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Control of dynamic foot-ground interactions in male and female soccer athletes: Females exhibit reduced dexterity and higher limb stiffness during landing

Mark A. Lyle [a,c,*], Francisco J. Valero-Cuevas [a,b], Robert J. Gregor [a,c], Christopher M. Powers [a]

[a] *Division of Biokinesiology and Physical Therapy, University of Southern California, Los Angeles, CA, United States*
[b] *Department of Biomedical Engineering, Viterbi School of Engineering, University of Southern California, Los Angeles, CA, United States*
[c] *School of Applied Physiology, Georgia Institute of Technology, Atlanta, GA 30332-0356, United States*

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ABSTRACT

Controlling dynamic interactions between the lower limb and ground is important for skilled locomotion and may influence injury risk in athletes. It is well known that female athletes sustain anterior cruciate ligament (ACL) tears at higher rates than male athletes, and exhibit lower extremity biomechanics thought to increase injury risk during sport maneuvers. The purpose of this study was to examine whether lower extremity dexterity (LED) – the ability to dynamically control endpoint force magnitude and direction as quantified by compressing an unstable spring with the lower limb at submaximal forces – is a potential contributing factor to the "at-risk" movement behavior exhibited by female athletes. We tested this hypothesis by comparing LED-test performance and single-limb drop jump biomechanics between 14 female and 14 male high school soccer players. We found that female athletes exhibited reduced LED-test performance ($p=0.001$) and higher limb stiffness during landing ($p=0.008$) calculated on average within 51 ms of foot contact. Females also exhibited higher coactivation at the ankle ($p=0.001$) and knee ($p=0.02$) before landing. No sex differences in sagittal plane joint angles and center of mass velocity at foot contact were observed. Collectively, our results raise the possibility that the higher leg stiffness observed in females during landing is an anticipatory behavior due in part to reduced lower extremity dexterity. The reduced lower extremity dexterity and compensatory stiffening strategy may contribute to the heightened risk of ACL injury in this population.

1. Introduction

Controlling the dynamic interactions between the lower limb and the ground is requisite for success when performing skilled locomotor tasks. For example, the lower limbs must regulate the magnitude and direction of the ground reaction force to initiate, terminate, and/or redirect the body center of mass (COM) during locomotor tasks such as walking, running, rapid turning, and landing (Hass et al., 2008; Kaya et al., 2006; Liu et al., 2008; Mathiyakom et al., 2006). The ability to regulate the magnitude and direction of foot-ground interaction forces, previously defined as *lower extremity dexterity*, has been proposed as a potentially important attribute for tasks that require deceleration and redirection of the body COM (Lyle et al., 2013).

Although currently available methods are routinely used to characterize whole-body kinematics, kinetics and center of pressure dynamics, such methods do not quantify lower extremity dexterity. Thus, we developed the lower extremity dexterity test (LED-test) to assess the capability of the lower limb to regulate endpoint force magnitude and direction (Lyle et al., 2013). The LED-test, an adaptation of a test to quantify finger dexterity (Valero-Cuevas et al., 2003), evaluates the ability of an individual to compress an unstable spring with the lower limb at submaximal forces. The LED-test has been shown to be reliable and evaluates a dimension of dynamic lower limb function that is independent of isometric strength (knee extensors, knee flexors, hip extensors), height, and body mass (Lyle et al., 2013). Here, we examine whether limb dexterity could explain, in part, a serious and complex problem in sports medicine: why do young female athletes sustain non-contact anterior cruciate ligament (ACL) injuries at a rate 2–6 times greater than their male counterparts (Agel et al., 2005; Borowski et al., 2008; Yard et al., 2008)? This is an important clinical problem because most athletes that tear their ACL do not return to the same level of competitive play

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* Corresponding author at: School of Applied Physiology, Georgia Institute of Technology, 555 14th Street NW Atlanta, GA 30332-0356, United States. Tel.: +1 323 894 3986; fax: +1 404 894 9982.
E-mail address: mlyle@ap.gatech.edu (M.A. Lyle).

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Table 1
Participant characteristics (values are mean ± SD).

	Females $n=14$	Males $n=14$	p
Age, yr	16.2 ± 0.8	15.9 ± 0.7	0.33
Height, m	1.67 ± 0.06	1.79 ± 0.07	< 0.001
Body mass, kg	63.9 ± 11.6	67.8 ± 8.9	0.34
Total soccer experience, yr	10.9 ± 1.8	10.3 ± 2.1	0.46
Club soccer experience, yr	5.4 ± 1.9	4.5 ± 1.8	0.24

(Soderman et al., 2002), and it has been shown that approximately 50% of ACL injured athletes will experience knee osteoarthritis within 12–14 years of injury (Lohmander et al., 2004; von Porat et al., 2004).

The higher rate of ACL injuries in females is believed to result from them performing sport maneuvers with limb mechanics that increase ACL loading. For example, studies have shown that females decelerate body momentum by absorbing greater energy at the ankle and knee, whereas males tend to absorb more energy at the knee and hip (Decker et al., 2003; Schmitz et al., 2007; Sigward et al., 2011). In addition, the movement behavior exhibited by females has been characterized by smaller excursions of knee and hip flexion and higher ground reaction forces. This biomechanical pattern has been referred to as a “stiffening strategy” (Decker et al., 2003; Devita and Skelly, 1992; Pollard et al., 2010; Schmitz et al., 2007; Sigward et al., 2011) and shown to result in higher peak ACL forces when compared to a “soft landing strategy” (Laughlin et al., 2011). Moreover, there is evidence suggesting that limited joint excursions in the sagittal plane lead to greater frontal plane motion and moments at the knee (Pollard et al., 2010) which also has been linked to ACL injury risk (Hewett et al., 2005). In this study, we use average leg stiffness, defined as the ratio of peak vertical ground reaction force and COM displacement, as a global measure of multi-joint coordination to characterize the “stiffening strategy” described above (Butler et al., 2003; Farley et al., 1998; Kulas et al., 2006).

Several factors have been proposed to explain the movement behavior and higher ACL injury rates in females (e.g. hormonal, anatomical, environmental, neuromuscular) (Griffin et al., 2006). However, literature suggests that lower limb strength and anthropometry do not fully explain the sex disparity in movement behavior or injury rates (Beutler et al., 2009; Herman et al., 2008; Mizner et al., 2008; Shultz et al., 2009). Moreover, evidence demonstrating that exercise interventions emphasizing multiplanar jumping and landing drills reduce ACL injuries (Gilchrist et al., 2008; Kiani et al., 2010; Mandelbaum et al., 2005; Olsen et al., 2005) suggests modifiable factors other than strength may be responsible. For example, the ability to control dynamic foot-ground interactions as defined here (i.e. dexterity) is one potential factor that has yet to be examined.

The purpose of this study was to determine whether lower extremity dexterity is a potential factor underlying altered movement behavior in female athletes. We hypothesized that females would exhibit reduced LED-test performance when compared to the male athletes. Moreover, we hypothesized that the “stiffening strategy” used by females is due, in part, to reduced lower extremity dexterity. This hypothesis would be supported if female athletes exhibit both reduced dexterity and higher leg stiffness during a single-limb drop jump when compared to males. Because leg stiffness can be modulated by varying muscle activation before foot contact and/or limb kinematics at the time of foot contact (Farley et al., 1998; Fu and Hui-Chan, 2007; Moritz and Farley, 2004; Potthast et al., 2010), knee and ankle coactivation prior to foot contact and sagittal plane joint angles at foot contact were quantified. The time to peak vertical ground reaction force also was evaluated so that the landing behavior could be interpreted in terms of potential neural control mechanisms. For example, a finding of higher coactivation prior to foot contact and higher leg stiffness calculated at a time before reflex activity could likely influence limb mechanics (e.g. 50 ms) would be suggestive of a feedforward control strategy (Santello, 2005).

2. Methods

2.1. Subjects

Fourteen female and 15 male high school soccer athletes between the ages of 15–18 participated. To control for experience, the athletes were matched by age and skill level by recruiting players from the same competitive club or high school soccer division. Total years of soccer experience and club experience were similar between groups (Table 1). Participants were free of current lower extremity pain or injury. We excluded participants who reported any of the following: (1) history of previous ACL injury; (2) previous knee surgery; or (3) recent injury that had prevented them from participating fully in soccer for greater than 3 weeks within the last 6 months.

Participants attended a single session in which they completed the LED-test and a single-limb drop jump task. Prior to testing, subjects and their parent/guardian provided written informed assent and consent as approved by the Institutional Review Board of the University of Southern California. Participants were fitted with the same style of athletic shoe (New Balance Inc., Boston, MA). Only the dominant lower extremity was tested (i.e. preferred foot used to kick a ball).

2.2. Lower extremity dexterity test

For a detailed description see Lyle et al., (2013). 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. The spring characteristics were as follows: mean diameter: 3.08 cm, spring rate: 36.8 N/cm, hard drawn wire (#850, Century Spring Corp., Los Angeles, CA). The spring 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, Waterton, MA). Vertical reaction forces were low-pass filtered at 15 Hz and displayed for participants as visual force feedback using LabVIEW (National Instruments Corp., Austin, TX).

Participants performed the LED-test in an upright partially supported posture with weight equally distributed on a bike saddle and the non-test limb, which rested on a step 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. Participants were informed that it is natural for the spring to bend and become unsteady when force is applied. Despite the inherent instability, the goal was to sustain the highest vertical force possible during each 16 s trial. Subjects were instructed to avoid using the contralateral limb or arms to help direct the movement of the test limb.

Participants completed 5 practice trials. Then, subjects completed between 21 and 25 trials. Testing was stopped after trial 21 if performance on this trial was not among the best 3 of the previous 20 trials. Additional trials were completed up to 25 if performance on the 21st trial was one of the top 3 achieved. Thirty second rest periods were provided between trials and 2 min of rest was provided after every 5th trial. Verbal encouragement was provided to facilitate maximum performance.

2.2.1. Data analysis

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 ground reaction force (Lyle et al., 2013). Maximal values were considered for analysis if the coefficient of variation was $\leq 10\%$ 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. compression forces) were controlled (Lyle et al., 2013; Venkadesan et al., 2007). Participants had to complete at least 15 trials that met the coefficient of variation criterion. Failure to meet this criterion resulted in a subject being excluded from the analysis. The average of the best 3 trials was used for analysis. We have previously reported that the LED-test as described above has excellent test-retest reliability ($ICC_{(2,3)}=0.94$) (Lyle et al., 2013).