Original Research

Effects of Sex and Fatigue on Biomechanical Measures During the Drop-Jump Task in Children

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Background: Female athletes have a higher rate of anterior cruciate ligament (ACL) injury than males from adolescence and into maturity, which is suggested to result from sex-specific changes in dynamic movement patterns with maturation. Few studies have studied movement strategies and response to fatigue in children.

Purpose: To evaluate the effect of fatigue on biomechanical variables associated with increased risk for ACL injury during a drop-jump (DJ) performance in children.

Study Design: Controlled laboratory study.

Methods: A total of 116 children (mean age, 10.4 years) were recruited from local sports clubs and performed 5 repetitions of a DJ task before and after a fatigue protocol. Kinematic and kinetic data from initial contact (IC) to the first peak vertical ground reaction force (vGRF) were analyzed for both limbs, including limb and fatigue as within-subject factors for analyses between boys and girls. Pearson correlation coefficients were calculated to identify associations between variables of interest.

Results: Girls demonstrated greater peak vGRF values than boys (by 8.1%; $P < .05$), there were greater peak vGRF values for the right limb than the left (by 6.2%; $P < .001$), and fatigue led to slightly greater values ($P < .05$). Although weak, the correlation between peak vGRF values and knee flexion excursion was stronger for girls ($r = -0.20$) than boys ($r = -0.08$) ($P < .006$). Fatigue resulted in greater knee flexion angles at IC and less excursion during landing, more so for girls (by 6.1° vs 1.4°; interaction, $P < .001$), although the knee flexion moment was generally lowered by fatigue ($P < .001$). Limb asymmetry in knee flexion moments was more pronounced for boys than for girls (interaction, $P < .05$), contrary to that seen in frontal plane knee moments, where asymmetry was much greater in girls than boys (interaction, $P < .001$).

Conclusion: Even as young athletes, girls and boys seem to adopt dissimilar movement strategies and are differently affected by fatigue.

Clinical Relevance: Injury prevention programs should be considered at an earlier age in an effort to lower the risk of ACL injury in athletes.

Keywords: knee; ACL; biomechanics; pediatric sports medicine; motion analysis; injury prevention

An acute anterior cruciate ligament (ACL) rupture is a devastating knee injury that involves months of rehabilitation, regardless of whether the ligament is reconstructed. Such serious knee injury may increase risk of early onset and rapid progression of osteoarthritis (OA) of the knee joint[1,23] and it is therefore of great importance to improve strategies toward injury prevention. Most ACL injuries are noncontact in nature[17] and typically occur within the first 100 ms after the foot touches the ground.[16,18,20] The injury primarily occurs as a result of anterior shear force at the knee, in particular when coupled with valgus, varus, and internal rotation moments that may significantly affect ACL loading.[6] The number of knee injuries in children and adolescents increases with age,[19,29,32,40] and over 30% of young soccer players' injuries leading to absence from practice are

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reportedly joint and ligament injuries,[32] with greater injury incidence toward the end of each half.[29] Through puberty, girls see a greater increase in ACL injury rates than boys,[40,44] and from adolescence into maturity, female athletes have a higher ACL injury rate than males when adjusted to equal time spent at practice and competition of the same sports.[3]

Clinical tests to evaluate risk of ACL injury include the drop-jump (DJ) task, where strategies such as limb dominance (reliance on one over the other leg) and greater knee valgus and knee flexion angles are observed.[8,27] Biomechanical studies on risk factors that may explain greater female risk of noncontact ACL rupture have primarily been conducted on high-level, mature athletes. Sex-dependent differences in neuromuscular control of lower limb biomechanics, in particular knee joint loading, are thought to contribute to the female ACL injury mechanism.[15,43] Asymmetry in multiplanar lower limb movement patterns is thought to increase the risk of injury in females.[11,26,33] Fatigue may further induce multiplanar changes in kinematic and kinetic factors during functional tasks, which may make the knee more susceptible to injury.[5,25,35] Furthermore, fatigue has been shown to affect females differently than males during testing of landing mechanics.[15,22,25]

The assumption has been made that prepubertal girls and boys use similar movement strategies during sports play,[10,45] and sex-specific changes in dynamic movement patterns with maturation have been suggested to explain the increase in ACL injury rates in females seen through puberty.[7,9] Increased power, strength, and coordination with maturation of males, while females show little corresponding change, are among factors that have been suggested to predispose females to noncontact ACL injury.[30,37] A few recent biomechanical studies on adolescents and children have been performed, indicating that biomechanical differences may exist at an earlier age[12,13,24,36,45] while others have not shown differences.[7]

Biomechanical risk factors for ACL injury and the effects of fatigue have been studied extensively in mature athletes of both sexes but less in younger age groups. More research is needed to provide greater insight into functional movement patterns of children who regularly train and compete in sports and the effects of fatigue on performance. If modifiable risk factors are identified in young athletes, these may provide a rationale for developing screening and training protocols for children to lower risk of serious knee injury as they mature. The aim of this study was to examine movement patterns of young athletic children to identify sex-dependent differences and fatigue-induced changes in select biomechanical factors in a population of athletic children during a DJ task. Primary outcomes included sagittal and frontal plane kinematic and kinetic variables of the knee joint, as well as the vertical ground reaction force (vGRF) and its relation to knee joint kinematics during the early landing phase of a DJ task. Trunk kinematics were assessed as a secondary outcome to strengthen interpretation of results. We hypothesized that differences would be found between the sexes in biomechanical outcome measures and that fatigue would result in altered outcomes in both boys and girls.

METHODS

Study Design and Recruitment

The data analyzed for this study are baseline data of a cluster randomized controlled trial. The protocol was approved by the National Bioethics Committee and the Data Protection Authority. Participants were recruited from children aged 10 to 11 years (N = 116; 68 females and 48 males; mean age, 10.4 years) who were registered athletes in team handball or football (soccer) at local athletic clubs. Exclusion criteria were history of torn knee ligaments or muscles of the lower extremities, intra-articular corticosteroid injection within the previous 3 months, neurological impairment, impaired balance, and any orthopaedic problems of the lower limb. If the potential participant met the inclusion criteria, had parental consent, and was interested in taking part in the study, an appointment was made for a testing session at the motion laboratory of the University of Iceland's Research Centre of Movement Science. Before the testing session, all participants and their guardians signed an informed consent form.

Data Collection

After warming up on a stationary bicycle for 5 minutes and performing preparatory self-initiated jumps, participants performed 5 repetitions of a DJ task from a 25-cm-high platform according to standardized instructions asking them to drop from the box, land on both feet, and jump as high as they could. The test is appropriate for evaluating risk factors for noncontact ACL injury.[8] A fatigue protocol was then implemented, after which the subject performed another set of DJ tasks. To fatigue the lower extremity muscle groups, a slide board was used. Bumpers were located on each end of the board with the distance between them set at 1.5 times the participant's leg length. The participants stood on the board, pushed laterally off one bumper and glided to the other side of the slide board, where the same movement was performed to glide back, maintaining a slightly flexed position throughout the protocol. The task ensures multiplanar exertion through both lower limbs. This was repeated for 5 minutes, gradually increasing the effort at the end of each of the first 4 minutes to maximal effort during the last minute, after which the motion analysis protocol was repeated. After the fatigue protocol, participants rated their level of fatigue from 0 (none) to 10 (exhausted) on a numeric rating scale (NRS).[28]

An 8-camera Qualisys Oqus 300 motion capture system (Qualisys AB) was synchronized to 2 force platforms (AMTI) embedded into the laboratory floor. Qualisys track manager (QTM) software simultaneously recorded marker and force plate data, sampling at 200 Hz. A total of 46 retroreflective markers were used to define and track trunk, pelvis, and bilateral thigh, shank, and foot segments. A static measurement was used to define segments and joint centers based on anatomic markers, while clusters of 4 to 5 markers tracked each segment during dynamic trials.

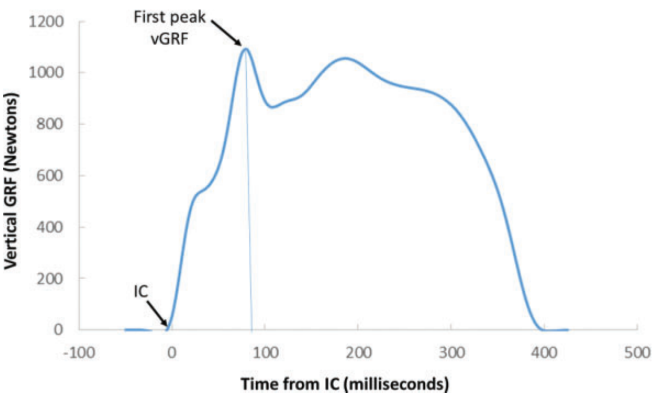

Figure 1. Vertical ground reaction force (vGRF) during early landing phase of drop-jump performance, from initial contact (IC) to the first peak.

Data Processing and Statistical Analysis

Commercial software (Visual3D; C-Motion) was used to process raw data, filtering target and force data at 8 and 20 Hz, respectively. Rigid-body analysis and inverse-dynamics postprocessing were conducted to obtain kinematic and kinetic variables of the lower limbs. Frontal plane trunk motion was calculated with regard to the pelvis, whereas sagittal plane kinematics were calculated with respect to the laboratory's coordinate system to derive trunk position without the influence of pelvic tilt. Initial contact (IC) was determined using force plate data (threshold of 15 N for the vertical vector), and the early landing phase of the DJ task was defined as the time from IC until the first peak vGRF obtained from the respective force plates (Figure 1).

Variables of interest included normalized values for the peak vGRF (% body weight [BW]), knee angles in the frontal and sagittal planes at IC and at peak vGRF (thereby providing the excursion of joint motion during the early landing phase), as well as sagittal and frontal plane external knee joint moments at peak vGRF, normalized to body mass. Each participant's age, height, weight, and body mass index (BMI) were also registered, as well as their perceived fatigue rating, trunk angle at IC and peak vGRF, and the time from IC to peak vGRF.

Mixed-model, full-factorial analysis of variance (ANOVA) was used to analyze each kinematic and kinetic outcome variable. The between-subject explanatory variable used was sex, and the within-subject explanatory variables were right versus left limb, pre- versus postfatigue, and trial repetition (within-subject data). Post hoc testing was conducted where appropriate using Tukey-Kramer adjustments. Standardized effect sizes (ESs) are presented with 95% CIs for effects of interest, where ES is defined as d/SD (d = differences of estimated least square means of the mixed-model ANOVA; $SD = SD_{within}$ for within-subject comparison and $SD = SD_{between}$ for between-subject comparison). The sample size in this study has an 80% statistical power to detect an ES of 0.52 for between-subject comparison and an ES of 0.37 for within-subject comparison. Pearson product-moment correlation coefficients were calculated to evaluate associations between kinematic and force plate variables. Alpha was set at 0.05.

TABLE 1
Participant Characteristics and NRS Fatigue Rating After Fatigue Protocol[a]

	Females (n = 68)	Males (n = 48)	All Participants (N = 116), Range
Age, y	10.4 ± 0.6	10.5 ± 0.5	10-11
Height, cm	147.4 ± 8.3	149.3 ± 7.1	132-171
Weight, kg	40.5 ± 9.5	40.2 ± 6.6	27.8-79.3
BMI, kg/m^2	18.5 ± 3.1	17.9 ± 2.1	13.6-30.2
NRS (0-10)	6.8 ± 1.7	7.3 ± 1.9	1-10

[a]Data are reported as mean ± SD unless otherwise indicated. There were no statistically significant differences in any values between males and females. BMI, body mass index; NRS, numeric rating scale.

RESULTS

No differences were found between boys and girls for mean age, height, weight, BMI, or fatigue rating (Table 1). A total of 109 (94%) participants were identified as right-leg dominant.

Vertical Ground Reaction Force

The first peak vGRF occurred at a mean (±SD) 60.5 ± 25.8 ms after IC, as demonstrated by force plate data. Girls generally demonstrated greater normalized peak vGRF values than boys (1.74 ± 0.50 vs 1.61 ± 0.45 times BW, or by 8.1%; $P = .037$, ES = 0.39 [95% CI, 0.03-0.76]) and overall, fatigue resulted in a slight (2.2%) increase in peak values ($P = .022$, ES = 0.30 [95% CI, 0.04-0.56]). A sex × fatigue interaction, suggesting greater effects of fatigue on girls, was not statistically significant ($P = .06$) (Figure 2). A main effect of limb was also found, as participants demonstrated significantly greater values for the mean first peak vGRF for their right lower limb than their left (1.74 ± 0.49 vs 1.64 ± 0.47 times BW, or by 6.2%; $P < .001$, ES = 0.86 [95% CI, 0.60-1.12]).

Sagittal Plane Joint Motion and Moments

A significant sex × fatigue interaction was seen for knee flexion angle at IC ($P = .014$) and at peak vGRF ($P = .005$). Fatigue led to a slightly greater increase in knee flexion angles at IC for girls than boys, and while fatigue also led to a greater knee flexion angle at peak vGRF for boys, the angle decreased for girls. Thereby, a fatigue-induced reduction in knee flexion excursion during the landing phase was more pronounced for girls than for boys (6.1° vs 1.5°; $P < .001$, ES = 1.75 [95% CI, 1.26-2.23] vs 0.34 [95% CI, –0.14 to 0.83]) (Figure 3). A main effect of sex was found during the early landing phase due to less trunk excursion demonstrated by girls than boys (0.5° ± 7.2° vs 4.5° ± 5.9°;

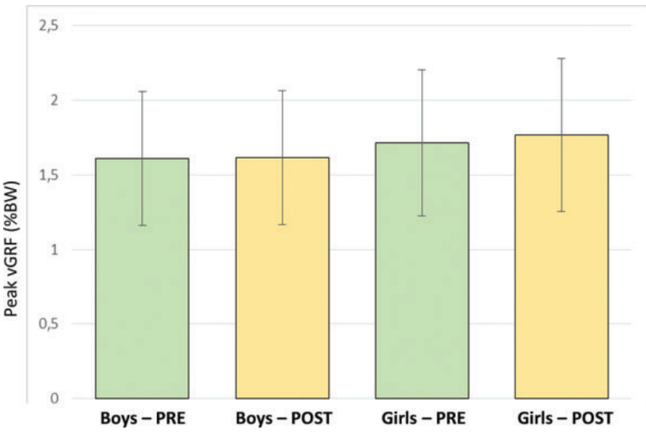

Figure 2. Mean first peak vertical ground reaction force (vGRF) during the early landing phase, normalized to body weight (BW) before (PRE) and after (POST) the fatigue protocol. Error bars indicate SDs. There were statistically significantly greater values for girls compared with boys (main effect, $P < .05$) and for post- versus prefatigue values (main effect, $P < .05$).

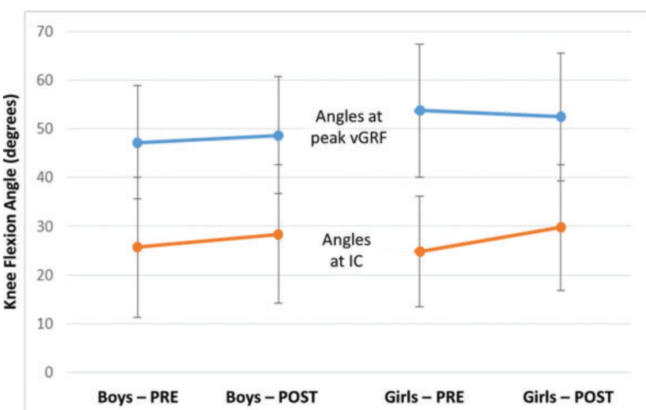

Figure 3. Mean knee joint flexion angles at initial contact (IC) and at the first peak vertical ground reaction force (vGRF) during the early landing phase for boys and girls across both limbs before (PRE) and after (POST) the fatigue protocol. Error bars indicate SDs. There was a statistically significant interaction of sex and fatigue for degree of change in knee flexion excursion ($P < .001$).

$P < .001$, ES = 0.78 [95% CI, 0.42-1.15]). A main effect of fatigue was also found due to greater post- versus prefatigue trunk flexion, by 2.1° ± 2.5° at IC ($P < .001$, ES = 0.87 [95% CI, 0.61-1.13) and by 2.2° ± 2.5° at peak vGRF ($P < .001$, ES = 0.90 [95% CI, 0.64-1.16]). A weak but statistically significant negative correlation was found between the first peak vGRF and knee flexion excursion across all participants, stronger within the group of girls ($r = –0.20$; $P < .001$) compared with the group of boys ($r = -0.08$; $P < .05$), and this difference between the sexes reached statistical significance ($P = .007$). Similarly, a moderate negative correlation was found between the first peak

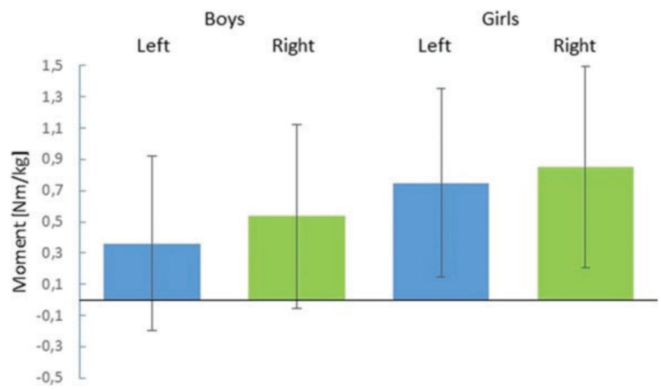

Figure 4. Mean external knee flexion moments at peak vertical ground reaction force during landing. Values are given for the right and left knee across all trials for girls and boys. Error bars indicate SDs. There was a statistically significant interaction of sex and limb due to greater asymmetry of boys ($P < .05$).

vGRF and trunk flexion excursion across all participants ($r = -0.37$; $P < .001$).

Although main effects demonstrated an overall greater knee flexion moment at peak vGRF for girls compared with boys ($P < .001$) and for the right compared with left knee ($P < .001$), a significant sex × limb interaction was seen due to greater interlimb difference in the knee flexion moment demonstrated by boys than girls ($P = .036$) (Figure 4). A main effect of fatigue was demonstrated by a significant reduction of the knee flexion moment after the fatigue protocol (0.69 ± 0.60 vs 0.62 ± 0.66 N·m/kg; $P < .001$, ES = 0.57 [95% CI, 0.31-0.83]).

Frontal Plane Joint Motion and Moments

Overall, there was a main effect of sex with respect to frontal plane knee angles at IC ($P < .001$, ES = 0.63 [95% CI, 0.26-1.00]) as girls demonstrated a slight valgus of 0.5° ± 5.5° but boys a slight varus of 2.0° ± 4.6°. Overall, participants demonstrated a side-to-side difference in that the left knee was in slightly greater varus than the right knee; a difference of 1.2° ± 1.1° ($P < .001$, ES = 1.15 [95% CI, 0.89-1.41]). Fatigue had no effect on frontal plane knee angles at IC and no interactions were observed. However, knee joint excursion (from IC to peak vGRF) was significantly affected by fatigue ($P = .016$, ES = 0.32 [95% CI, 0.06-0.58]) across both limbs. Before fatigue, participants generally demonstrated an excursion toward varus (mean ± SD, 0.2° ± 4.2°), but after the fatigue protocol, this shifted toward valgus excursion (0.2° ± 4.1°). On average, the frontal plane trunk angle was 0.1° ± 4.3° toward the left at IC and 0.1° ± 4.3° toward the right at the first peak vGRF. No main effects or interactions were found, and no correlations were found between the first peak vGRF and frontal plane trunk angles for the left ($r = 0.01$; $P = .846$) or right side ($r = -0.06$; $P = .056$).

A sex × limb interaction ($P < .001$) was found for frontal plane knee moments at the first peak vGRF, as

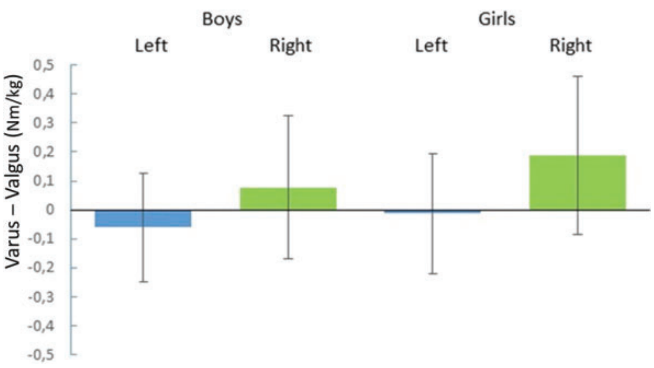

Figure 5. Mean external frontal plane moments at peak vertical ground reaction force during landing. Values are given for the right and left knee across all trials for girls and boys. Error bars indicate SDs. There was a statistically significant interaction of sex and limb due to greater asymmetry of girls ($P < .001$).

demonstrated by the much greater interlimb difference found for girls than boys (Figure 5).

DISCUSSION

The aim of the study was to identify sex-dependent differences in biomechanical parameters during the early landing phase of a DJ performed by athletic children and assess the effect of fatigue on those outcomes. The main results of the study demonstrated dissimilar interlimb loading patterns between boys and girls. While both sexes applied greater forces through the right limb, boys showed significantly greater right than left loading in the sagittal plane but girls in the frontal plane, as demonstrated by knee joint moments. The fatigue intervention affected girls more than boys during this early phase of landing, with diminished knee flexion excursion and a tendency for increased peak vGRF. Greater knee and trunk flexion excursion were associated with lower vGRF values, reflecting the important role of sagittal plane motion in dissipating forces during this dynamic task. Importantly, the duration of the defined early landing phase (from IC to the first peak vGRF) was compatible with estimated timing of noncontact ACL injury.[16,18,20] Overall, self-reported scores indicated that participants experienced moderate fatigue after the protocol.

Vertical Ground Reaction Force

Ineffective shock absorption and biomechanical alterations caused by fatigue has been suggested to increase the risk of ACL injury.[34] Overall, girls demonstrated higher values for the first peak vGRF than boys (by 8.1%), which is in accordance with the results of Kernozek et al[15] for peak vGRF during single-limb landing in an older cohort. The main effect of limb seen for the vGRF may represent an overall right limb preference during landing and/or frontal plane trunk control, both considered risk factors for ACL injury.[11] Fatigue led to a significantly greater first peak vGRF and a trend toward greater effects on girls than boys (Figure 2), which is an important consideration within the context of ACL injury risk and incidence. Studies involving mature males and females have shown conflicting results; there was no effect of fatigue during single-limb landing,[15] or either increased[2] or decreased[39] peak vGRF for the complete stance phase of a DJ. In addition to age and maturation, the discrepancy may be due to a different focus with respect to timing or different methods used to induce fatigue. Notably, James et al[14] showed that fatigue may lead to a significant increase in the first peak vGRF while lowering the second peak.

Sagittal Plane Joint Motion and Moments

The degree of knee flexion at IC seen overall for boys and girls was generally greater than reported for adults.[25,42] The results of the present study support previous reports associating greater knee flexion excursion with lower peak vGRF,[38] in particular for females, which is in tune with the notion that sagittal plane motion and strength of extensor muscles are important for absorbing forces through the lower limb.[7] Girls demonstrated a marked decrease in knee flexion excursion after the fatigue intervention (Figure 3), which may indicate a less efficient postfatigue shock absorption strategy, in particular when considering the limited trunk flexion excursion used by girls compared with boys. Smith et al[39] showed the same sex × fatigue interaction for knee flexion excursion. No main effect of sex was seen for knee flexion angle at IC, which is in contrast to a recent study involving adolescents[13] but in line with another on prepubertal and pubertal children[7] and adults.[22]

One might have expected the greater postfatigue peak vGRF to result in overall greater external knee flexion moments, but quite the opposite was seen. A likely explanation is the slight increase in trunk flexion demonstrated, possibly in response to quadriceps fatigue, which would move their center of mass forward and result in a shift of moments from the knee to the hips.[4,21] Such a response to fatigue has been reported previously.[15] The sex × limb interaction demonstrated a greater difference between right versus left knee flexion moment for boys than girls (Figure 4). Knee flexion angles were quite symmetrical during landing and therefore the greater knee flexion moments that boys demonstrated on the right versus left side result from interlimb differences in forces traveling up the chain. Frontal plane positioning of the trunk might influence the degree of relative weightbearing, but such a strategy was not indicated by the kinematic trunk data.

Frontal Plane Joint Motion and Moments

The knee has limited motion in a purely frontal plane and excursions would be expected to be small during the early landing phase that is the focus of this study. Furthermore, when the degree of variability is relatively large, as seen for this cohort, the resulting mean values are small and confidence intervals large. Nonetheless, a slight difference was seen between boys and girls with respect to varus versus valgus frontal plane angles at IC. This may reflect structural differences that are recognized for adults during DJ performance,[8] but may be present even in the prepubertal and pubertal years.[7] Degree of excursion during the early landing phase was generally similar for boys and girls, and the prefatigue varus excursion is generally in agreement with results of Holden et al[13] for adolescents, although they found that varus excursion was greater for males. The clinical significance of the small differences seen in the present study may be called into question, but the results indicated that fatigue generally resulted in a greater inclination to move toward knee valgus, which is generally associated with ACL injury risk.[9]

In the absence of valgus collapse, the resultant GRF vectors will be oriented medially, toward the center of mass, and frontal plane knee moments during DJ performance might therefore be expected to be varus, bilaterally. The difference in right versus left frontal plane moments of girls was particularly striking, and similar results have not previously been reported to our knowledge. The large valgus moment seen on the right may not only reflect their tendency to place more loading onto the right limb, as reflected by the vGRF, but also other factors influencing landing during weight acceptance, such as timing of events for each limb and rate trunk motion.

Strengths and Limitations

The study results must be viewed and interpreted in light of the fact that participants' movement patterns varied considerably, as is to be expected as during this period children develop at different rates, both with respect to physical structure and athletic ability. However, the large numbers in each group and number of repeated trials give ample statistical power, and therefore, differences between the sexes and effects of fatigue do emerge. Participants were children, which may affect the consistency of their performance, as they are still developing motor control and athletic skills. The cohort may be considered representative for physically active children of this age group, although we did not collect information regarding years of sports participation. Pubertal stage was not determined, and some children may therefore have been commencing puberty. Participants were verbally encouraged during the fatigue protocol, and the mean NRS indeed indicates that participants were generally closer to exhaustion than no fatigue at all. Their youth may have affected their willingness to exert themselves and the reliability of self-reported fatigue ratings, as demonstrated by the range of scores after the progressive fatigue protocol, but ratings of perceived exertion are considered a good indicator for the training load this age group experiences.[31] Furthermore, although the focus on the first peak vGRF during the early landing phase of the DJ task is important from an injury perspective, it is unusual and therefore there were few publications to contrast the results with. Most have assessed the peak values that occur later during the stance phase, which may not be strongly associated with those that occur during the first 100 ms. Although interlimb comparison involved right versus left rather than dominant versus nondominant limb, the right leg has been shown to be the dominant one in over 93% of cases,[41] which is consistent with the 94% seen in our cohort. Further studies are needed to assess the effects of specific training to reduce limb asymmetry of factors associated with ACL injury during the early landing phase and whether greater symmetry results in lower incidence of ACL rupture.

In conclusion, landing strategies differed between young male and female athletes, as reflected by the magnitude of interlimb loading observed in the frontal (girls) and sagittal (boys) planes. Notably, fatigue led to greater trunk and knee flexion at IC and lower knee flexion moments at peak vGRF, which may be considered positive from an injury risk perspective. However, the effect of fatigue on girls may give cause for some concern, in light of the increase in vGRF, decreased knee flexion excursion, minimal trunk excursion, and a landing strategy characterized by limb asymmetry in the frontal plane. The differences identified indicate that specific sports training to reduce risk of serious knee injury may have a role at an earlier age than current practice suggests, in particular for females. Sports training of children should encourage symmetrical loading during jumping maneuvers, and injury prevention training may also be introduced to athletes in a fatigued state.

REFERENCES

1. Amin S, Guermazi A, Lavalley MP, et al. Complete anterior cruciate ligament tear and the risk for cartilage loss and progression of symptoms in men and women with knee osteoarthritis. *Osteoarthritis Cartilage*. 2008;16:897-902.
2. Bell DR, Pennuto AP, Trigsted SM. The effect of exertion and sex on vertical ground reaction force variables and landing mechanics. *J Strength Cond Res*. 2016;30:1661-1669.
3. Beynnon BD, Vacek PM, Newell MK, et al. The effects of level of competition, sport, and sex on the incidence of first-time noncontact anterior cruciate ligament injury. *Am J Sports Med*. 2014;42:1806-1812.
4. Blackburn JT, Padua DA. Sagittal-plane trunk position, landing forces, and quadriceps electromyographic activity. *J Athl Train*. 2009;44:174-179.
5. Borotikar BS, Newcomer R, Koppes R, McLean SG. Combined effects of fatigue and decision making on female lower limb landing postures: central and peripheral contributions to ACL injury risk. *Clin Biomech (Bristol, Avon)*. 2008;23:81-92.
6. Dai B, Mao D, Garrett WE, Yu B. Anterior cruciate ligament injuries in soccer: loading mechanisms, risk factors, and prevention programs. *J Sport Health Sci*. 2014;3:299-306.
7. DiStefano LJ, Martinez JC, Crowley E, et al. Maturation and sex differences in neuromuscular characteristics of youth athletes. *J Strength Cond Res*. 2015;29:2465-2473.
8. Earl JE, Monteiro SK, Snyder KR. Differences in lower extremity kinematics between a bilateral drop-vertical jump and a single-leg step-down. *J Orthop Sports Phys Ther*. 2007;37:245-252.
9. Ford KR, Shapiro R, Myer GD, Van Den Bogert AJ, Hewett TE. Longitudinal sex differences during landing in knee abduction in young athletes. *Med Sci Sports Exerc*. 2010;42:1923-1931.
10. Hamstra-Wright KL, Swanik CB, Sitler MR, et al. Gender comparisons of dynamic restraint and motor skill in children. *Clin J Sport Med*. 2006;16:56-62.
11. Hewett TE, Di Stasi SL, Myer GD. Current concepts for injury prevention in athletes after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2013;41:216-224.

12. Holden S, Boreham C, Delahunt E. Sex differences in landing biomechanics and postural stability during adolescence: a systematic review with meta-analyses. *Sports Med*. 2016;46:241-253.
13. Holden S, Boreham C, Doherty C, Wang D, Delahunt E. Clinical assessment of countermovement jump landing kinematics in early adolescence: sex differences and normative values. *Clin Biomech (Bristol, Avon)*. 2015;30:469-474.
14. James CR, Scheuermann BW, Smith MP. Effects of two neuromuscular fatigue protocols on landing performance. *J Electromyogr Kinesiol*. 2010;20:667-675.
15. Kernozek TW, Torry MR, Iwasaki M. Gender differences in lower extremity landing mechanics caused by neuromuscular fatigue. *Am J Sports Med*. 2008;36:554-565.
16. Kiapour AM, Quatman CE, Goel VK, Wordeman SC, Hewett TE, Demetropoulos CK. Timing sequence of multi-planar knee kinematics revealed by physiologic cadaveric simulation of landing: implications for ACL injury mechanism. *Clin Biomech (Bristol, Avon)*. 2014;29: 75-82.
17. Kluczynski MA, Marzo JM, Rauh MA, Bernas GA, Bisson LJ. Sex-specific predictors of intra-articular injuries observed during anterior cruciate ligament reconstruction. *Orthop J Sports Med*. 2015;3: 2325967115571300.
18. Koga H, Nakamae A, Shima Y, et al. Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. *Am J Sports Med*. 2010;38:2218-2225.
19. Kraus T, Svehlik M, Singer G, Schalamon J, Zwick E, Linhart W. The epidemiology of knee injuries in children and adolescents. *Arch Orthop Trauma Surg*. 2012;132:773-779.
20. Krosshaug T, Nakamae A, Boden BP, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med*. 2007;35:359-367.
21. Kulas A, Zalewski P, Hortobagyi T, DeVita P. Effects of added trunk load and corresponding trunk position adaptations on lower extremity biomechanics during drop-landings. *J Biomech*. 2008;41:180-185.
22. Liederbach M, Kremenic IJ, Orishimo KF, Pappas E, Hagins M. Comparison of landing biomechanics between male and female dancers and athletes, part 2: influence of fatigue and implications for anterior cruciate ligament injury. *Am J Sports Med*. 2014;42:1089-1095.
23. Lohmander LS, Ostenberg A, Englund M, Roos H. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis Rheum*. 2004;50:3145-3152.
24. McKay H, Tsang G, Heinonen A, MacKelvie K, Sanderson D, Khan KM. Ground reaction forces associated with an effective elementary school based jumping intervention. *Br J Sports Med*. 2005;39:10-14.
25. McLean SG, Fellin RE, Suedekum N, Calabrese G, Passerallo A, Joy S. Impact of fatigue on gender-based high-risk landing strategies. *Med Sci Sports Exerc*. 2007;39:502-514.
26. Myer GD, Ford KR, Di Stasi SL, Foss KD, Micheli LJ, Hewett TE. High knee abduction moments are common risk factors for patellofemoral pain (PFP) and anterior cruciate ligament (ACL) injury in girls: is PFP itself a predictor for subsequent ACL injury? *Br J Sports Med*. 2015; 49:118-122.
27. Myer GD, Ford KR, Khoury J, Succop P, Hewett TE. Development and validation of a clinic-based prediction tool to identify female athletes at high risk for anterior cruciate ligament injury. *Am J Sports Med*. 2010;38:2025-2033.
28. Ornetti P, Dougados M, Paternotte S, Logeart I, Gossec L. Validation of a numerical rating scale to assess functional impairment in hip and knee osteoarthritis: comparison with the WOMAC function scale. *Ann Rheum Dis*. 2011;70:740-746.
29. Price R, Hawkins R, Hulse M, Hodson A. The Football Association medical research programme: an audit of injuries in academy youth football. *Br J Sports Med*. 2004;38:466-471.
30. Quatman-Yates CC, Myer GD, Ford KR, Hewett TE. A longitudinal evaluation of maturational effects on lower extremity strength in female adolescent athletes. *Pediatr Phys Ther*. 2013;25:271-276.
31. Rodriguez-Marroyo JA, Antonan C. Validity of the session rating of perceived exertion for monitoring exercise demands in youth soccer players. *Int J Sports Physiol Perform*. 2015;10:404-407.
32. Rossler R, Junge A, Chomiak J, Dvorak J, Faude O. Soccer injuries in players aged 7 to 12 years: a descriptive epidemiological study over 2 seasons. *Am J Sports Med*. 2016;44:309-317.
33. Schmitt LC, Paterno MV, Ford KR, Myer GD, Hewett TE. Strength asymmetry and landing mechanics at return to sport after anterior cruciate ligament reconstruction. *Med Sci Sports Exerc*. 2015;47: 1426-1434.
34. Schmitz RJ, Kim H, Shultz SJ. Neuromuscular fatigue and tibiofemoral joint biomechanics when transitioning from non-weight bearing to weight bearing. *J Athl Train*. 2015;50:23-29.
35. Shultz SJ, Schmitz RJ, Cone JR, et al. Changes in fatigue, multiplanar knee laxity, and landing biomechanics during intermittent exercise. *J Athl Train*. 2015;50:486-497.
36. Sigward SM, Pollard CD, Havens KL, Powers CM. Influence of sex and maturation on knee mechanics during side-step cutting. *Med Sci Sports Exerc*. 2012;44:1497-1503.
37. Sigward SM, Pollard CD, Powers CM. The influence of sex and maturation on landing biomechanics: implications for anterior cruciate ligament injury. *Scand J Med Sci Sports*. 2012;22:502-509.
38. Slater A, Campbell A, Smith A, Straker L. Greater lower limb flexion in gymnastic landings is associated with reduced landing force: a repeated measures study. *Sports Biomech*. 2015;14:45-56.
39. Smith MP, Sizer PS, James CR. Effects of fatigue on frontal plane knee motion, muscle activity, and ground reaction forces in men and women during landing. *J Sports Sci Med*. 2009;8:419-427.
40. Stracciolini A, Stein CJ, Zurakowski D, Meehan WP 3rd, Myer GD, Micheli LJ. Anterior cruciate ligament injuries in pediatric athletes presenting to sports medicine clinic: a comparison of males and females through growth and development. *Sports Health*. 2015;7: 130-136.
41. Strandberg S, Lindström M, Wretling ML, Aspelin P, Shalabi A. Muscle morphometric effect of anterior cruciate ligament injury measured by computed tomography: aspects on using non-injured leg as control. *BMC Musculoskelet Disord*. 2013;14:150.
42. Thomas AC, Palmieri-Smith RM, McLean SG. Isolated hip and ankle fatigue are unlikely risk factors for anterior cruciate ligament injury. *Scand J Med Sci Sports*. 2011;21:359-368.
43. Weinhold PS, Stewart JD, Liu HY, Lin CF, Garrett WE, Yu B. The influence of gender-specific loading patterns of the stop-jump task on anterior cruciate ligament strain. *Injury*. 2007;38:973-978.
44. Wild CY, Steele JR, Munro BJ. Why do girls sustain more anterior cruciate ligament injuries than boys? A review of the changes in estrogen and musculoskeletal structure and function during puberty. *Sports Med*. 2012;42:733-749.
45. Yu B, McClure SB, Onate JA, Guskiewicz KM, Kirkendall DT, Garrett WE. Age and gender effects on lower extremity kinematics of youth soccer players in a stop-jump task. *Am J Sports Med*. 2005;33: 1356-1364.