independent variable). The sum of squared errors (SSE) and degrees of freedom (DF) obtained from both the full and reduced models, and the mean squared errors (MSE) from the full model were used to calculate an *F* statistic using the

Table 1. Pearson product–moment correlation between agility and predictor variables

	Knee extensor strength	Knee flexor strength	Hip extensor strength	Jump height	LED-test
Double-limb agility					
Females	0.32	0.22	–0.18	–0.13	–0.78*
Males	–0.02	–0.11	–0.19	–0.39	–0.62*
Single-limb agility					
Females	0.19	–0.06	–0.22	0.04	–0.65*
Males	0.20	–0.08	–0.04	–0.42	–0.73*

$^{*}P < 0.05.$

following equation: $F = [SSE(reduced) – SSE(full)]/[DF(full) – DF(reduced)]/MSE(full)$. The F statistic tested the null hypothesis that $\beta_2 = \beta_3 = 0$. A significant F-test, indicating the regression lines were statistically different between sexes, would justify reporting the linear associations separately for male and female athletes; whereas, a non-significant F-test would justify reporting the linear association based on pooled data from the male and female athletes.

One-way multivariate analysis of variance (MANOVA) was used to examine sex differences in agility performance (double-limb and single-limb) and lower extremity strength and power. Univariate ANOVA tests were performed if the omnibus MANOVA was significant. The one-way MANOVA and post-hoc univariate ANOVAs were justified as the data were normally distributed with homogeneity of covariances and variances between groups. All statistical analyses were conducted with the Statistical Package for the Social Sciences software (IBM Corporation, Armonk, New York, USA) using a significance level of $P \leq 0.05$.

Results

One male participant was excluded from the analyses because he did not complete the minimum of 15 LED-test trials that met the coefficient of variation criterion of 10%. Thus, the following analyses are from 14 male athletes and 14 female athletes. Double-limb and single-limb agility performance were found to be significantly correlated with lower extremity dexterity in both female and male athletes, whereas measures of maximal voluntary lower extremity strength and power were not significantly associated with time to complete the agility tests (Table 1). Given that LED-test performance was significantly correlated with agility across sexes, multiple linear regression analyses were performed to test whether the linear regression lines differed between male and female athletes. These analyses indicated that the linear associations were not different between the female and male athletes (double-limb: $F_{(2,24)} = 0.71$, $P = 0.50$; single-limb: $F_{(2,24)} = 0.29$, $P = 0.75$). The significant linear associations between agility performance and LED-test performance using the pooled data are shown in Fig. 2.

The multivariate test of overall sex differences was statistically significant ($P = 0.001$). On average, male soccer athletes took less time to complete the double-limb and single-limb agility tests when compared with the female athletes (mean ± SD; double-limb: 4.74 ± 0.47 vs

(a)

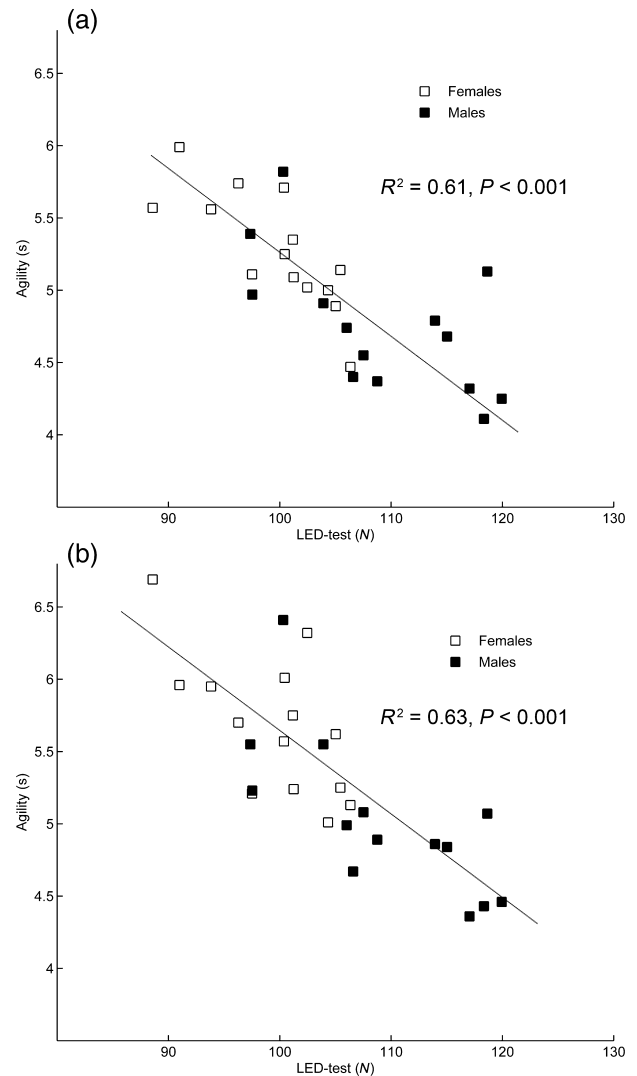$R^2 = 0.61$, $P < 0.001$

(b)

$R^2 = 0.63$, $P < 0.001$

Fig. 2. Scatter plot of lower extremity dexterity (LED)-test performance and the cross-agility test completed with (a) both limbs and (b) a single limb. Strong and significant associations were found between LED-test performance and both double- and single-limb agility. The coefficient of determination values are from pooled data because regression analyses indicated no difference between the linear regression lines between sexes.

5.28 ± 0.4 s, $P = 0.003$; single-limb: 5.0 ± 0.54 vs 5.67 ± 0.49 s, $P = 0.003$; Fig. 3). Male soccer athletes also had greater lower extremity strength and power than female athletes (Table 2).

Discussion

The ability to quickly change direction is relevant for sport maneuvers and activities of daily living such as transitions around objects or people in a busy street. Identifying factors that influence change-of-direction

Fig. 3. Male athletes completed the (a) double-limb and (b) single-limb cross-agility test in significantly less time when compared with female athletes ($P = 0.003$ and $P = 0.003$, respectively). The central horizontal line within the box represents the median value, the box edges represent 25th and 75th percentile, and the whiskers represent the outermost data points up to 1.5 times the interquartile range (plus sign represents an outlier).

ability, therefore, has the potential to inform exercise interventions that aim to improve function and mitigate athletic injuries and falls. The purpose of this study was to examine whether lower extremity dexterity was associated with agility in male and female soccer athletes. In support of the hypothesis, the primary finding of this study was that 60–63% of the variance in change-of-direction ability was explained by performance on the LED-test. These results suggest that the unique sensorimotor capability assessed by the LED-test is an important experimental construct highly associated with the ability to make change-of-direction maneuvers quickly.

The LED-test was designed to quantify the sensorimotor capability of the lower extremity to compress a slender spring that becomes unstable at submaximal forces (i.e., approximately 16% of body weight). When the spring platform system is compressed by the limb with higher forces, the test device becomes increasingly unstable with the capacity to deviate in 6 degrees of freedom. The 16-s time period for each trial allowed for continuous dynamic interactions between the lower limb and spring platform system so as to quantify the highest instability that could be controlled for a sustained period of time. We propose that the dynamic interactions between the lower limb and the spring, while characterized by lower force magnitudes when compared with locomotor tasks, are similar in principle to how the lower limb must interact with the ground to change the velocity and/or redirect the body center-of-mass during quick change-of-direction movements (Lyle et al., 2013a). Thus, the robust association found in this study provides a novel explanation for agility performance in the context of dynamic lower extremity control. Moreover, exercise interventions that have been shown to improve agility include multiplanar jumping and landing, and change-of-direction maneuvers (Young et al., 2001; Miller, 2006; Meylan & Malatesta, 2009). Our results provide empirical support for this approach and imply that improvements in agility as a result of such training could be attributed, in part, to enhanced lower extremity dexterity (i.e., training may improve the ability of the lower limb to redirect body center-of-mass in varying directions and speeds). Future work is needed to test this hypothesis.

Dynamic maneuvers involving rapid whole body change-of-direction are demanding, from both a musculoskeletal and a sensorimotor control perspective. Prior
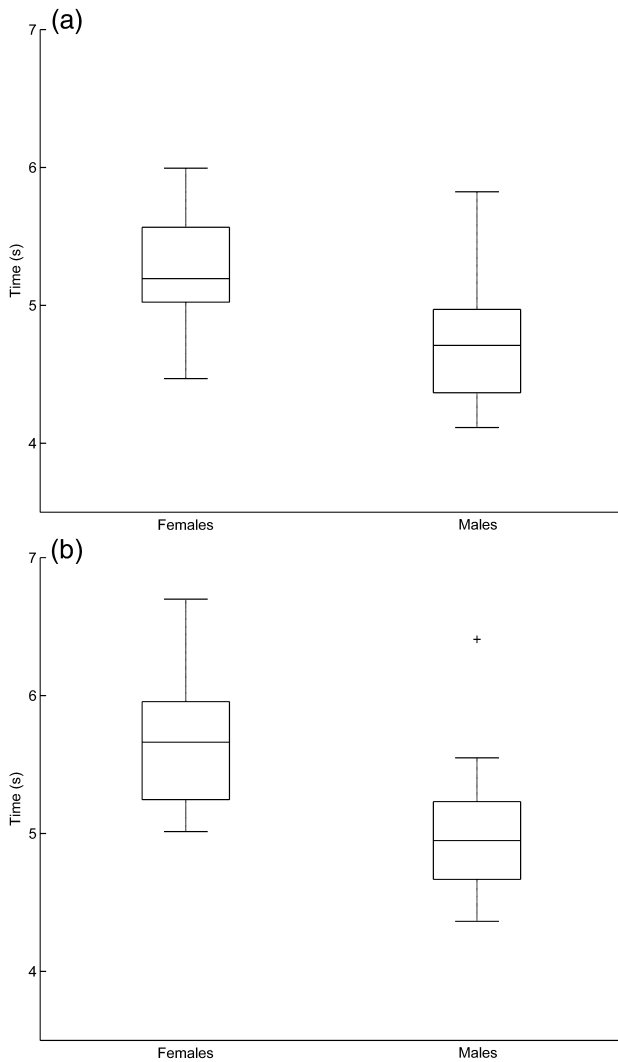
Table 2. Sex comparison of lower extremity strength and power

	Females (n = 14)	Males (n = 14)	P [†]
Knee extensor strength, N/m/kg	3.09 ± 0.46	3.47 ± 0.41	0.03
Knee flexor strength, N/m/kg	1.43 ± 0.33	1.75 ± 0.35	0.02
Hip extensor strength, N/m/kg	2.57 ± 0.55	3.29 ± 0.43	0.001
Vertical jump height, cm	39.5 ± 4.9	55.3 ± 10.5	<0.001

All values are mean ± SD.
[†]Significant MANOVA (P values are from univariate tests).

studies have emphasized the former by examining the influence of lower extremity strength and vertical jump height (i.e., power) on agility. While these measures of lower limb function could be important for some aspects of sport performance, the relatively weak and non-significant correlations between lower extremity muscle performance and agility found in the current study, and in other investigations (Barnes et al., 2007; Markovic, 2007; Jones et al., 2009), suggest that maximal strength and power have a limited role in one's ability to change direction rapidly as assessed in this study. Taken together, our findings suggest that the ability to coordinate lower limb muscles, i.e., sensorimotor control, to regulate foot–ground interactions to stabilize an unstable interface with the ground plays an important role when performing rapid change-of-direction maneuvers.

Consistent with previous literature, male athletes in the current study had superior agility performance, on average, when compared with the female soccer athletes. Performance on agility tests that require some sprinting (e.g., t-test, 5-0-5) has been shown to be faster by 11–17.5% in male athletes when compared with female athletes (Pauole et al., 2000; Meylan et al., 2009; Mujika et al., 2009; Munro & Herrington, 2011). Pauole et al. (2000), however, reported a difference of 7% between sexes completing a hopping sequence that required rapid change of directions (i.e., hexagon test) in recreational athletes and 5% in collegiate athletes. In the current study, male athletes completed the cross-agility test 10% faster (i.e., 540 ms) using both limbs and 12% faster (i.e., 670 ms) using a single limb than the female athletes. Although female athletes' ability to change direction was reduced when compared with that of male athletes on average, it is important to note that the regression analysis indicated that sex was not the primary determinant of agility performance. Rather, dynamic lower extremity muscle coordination as assessed by the LED-test was the distinguishing feature.

Apart from sex differences in agility performance, female athletes exhibited decreased strength and vertical jump height when compared with the male athletes in this study. As discussed earlier, these differences in muscle performance did not account for the slower agility times in female athletes. Nonetheless, our findings compare well with other studies evaluating vertical jump height in skilled soccer athletes with a similar age range. The vertical jump height of skilled female club soccer athletes in a study by Vescovi et al. (2011) was almost identical to the female athletes in the current study (i.e., 39 vs 39.5 cm). The vertical jump height of the male athletes in the current study was slightly higher compared with a group of skilled male soccer athletes in a previous report (52 vs 55.3 cm; Mujika et al., 2009). While the jump height values reported in the current article are similar to previous reports, it has been reported that the Vertec device may underestimate true jump height, albeit slightly, when compared with values

obtained using a force mat or motion capture system (Leard et al., 2007).

Our results reveal a potentially critical factor that contributes to agility in the context of dynamic lower extremity control. We propose that the most likely explanation for varied levels of agility and dexterity lies in the varied levels of exposure or practice that has challenged and therefore promoted dynamic lower extremity coordination. It is clear that exercise interventions that incorporate landing and change-of-direction maneuvers can improve agility (Young et al., 2001; Miller, 2006; Meylan & Malatesta, 2009). As such, one potential explanation for the superior performance observed in male athletes could reflect a practice effect. That is, male athletes may challenge their sensorimotor system more often and/or to a greater extent than female athletes during practice and competition. Advancing skill level within a sport would, therefore, be expected to provide a higher competitive level and potentially a stimulus to improve lower extremity dexterity. Indeed, studies have shown that performance on agility tests is better in higher division players (Pauole et al., 2000; Reilly et al., 2000; Kaplan et al., 2009; Mujika et al., 2009). Likewise, differences in agility between sexes become smaller with advancing skill level (Pauole et al., 2000; Mujika et al., 2009). In the current study, athletes were matched for level of competition and years of experience; therefore, the differences in agility between sexes could potentially be attributed to a difference in playing intensity and/or reduced adaptation to practice. These hypotheses warrant future study.

In addition to sports performance, the findings from this study may have implications for injury risk. Given that non-contact lower extremity injuries (e.g., anterior cruciate ligament injuries) occur most often during sudden deceleration and change-of-direction maneuvers, change-of-direction ability could influence lower extremity injury risk. As discussed, exercise interventions that have incorporated plyometrics and sports-specific change-of-direction training have been shown to improve agility performance (Young et al., 2001; Miller, 2006; Meylan & Malatesta, 2009). Importantly, multiplanar jumping and landing, and change-of-direction training has also been shown to decrease anterior cruciate ligament injury rates in female athletes (Mandelbaum et al., 2005; Olsen et al., 2005; Gilchrist et al., 2008; Kiani et al., 2010). We propose that adaptations of the sensorimotor system in response to training, as suggested above for the sex difference in agility, may also underlie reduced injury risk and effective rehabilitation strategies.

This study raises several questions that warrant future study. Although almost 65% of the variance in agility performance could be explained by performance on the LED-test, a significant amount of variance in agility performance remains unexplained. An implicit goal of the agility task at the whole body level is to redirect total

body momentum to each target as quickly as possible. We speculate that a potential source of unexplained variance could arise from technique in this regard. For example, orienting the trunk in line with the subsequent ground reaction force during foot contact would minimize angular momentum and likely assist in effectively redirecting the center-of-mass.

There are several limitations of our study that should be acknowledged. First, it should be noted that test–retest reliability is unknown for the cross-agility task. We made every effort to record athletes' best performance in this study by recording at least six trials per subject and using the cross-agility task as a warm-up before data collection (i.e., familiarization with hopping sequence) to mitigate a learning effect. Second, the LED-test was designed to evaluate an important attribute required to rapidly change whole body velocity and direction (i.e., ability of the lower limb to dynamically regulate force magnitude and direction when interacting with the ground). Likewise, the change-of-direction task evaluated in this study was chosen to represent the general ability of athletes to rapidly change whole body direction. Future work is needed to clarify whether the attributes evaluated by the LED-test and cross-agility task are attributes informative of skill specific to soccer or generalize across athletes and non-athletes. Moreover, we examined the performance of a homogenous sample of skilled soccer athletes. The extent to which the findings from this study can be generalized to other populations remains unknown. Lastly, a single agility task focusing on planned change of direction was used to test the hypothesis in this study. Recent literature advocates also using agility tasks that involve reactions to a stimulus (Sheppard & Young, 2006). Evaluating the influence of lower extremity dexterity on the performance of other planned and/or reactive agility tasks would provide additional insight regarding the unique construct of human performance assessed by the LED-test.

Perspectives

The primary finding of this study was that lower extremity dexterity as assessed by the LED-test was significantly associated with the ability to change direction rapidly in both male and female soccer athletes. In contrast, lower extremity strength and power were not associated with agility as evaluated in this study. As such, this study provides evidence that lower extremity dexterity is an important construct required for sudden deceleration and change-of-direction maneuvers in male and female soccer athletes. Our results provide a rationale for focusing exercise interventions intended to improve agility on tasks that challenge the capability of the lower limbs to dynamically regulate the magnitude and orientation of foot–ground reaction forces in all directions to control and redirect whole-body motion.

Key words: Sex difference, athlete performance, strength, skill, sensorimotor control.

Acknowledgements

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