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Sex differences in unilateral landing mechanics from absolute and relative heights

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ABSTRACT

Background: The prevalence of anterior cruciate ligament injuries in athletic populations and the sex disparity in injury rates are well documented. It is also recognized that landing from a jump is a common noncontact injury mechanism. Yet, most studies utilize absolute landing heights, and few have utilized landing heights equal to participants' maximal jumping ability. The purpose of this study was to examine unilateral landing mechanics from relative and absolute heights.

Methods: Twenty-one female and twenty male participants completed a series of landings from absolute heights of 30, 40, and 50 cm, as well as a height equal to their maximum jumping ability. Right leg three-dimensional kinematics, kinetics, and energetics were calculated from initial contact to maximum knee flexion.

Results: Females landed with greater peak posterior ground reaction force compared to males. Additionally, both female and male participants utilized the knee as the primary energy absorber, but females appear to emphasize greater ankle energy absorption compared to males. Females also displayed increased peak knee adduction moment, while males displayed decreased peak hip abduction moment as landing height increased.

Conclusions: It appears that females and males respond to increasing landing heights differently. However, landings from 40 and 50 cm may have represented an unrealistic mechanical demand for females, and influence subsequent inferences regarding ACL injury risk. Therefore, we suggest that comparisons between studies utilizing different landing heights be made with caution, and participants jumping ability be taken into account whenever possible.

Clinical relevance: The findings of this study offer novel insights with regard to landing height and lower extremity mechanics with the potential to inform anterior cruciate ligament injury intervention programs.

1. Introduction

The prevalence of anterior cruciate ligament (ACL) injuries in athletic populations is well documented [1–3], and a majority of these injuries are reported to be caused by noncontact mechanisms [4]. These noncontact mechanisms typically include sudden deceleration and/or rapid direction changes such as landing from a jump, cutting, or pivoting motions [5]. Although ACL tears can occur during bilateral landings, unilateral landings are considered more dangerous due to a decreased base of support and increased demand on musculature of only one leg to absorb the impact [4]. Furthermore, recent epidemiological evidence indicates that females are more than twice as likely to have a first-time noncontact ACL injury compared to males [6]. This increased risk of injury, along with increased female participation in high school and collegiate sports, has led to a rapid rise in ACL injuries in female athletes [5] and fueled many task- and sex-specific mechanistic investigations [7–20].

In general, females land with increased peak vertical [11] and posterior ground reaction forces (GRFs) compared to males [8]. Females also perform playing actions with decreased hip flexion, hip abduction, and knee flexion and knee abduction [7–10]. Furthermore, compared to males, females exhibit increased frontal plane hip and knee loading [7–10]. Finally, while males rely on the larger hip musculature to absorb energy, females absorb more energy at the knee and ankle [10–13]. These sex differences in landing kinematics, kinetics, and energetics have been attributed to decreased use of hip musculature to absorb the forces [11,12].

The effect of landing height (LH) on landing mechanics, and apparent injury risk, has also been well documented [21–25]. For example, lower extremity joint moments and work increase with increasing LH [22–25]. However, there is a divergence in knee joint kinematics between males and females as LH increases [21], suggesting that the relative demand of landing tasks may vary across individuals, and it may be beneficial to evaluate sex differences in landing mechanics from heights relative to maximum jumping ability.

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While several studies on lower extremity landing mechanics utilize absolute heights, few studies have examined those same variables while participants land from a height relative to jumping ability [10, 26] or equalized task demand [15]. When landing from a height relative to jumping ability, females exhibit difference in hip and knee kinematics [10]. Specifically, females exhibit decreased hip and knee flexion range of motion, as well as decreased hip abduction at initial contact compared to males [10]. These findings provide functional relevance, as athletes rarely land from heights greater than their maximal jumping capability. When task demand is equalized relative to lower extremity lean mass, the difference in absolute hip and knee energy absorption between sexes increases, but there is no effect on relative joint contributions to total energy absorption [15].

Therefore, absolute LHs potentially create inequitable task difficulty and expose participants to mechanical demands exceeding those faced in real-life, sport specific situations where most ACL injuries occur. Considering few studies have observed participants performing landings relative to maximal jumping ability [10], the purpose of this study was to examine sex differences in GRF, kinematics, kinetics, and energetics during unilateral landings from relative and absolute LHs. We hypothesized that females would not exhibit increased high-risk mechanics compared to males when landing from a height relative to their maximum jumping ability, but would during landings from absolute LHs due to the inequitable relative task demand.

2. Methods

2.1. Participants

Prior to data collection, experimental procedures received ethical approval from the university's Institutional Review Board. Forty-four healthy, recreationally active individuals between 18 and 30 years of age volunteered to participate. Each volunteer provided written, informed consent and completed a background questionnaire to screen for health status prior to participation. Volunteers were accepted if they had no history of lower extremity injury requiring surgical repair, and had not suffered a lower extremity injury within the previous six months. Recreationally active was defined as being physically active at least three times per week for a minimum of 30 min. At least one of these activity sessions was required to include jumping and landing components (e.g., basketball, volleyball). Additionally, participants were required to be pain free in the lower extremity on testing days. All participants wore spandex shorts and standard laboratory footwear (Air Max Glide, Nike, Beaverton, OR).

2.2. Experimental protocol

Participants' dominant leg was first determined as the leg which could kick a ball the farthest. Participants then completed three maximal effort countermovement jumps on a force plate (Bertec FP460, Columbus, OH) while GRF data were recorded at 2000 Hz with custom software (LabVIEW, v11.0, National Instruments Corporation, Austin, TX). Jump height was calculated using the impulse–momentum relationship, and participants' maximum vertical jumping ability was defined as the highest of three jumps.

Retro-reflective markers were then placed on specific anatomical landmarks [10]. Markers used exclusively for the standing calibration trial were placed bilaterally on the acromioclavicular joints, iliac crests, greater trochanters, medial and lateral femoral epicondyles, medial and lateral malleoli, and the first and fifth metatarsophalangeal joints. Rigid plates with four retro-reflective marker clusters were attached to the torso and pelvis, as well as bilateral thighs, shanks, and heels of the shoes for segment tracking during motion trials.

Once markers were attached in the proper locations, a three second standing calibration trial was collected. Calibration markers were removed and participants completed five successful unilateral landings on their dominant limb from heights of 30 cm (D30), 40 cm (D40), 50 cm (D50), and a height equal to their maximum jumping ability (DR). These absolute heights were chosen because they are commonly used to assess sex differences in unilateral landing mechanics [27]. Participants were instructed to keep their arms folded across their chest throughout the landing. While arm placement may alter landing mechanics [28], this position was chosen to remain consistent with previous research [10,11,29] and eliminate variability in landing mechanics due to arm motion. A successful trial was defined as participants' ability to perform the task without stepping down or jumping up from the box and their entire dominant foot landed on the force plate while refraining from hopping upon landing, touching down their contralateral foot or uncrossing their arms to help control the landing. Order of landing tasks was randomized. For all trials, marker coordinate data were collected at 200 Hz with an eight-camera motion analysis system (Vicon, Centennial, CO, USA), while GRF data were collected synchronously at 2000 Hz with the force plate.

2.3. Data analysis

Data reduction and analysis were implemented with Visual3D (v5.00, C-Motion Inc., Rockville, MD). Raw three-dimensional marker coordinate and GRF data were low-pass filtered using a fourth-order, zero lag, recursive Butterworth filter with cutoff frequencies of eight and 50 Hz, respectively [30]. Right-handed Cartesian segmental coordinate systems were defined to describe trunk and pelvis, as well as bilateral thigh, shank, and foot position and orientation using an unweighted least squares procedure [31]. Three-dimensional hip, knee, and ankle angles were determined using a joint coordinate system approach [32]. Hip joint centers were placed 25% of the distance from ipsilateral to contralateral greater trochanter markers [33]. Knee joint centers were the midpoint between femoral epicondyle markers [32], and ankle joint centers were the midpoint between malleoli markers [34]. Three-dimensional joint kinetics were calculated using a Newton–Euler approach [35], and reported in the distal segment reference frame. Body segment parameters were estimated from Dempster [36].

Predefined GRF, kinematic, kinetic, and energetic variables were identified based on those suggested previously to impact ACL injury risk [5,7,10,15–17,37]. GRF variables included peak vertical GRF (VGRF) and posterior GRF (PGRF). Kinematic variables included hip flexion and adduction, knee flexion and adduction, as well as ankle plantarflexion and inversion at initial contact (IC), defined as the instant VGRF first exceeding 10 N. Kinetic variables included peak hip extensor and abductor, knee extensor and adductor, as well as ankle plantarflexor and eversion moments. Finally, energetic variables included hip, knee, and ankle sagittal plane net joint work, calculated during the landing phase by integrating the respective joint power curves. Joint moments and GRF were normalized to body mass times the square root of LH, because GRF during landing is approximately proportional to the square root of LH based on the impulse–momentum relationship and properties of uniformly accelerated motion [38]. Energy absorption at each joint was normalized by body mass times LH, because total mechanical energy is directly proportional to LH [10].

2.4. Statistical analysis

Dependent variables were submitted to four (GRF, kinematic, kinetic, and energetic) separate 2×4 (sex × LH) MANOVAs in SPSS (SPSS v21.0, SPSS Inc., Chicago, IL). Follow-up univariate ANOVA was conducted in the event of significant MANOVAs ($p < 0.05$). Dependent variables that demonstrated significant univariate sex × LH interactions and LH effects were subsequently examined using post hoc pairwise comparisons with Bonferroni-adjusted p-values of $p \le 0.003$ and $p \le 0.008$, respectively. Significance for univariate sex effects was $p < 0.05$.