2005

Effects of developmental stage and sex on lower extremity kinematics and vertical ground reaction forces during landing

Erik E. Swartz
University of New Hampshire - Main Campus

Laura C. Decoster
New Hampshire Musculoskeletal Institute

Pamela J. Russell
Bridgewater State College, prussell@bridgew.edu

Ronald V. Croce
University of New Hampshire - Main Campus

Journal of Athletic Training 2005;40(1):9–14

www.journalofathletictraining.org

original research

Effects of Developmental Stage and Sex on Lower Extremity Kinematics and Vertical Ground Reaction Forces During Landing

Erik E. Swartz*; Laura C. Decoster†; Pamela J. Russell‡; Ronald V. Croce*

*University of New Hampshire, Durham, NH; †New Hampshire Musculoskeletal Institute, Manchester, NH; ‡Bridgewater State College, Bridgewater, MA

Erik E. Swartz, PhD, ATC, contributed to the conception and design; acquisition and analysis and interpretation of the data; and drafting and final approval of the article. Laura C. Decoster, ATC, contributed to conception and design; acquisition and analysis and interpretation of the data; and drafting, critical revision, and final approval of the article. Pamela J. Russell, PhD, and Ronald V. Croce, PhD, contributed to conception and design; acquisition of the data; and critical revision and final approval of the article.

Address correspondence to Erik E. Swartz, PhD, ATC, 124 Main Street/NH Hall, Department of Kinesiology, University of New Hampshire, Durham, NH 03824. Address e-mail to eswartz@cisunix.unh.edu.

Context: The presence or absence of biomechanical differences between the sexes before puberty may provide clues about the onset of adult landing pattern differences, which may help to explain the greater number of anterior cruciate ligament injuries in females than in males and provide the basis for interventions to reduce those injuries.

Objective: To identify developmental sex-related and biomechanical differences during vertical jump landings.

Design: A 2 × 2 developmental stage (prepubescent or postpubescent) × sex (male or female) between-subjects design.

Setting: Controlled laboratory setting.

Patients or Other Participants: Thirty prepubescent subjects (15 boys, age = 9.63 ± 0.95 years; 15 girls, age = 9.19 ± 1.00 years) and 28 postpubescent subjects (14 men, age = 23.57 ± 3.23 years; 14 women, age = 24.22 ± 2.27 years).

Intervention: Subjects performed a vertical jump to a target set at 50% of their maximum vertical jump height ability.

Main Outcome Measure(s): Hip and knee kinematics of the dominant lower extremity and vertical ground reaction forces during impact were analyzed.

Results: We found significant main effects for developmental stage. Children demonstrated greater knee valgus and less hip flexion at initial contact and at maximum vertical force, less knee flexion at maximum vertical force, greater maximum vertical force and impulse, and a shorter time to maximum vertical force than the adults. No sex differences were found among the biomechanical variables measured.

Conclusions: The presence of significant biomechanical differences between children and adults suggests that physical development influences landing patterns. Sex does not appear to influence landing patterns during a 50% maximum vertical jump landing. These findings add to the body of knowledge regarding developmental and sex comparisons in a functional landing task.

Key Words: anterior cruciate ligament injury, noncontact knee injury, functional movement

Strong epidemiologic evidence supports the shared belief among athletic trainers, sports medicine physicians, and investigators that women suffer more anterior cruciate ligament (ACL) injuries than men.[1–3] Some researchers have attempted to associate these disparate injury rates with intrinsic factors such as physiologic, hormonal, or structural differences between adult men and women.[4,5] Interest in biomechanics research[6–16] has increased because a large percentage of ACL injuries occur during noncontact movements such as cutting and landing.[17–20] Observation of filmed ACL injuries suggests that the knee is often in an extended and valgus position with the tibia externally rotated close to the time of ACL failure,[21] and investigators have demonstrated that the ACL experiences higher strain when external loads are applied to the knee in this position.[22,23] Although some experts have suggested that this landing position (extension, valgus, external rotation) may be more common in women,[7,13,14,24] other studies have not supported this suggestion.[25–27]

An extensive literature search yielded a small body of literature regarding the landing characteristics of children.[28–30] An investigation[31] of 143 children landing from a vertical jump did not support grade-level or sex differences in knee angle at landing. An earlier study of 24 children aged 8–12 years showed that the oldest children landed from drop jumps with less vertical impact force.[32] A recent investigation compared prepubescent and postpubescent girls landing from 3 types of stride jumps.[33] This study was, perhaps, the first attempt to explain reported differences between females in landing techniques from a developmental perspective (prepubescent versus postpubescent).[33] However, to our knowledge, no researchers have reported comparing landing characteristics in males with those of females from a developmental perspective.

Table 1. Subject Characteristics (Mean ± SD)

Group	Age (years)	Height (cm)	Mass (kg)	Vertical Jump (cm)
Children				
n = 30	9.41 ± 0.99	136.63 ± 9.51	33.85 ± 7.90	29.85 ± 5.58
Girls				
n = 15	9.19 ± 1.00	136.67 ± 6.15	32.91 ± 8.10	27.94 ± 4.97
Boys				
n = 15	9.63 ± 0.95	136.60 ± 12.23	34.79 ± 7.86	31.75 ± 5.66
Adults				
n = 28	23.90 ± 2.76	170.91 ± 9.49	72.83 ± 14.75	48.85 ± 10.85
Women				
n = 14	24.22 ± 2.27	163.54 ± 6.22	62.37 ± 9.11	41.91 ± 4.62
Men				
n = 14	23.57 ± 3.23	178.29 ± 5.59	83.29 ± 11.53	55.79 ± 10.93

The presence or absence of biomechanical differences between the sexes before puberty may provide clues about the onset of adult landing pattern differences, should they in fact exist. Therefore, the purpose of our study was to identify developmental and sex differences in knee and hip kinematics and vertical ground reaction forces during vertical jump landings.

METHODS

Subjects

Fifty-eight subjects with no history of back or lower extremity injuries were divided into developmental stage and sex groupings (Table 1). Subjects were required to be within the set age range for either prepubescence or postpubescence. These groupings were based on guidelines established by Tanner,[34] in which the onset of puberty is correlated with the growth spurt (ie, the highest velocity gain in height or stature). The average age of onset for the growth spurt is 10.5 years for girls and 12.5 years for boys.[34] Prepubertal (children) subject groupings were set as age ranges before the onset of the growth spurt (ie, 7–10 years old for girls and 8–11 years old for boys). Prepubertal female subjects were screened for menarche, resulting in the exclusion of 1 subject. The children were similar in height, weight, and maximum vertical jump height. Puberty is complete by the age of approximately 17 years for girls and 20 years for boys.[34] Subjects in the postpubertal groups (adults) were 19–29 years old (men, n = 14; women, n =14).

All children invited to participate were current or recent past participants within a youth sports program that included jumping and landing activities (ie, basketball, volleyball, gymnastics). Adult subjects were recreationally active (at least 30 minutes of activity 3 times per week) and were excluded if they had participated in National Collegiate Athletic Association Division I jumping sports. Other criteria for exclusion included failure to fit into the prepubertal or postpubertal category and the inability to demonstrate a mature vertical jump.[35,36] This pattern includes a preparatory crouch with 60° to 90° of knee flexion[35] and a countermovement arm swing coordinated with complete extension at the hips, knees, and ankles at takeoff.[36]

Instrumentation

Three-dimensional position-time data were collected at 120 Hz using a 6-camera, 3-dimensional kinematic motion capture system (Motion Analysis, Inc, Santa Rosa, CA). Before each data-collection session, a 3-m by 7-m volume was calibrated using both cube and wand calibration techniques. The Motion Analysis system has been determined to have marker accuracy within 0.5 mm after cube and wand calibration.[37] Data collection was initiated before the vertical jump and terminated after the subject completed the landing (approximately 3–5 seconds). For each subject, the landing phase was operationally defined as beginning at initial ground contact and ending with maximum knee flexion. Ground reaction force data were collected using a force platform (model OR6-7-2000; Advanced Mechanical Technologies Inc, Watertown, MA) set at a sampling rate of 960 Hz interfaced with a 6-channel signal amplifier with a gain amplification of 2000 (model MSA-6; Advanced Mechanical Technologies). Analog force data were converted (model DT3002-16 bit; Data Translation Inc, Marlboro, MA) to digital data at the Motion Analysis personal computer interface. Raw data collection for video and ground reaction force data was simultaneously controlled through an external trigger and stored by the Motion Analysis and EVa software (version 6.01; Motion Analysis, Inc).

Procedures

Upon reporting to the biomechanics laboratory for a 2-hour data-collection session, adult subjects and parents of each child were required to sign a consent form approved by the institutional review board of the university. Subjects wore form-fitting shorts, a tank top, socks, and unused standardized footwear in appropriate sizes (New Balance Athletic Shoe Company, Lawrence, MA). Each subject's name, age, sex, height, weight, reach height, and sport history were recorded. Dominant leg was determined by asking the subject to jump up and land on 1 leg.[38] After visual confirmation from 2 of the investigators of a mature jumping pattern, maximum jump height was assessed (VERTEC; Sports Imports, Inc, Columbus, OH) with the subject using a double-leg takeoff with no approach steps. The target was set at the maximum height achieved in 3 trials. Subjects practiced the jumping and landing task until they felt comfortable with the movement. During this practice time, a self-selected takeoff position was determined and marked on the floor to standardize the takeoff position for each trial.

Retro-reflective markers (2.5-cm diameter) were then applied to the subject, creating a segment-linked model for 3-dimensional movement capture and subsequent analysis of joint kinematics. Markers were placed on the dominant leg and pelvic girdle at the following locations: right and left anterior-superior iliac spines, L5/S1, greater trochanter, anterior thigh, lateral femoral condyle, tibial tuberosity, middle tibia, and distal tibia. After the dynamic trials, an additional marker was placed on the patella for collection of a static trial, which was used for knee joint–center calculations.

After application of the markers, subjects were instructed to jump for a suspended target (inflatable ball, 64 cm in diameter) adjusted to 50% of their maximum vertical jump. Subjects started from the individual predetermined starting marker for all trials. This starting position allowed subjects to successfully jump for the target fixed to a retractable cord and bring it down with them as they landed on both feet, similar to a basketball rebound. The target was positioned directly in front of each subject's midline. Successful trials required that the subject reach the target, land balanced on both feet facing forward, with only the dominant foot on the force plate. Subjects were required to complete 4 successful trials. Each subject's static trial was recorded at the end of the session.

Data Reduction

Three-dimensional data were tracked and smoothed using a recursive, fourth-order, low-pass Butterworth filter (10 Hz). Digitized *x*, *y*, and *z* coordinates for the dynamic and static trials were then imported to the Motion Analysis Kintrak 6.02 software program. Joint centers were calculated for the static trial for each subject using an embedded right-hand Cartesian segment coordinate system. Joint kinematics were created using standard Euler angle calculations, whereby the flexion-extension motion of the lower extremity segment was identified as the first rotation occurring about the medial-lateral axis, with the second motion occurring in the frontal plane (valgus-varus) about the anterior-posterior axis. Variables and events of interest were calculated for each of the subjects' 4 trials for all groups. Group data were exported into spreadsheet form, and mean values for each subject's trials were prepared for statistical analysis.

Hip and knee flexion and knee valgus angles were analyzed at 2 points during landing: at initial contact and at the point of peak vertical ground reaction force (VGRF). Data from initial contact (IC) with the ground reflected the subject's preparation for landing. Hip and knee position at the time of peak VGRF represented how the body accommodated the vertical forces of the impact. Ground reaction force variables of interest were peak VGRF and the impulse (area beneath the force curve) from IC to peak VGRF as an expression of the subject's ability to absorb the forces over time.

Vertical Jump Versus Drop Landing

A drop landing from a standard height allows for the control of confounding factors introduced by varied takeoff strategies and differences in jump heights. However, we opted for a vertical jump not only for its functional applicability, but because it is inherently difficult to choose an appropriate standard height that accounts for individual jumping and landing abilities.

The decision to allow subjects to perform a jump based on their individual jumping ability created the challenge of how to appropriately compare ground reaction forces among subjects. Each subject performed a jump at 50% of his or her maximum vertical jump to provide a consistent jumping effort across subjects. However, because subjects landed from different heights, each jump yielded varied impact velocities. A single rigid body would predictably increase its impact force as its velocity at the moment of impact increased. However, because the human body is modeled as a series of rigid linked segments, velocity at impact—or jump height—does not account for all variations in force developed, as Dufek and Bates,[10,39] Caster and Bates,[6] and Hewett et al[26] have noted. Many researchers have addressed directly or indirectly the issue of touchdown velocity and its effect on impact forces.[6,8,9,26,31,40,41] Although reporting ground reaction forces in absolute Newtonian values or normalized by body weight is valuable in certain circumstances, such values do not take into consideration the touchdown velocity and are inappropriate here. Therefore, peak VGRF and impulse data were normalized to the subject's kinetic energy (KE) expressed as Newton/joules (N/J) for peak VGRF or as N/J · seconds for impulse:

$$\frac{N}{J} = \frac{VGRF}{\frac{1}{2}mv^2}$$

where N equals Newtons of vertical force, m equals subject mass in kilograms, and v equals instantaneous velocity for the center of mass 1 frame before IC in m/s (obtained through Kintrak software). The KE normalization procedure simultaneously considers body mass and different jump heights attained in each trial. Normalizing by KE presented a way to compare subjects with varied masses landing from different heights. This approach is similar to that used recently by James et al.[41]

Statistical Analysis

A power analysis was performed a priori to determine appropriate sample sizes. Effect sizes were calculated from selected literature with methods closest to the proposed methods of this project.[7,38,42] Effect sizes in the literature for related variables of video kinematics and ground reaction forces were calculated to be in the range of 0.02 to 1.4. Estimated sample sizes were calculated based on moderate to large effect statistics (according to the method described by Cohen[43]) with an alpha level of 0.05 and power of 0.8. For a large effect, the sample size for the proposed project was determined to be between 8 and 12. To assure adequate power, we used a higher sample size of 14 or 15 subjects for each group.

The independent variables established for the study were developmental stage (2 levels: children or adults) and sex (2 levels: male or female). A 2 × 2 (developmental stage × sex) multivariate analysis of variance (ANOVA) was used to analyze the following 6 dependent variables: knee flexion, hip flexion, and knee valgus at IC and at VGRF. A second 2 × 2 (developmental stage × sex) multiple ANOVA was used to identify differences in the following 3 normalized ground reaction force variables: peak VGRF, time to peak VGRF, and the impulse for VGRF from IC through peak VGRF.

In the event of significant interactions, appropriate follow-up tests were performed using ANOVA with Scheffé post hoc analysis to determine significant differences among cell means. All statistical analyses were tested with a 95% confidence level ($P = .05$) using SPSS for Windows (version 11.0; SPSS Inc, Chicago, IL).

Table 2. Knee and Hip Joint Kinematics (°) (Mean ± SD)

Group	Knee Flexion at Initial Contact	Knee Flexion at Maximal Vertical Ground Reaction Forces	Knee Valgus at Initial Contact	Knee Valgus at Maximal Vertical Ground Reaction Forces	Hip Flexion at Initial Contact	Hip Flexion at Maximal Vertical Ground Reaction Forces
Children						
n = 30	10.47 ± 6.39	29.60 ± 8.51*	12.02 ± 4.77†	10.23 ± 5.30†	6.81 ± 5.65*	11.56 ± 5.69*
Girls						
n = 15	10.7 ± 7.18	31.50 ± 6.17	11.67 ± 4.38	9.63 ± 4.73	7.12 ± 5.22	12.40 ± 5.18
Boys						
n = 15	10.25 ± 5.73	27.69 ± 10.20	12.37 ± 5.25	10.82 ± 5.92	6.51 ± 6.22	10.72 ± 6.21
Adults						
n = 28	12.65 ± 5.70	38.73 ± 16.13	8.14 ± 3.91	5.64 ± 5.91	12.60 ± 5.02	20.67 ± 9.32
Women						
n = 14	11.56 ± 6.24	38.00 ± 9.52	9.75 ± 2.7	7.68 ± 4.00	14.09 ± 5.12	21.49 ± 7.01
Men						
n = 14	13.75 ± 5.11	39.45 ± 21.17	6.54 ± 4.35	3.60 ± 6.89	11.11 ± 9.61	19.83 ± 11.39

*Significant main effects for developmental stage ($P < .05$), children less than adults.
†Significant main effects for developmental stage ($P < .05$), children more than adults.

RESULTS

The multiple ANOVA for hip and knee kinematics revealed no significant developmental stage-by-sex interactions (Wilks $\Lambda = .886$, $F_{6,49} = 1.048$, $P = .406$) or sex main effects (Wilks $\Lambda = .889$, $F_{6,49} = 1.016$ $P = .426$). However, significant main effects for developmental stage (Wilks $\Lambda = .644$, $F_{6,49} = 4.514$, $P = .001$) were detected, with follow-up testing showing significant differences in hip flexion ($F_{1,54} = 16.951$, $P = 0.001$) and knee valgus at IC ($F_{1,54} = 11.794$, $P = 0.001$) and knee flexion ($F_{1,54} = 7.247$, $P = 0.009$), knee valgus ($F_{1,54} = 10.064$, $P = 0.002$), and hip flexion ($F_{1,54} = 19.975$, $P = 0.001$) at peak VGRF. Inspection of the mean data revealed that except for knee flexion at IC, the children displayed statistically smaller amounts of knee and hip flexion during landing. Children also had greater knee valgus at IC and peak VGRF (Table 2).

The multiple ANOVA for normalized ground reaction forces revealed no significant developmental stage-by-sex interactions (Wilks $\Lambda = .975$, $F_{3,52} = 0.444$, $P = .723$) or sex main effects (Wilks $\Lambda = .935$, $F_{3,52} = 1.201$, $P = .319$). Main effects for developmental stage (Wilks $\Lambda = .555$, $F_{3,52} = 13.883$, $P = .001$) were detected for ground reaction force variables, with follow-up analysis revealing significant differences in time to peak VGRF ($F_{1,54} = 4.121$, $P = 0.047$), peak VGRF ($F_{1,54} = 34.623$, $P = 0.001$), and vertical impulse ($F_{1,54} = 5.652$, $P = .021$). Inspection of means revealed the children experienced greater vertical force and impulse than the adults but the adults had a longer time to peak VGRF (Table 3). Because we found no significant interactions in the kinematic or ground reaction force analyses, follow-up analyses of variance and post hoc tests were not performed.

Table 3. Ground Reaction Force Variables (Mean ± SD)

Group	Peak Vertical Ground Reaction Forces (N/J)	Time to Peak Vertical Ground Reaction Forces (s)	Impulse (N/J·s)
Children			
n = 30	8.23 ± 2.58*	0.04 ± 0.01†	0.15 ± 0.06*
Girls			
n = 15	8.21 ± 2.30	0.04 ± 0.01	0.15 ± 0.04
Boys			
n = 15	8.24 ± 2.90	0.04 ± 0.02	0.14 ± 0.07
Adults			
n = 28	4.93 ± 1.44	0.06 ± 0.04	0.11 ± 0.06
Women			
n = 14	5.28 ± 1.29	0.05 ± 0.02	0.12 ± 0.05
Men			
n = 14	4.57 ± 1.54	0.06 ± 0.06	0.10 ± 0.06

*Significant main effects for developmental stage ($P < .05$), children more than adults.
†Significant main effects for developmental stage ($P < .05$), children less than adults.

DISCUSSION

Developmental Stage Comparisons

Our purpose was to identify developmental and sex differences in knee and hip kinematics and VGRFs during vertical jump landings. For developmental stage, our results demonstrate that children landed with a different strategy than adults. Although the groups all exhibited similar knee-flexion angles at IC, the adults had greater flexion angles for the hip at IC and greater flexion angles for the hip and knee at the point of peak VGRF than the children. The adults also landed with less knee valgus at IC and during peak VGRF than the children. These kinematic characteristics may partially account for the children's different ground reaction forces. The children's greater knee and hip extension at impact demonstrated a stiffer landing technique than the adults, which likely led to the higher peak VGRF (Figure 1) and impulse and shorter time to the peak VGRF, even when considering the differences in mass and impact velocity.[9,44] Similar to the results reported by Sigg et al[31] and Ayalon et al,[32] our results suggest that the ability to modulate VGRFs upon impact and throughout landing improves with the process of aging, potentially due to various levels of contribution from physical maturation, skill development, and experience. Several researchers[15,26,45] have reported that increased jumping skill may help the performer better absorb landing forces. If one assumes that increased skill in the jumping task is represented by decreased ground reaction force in the landing and that adults are more skilled, our findings support those conclusions.

Our developmental stage results are not consistent with the

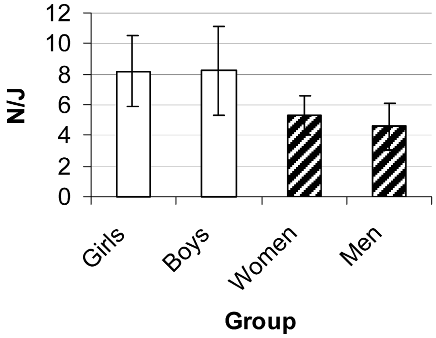

Figure 1. Vertical ground reaction forces normalized by kinetic energy.

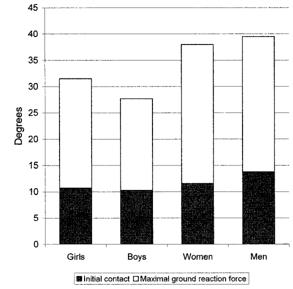

Figure 2. Knee range of motion from initial contact through peak vertical ground reaction forces for the 4 groups.

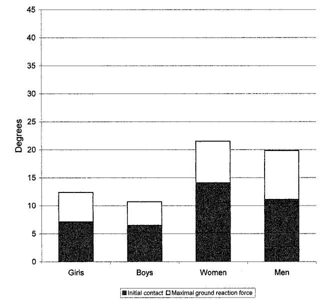

Figure 3. Hip range of motion from initial contact through peak vertical ground reaction forces for the 4 groups.

conclusions drawn by Hass et al,[33] who studied the landings of prepubescent and postpubescent females during 3 types of stride jumps. In the jump tasks, the women landed with more extension at the hip and knee. For the knee, Hass et al[33] reported that girls and women landed with flexion angles of 158° (or 22° in our reporting format) and 163° (or 17°), respectively; both sets of values are considerably greater than the angles exhibited by our female subjects. The authors suggested that an observed increase in extension angles in the postpubescent females might indicate the adults had adapted less than desirable landing characteristics as a result of development.[33] The difference in tasks performed may contribute to the difference in results between the two. The stride-jump task incorporates greater horizontal motion, whereas a vertical jump is primarily characterized by vertical motion. This exemplifies some of the difficulty in reaching an overall conclusion regarding the landing patterns employed by subjects performing varied tasks. Further discussion on the developmental stage comparison is limited by the lack of research comparing youth and adult landing biomechanics.

Sex Comparisons

That our findings do not support sex differences during landing is not unique. In a study using elementary school children, Sigg et al[31] found no differences in knee-flexion angles between boys and girls. Hewett et al[26] compared female high school volleyball players with untrained males and found no differences in ankle, knee, or hip angles at landing. Yet, studying elite collegiate basketball players, Fagenbaum and Darling[25] investigated the effect of fatigue and sex on landing during a maximum vertical jump and drop landings from 2 heights. They found that women landed with greater knee flexion than men, regardless of the type of landing or fatigue condition.

Our results also contradict several studies of drop-landing methods[13,14,24] to compare knee flexion during landing between the sexes. In a study comparing height-matched men and women,[13] women landed with a more extended knee during drop landings from heights of 40 and 60 cm but not from a 20-cm height. In another study of single-leg drop landings,[14] the women landed with a more extended knee than their male counterparts. It is possible that in drop-landing studies, female subjects may use less knee flexion when landing from higher heights simply because they are more accustomed to landing from lower heights, when the straighter knee is all that is required. This possibility may be worth consideration. Our study may not have identified sex differences because the task may not have been provocative enough to reveal differences in landing strategies. In other words, a higher relative jump for subjects (greater than 50% of their maximum vertical jump) may have exposed different landing strategies. However, the 50% vertical jump task was chosen after pilot testing, which revealed that this height allowed the younger subjects to consistently grasp the target. The lack of sex differences could also be due to the task being a ‘‘land-and-stop’’ task versus a ‘‘land-and-go’’ task, as used by Chappell et al.[46] Finally, our subjects were performing a planned task. In sport injury situations, it is likely that during the impact phase, an unanticipated perturbation may not allow sufficient time to adequately correct the landing pattern.

It is interesting to observe the range of motion of the hip and knee from IC through peak VGRF between males and females in our study (Figures 2 and 3). We did not expect to observe differences in landing technique between boys and girls, as prepubescent children are similar in their physical characteristics. However, even though previous literature does not universally support differences between men and women, we did expect to identify kinematic differences between the adults. Although subjects were landing from the same relative height—50% of their maximum vertical jump—our results revealed similar knee-flexion range of motion between the adult men and women, even though men were descending from a greater absolute height. Although the value was not significant, females incorporated more hip-flexion range of motion than males during landing, regardless of developmental stage.

CONCLUSIONS

Our findings demonstrate the existence of developmental differences between children and adults in hip and knee kinematics and VGRFs during vertical jump landings but do not support sex differences. Compared with adults, the children demonstrated a landing pattern with greater hip and knee extension and more knee valgus. Children also experienced higher, more abrupt VGRFs than the adults. Our results suggest that landing patterns change with physical development.

Adults appeared to have an improved ability to absorb the forces of impact. No sex differences in knee and hip kinematics were apparent among recreationally active children or adults when landing from a submaximal-effort vertical jump task. Further research investigating the effect of developmental stage and sex incorporating functional tasks is warranted due to the inconclusive nature of the findings in the literature.

ACKNOWLEDGMENTS

This study was fully funded by the National Athletic Trainers' Association Research and Education Foundation, Dallas, TX (grant 90166P008 to Erik E. Swartz). We thank New Balance Athletic Shoe Company (Lawrence, MA) for their contribution of new footwear for participants. We also thank Rebecca Scanlon, ATC, and Kevin Horn, ATC, for their assistance in data reduction and James Vailas, MD, of the New Hampshire Musculoskeletal Institute, for his support.

REFERENCES

1. Arendt EA, Dick R. Knee injury patterns among men and women in collegiate basketball and soccer: NCAA data and review of literature. *Am J Sports Med.* 1995;23:694–701.
2. Ireland ML, Gaudette M, Crook S. ACL injuries in the female athlete. *J Sport Rehabil.* 1997;6:97–110.
3. Malone T, Hardaker W, Garrett WE, Feagin JA, Bassett FH. Relationship of gender to anterior cruciate ligament injuries in intercollegiate basketball players. *J South Orthop Assoc.* 1993;2:36–39.
4. Hewett TE. Neuromuscular and hormonal factors associated with knee injuries in female athletes: strategies for intervention. *Sports Med.* 2000;29:313–327.
5. Huston LJ, Greenfield ML, Wojtys EM. Anterior cruciate ligament injuries in the female athlete: potential risk factors. *Clin Orthop.* 2000;372:50–63.
6. Caster BL, Bates BT. The assessment of mechanical and neuromuscular response strategies during landing. *Med Sci Sports Exerc.* 1995;27:736–744.
7. Cowling EJ, Steele JR. Is lower limb muscle synchrony during landing affected by gender? Implications for variations in ACL injury rates. *J Electromyogr Kinesiol.* 2001;11:263–268.
8. Decker MJ, Torry MR, Noonan TJ, Riviere A, Sterett WI. Landing adaptations after ACL reconstruction. *Med Sci Sports Exerc.* 2002;34:1408–1413.
9. Devita P, Skelly WA. Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Med Sci Sports Exerc.* 1992;24:108–115.
10. Dufek JS, Bates BT. Biomechanical factors associated with injury during landing in jump sports. *Sports Med.* 1991;12:326–337.
11. Ferris CM, Lephart SM, Riemann BL, Myers JB, Fu FH. Gender differences in lower extremity rotation during landing tasks [abstract]. *J Athl Train.* 2001;36(suppl):S-9.
12. Freedman AD, Riemann BL, Myers JB, Ferris CM, Lephart SM. The effect of fatigue induced quadriceps strength deficits on knee flexion patterns during landing tasks [abstract]. *J Athl Train.* 2001;36(suppl):S-31.
13. Huston LJ, Vibert B, Ashton-Miller JA, Wojtys EM. Gender differences in knee angle when landing from a drop-jump. *Am J Knee Surg.* 2001;14:215–219.
14. Lephart SM, Ferris CM, Riemann BL, Myers JB, Fu FH. Gender differences in strength and lower extremity kinematics during landing. *Clin Orthop.* 2002;401:162–169.
15. McNair PJ, Prapavessis H, Callender K. Decreasing landing forces: effect of instruction. *Br J Sports Med.* 2000;34:293–296.
16. Zhang SN, Bates BT, Dufek JS. Contributions of lower extremity joints to energy dissipation during landings. *Med Sci Sports Exerc.* 2000;32:812–819.
17. Shelbourne KD, Rowdon GA. Anterior cruciate ligament injury: the competitive athlete. *Sports Med.* 1994;17:132–140.
18. Hewett TE, Myer GD, Ford KR. Prevention of anterior cruciate ligament injuries. *Curr Womens Health Rep.* 2001;1:218–224.
19. Harmon KG, Dick R. The relationship of skill level to anterior cruciate ligament injury. *Clin J Sport Med.* 1998;8:260–265.
20. Harmon KG, Ireland ML. Gender differences in noncontact anterior cruciate ligament injuries. *Clin Sports Med.* 2000;19:287–302.
21. Boden BP, Dean GS, Feagin JA Jr, Garrett WE Jr. Mechanisms of anterior cruciate ligament injury. *Orthopedics.* 2000;23:573–578.
22. Kanamori A, Woo SL, Ma CB, et al. The forces in the anterior cruciate ligament and knee kinematics during a simulated pivot shift test: a human cadaveric study using robotic technology. *Arthroscopy.* 2000;16:633–639.
23. Beynnon BD, Fleming BC. Anterior cruciate ligament strain in-vivo: a review of previous work. *J Biomech.* 1998;31:519–525.
24. Malinzak RA, Colby SM, Kirkendall DT, Yu B, Garrett WE. A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clin Biomech (Bristol, Avon).* 2001;16:438–445.
25. Fagenbaum R, Darling WG. Jump landing strategies in male and female college athletes and the implications of such strategies for anterior cruciate ligament injury. *Am J Sports Med.* 2003;31:233–240.
26. Hewett TE, Stroupe AL, Nance TA, Noyes FR. Plyometric training in female athletes: decreased impact forces and increased hamstring torques. *Am J Sports Med.* 1996;24:765–773.
27. Buchanan PA, Vardaxis VG. Hamstrings and quadriceps ratios do not reflect gender differences in ACL injury rates in competitive youth basketball players [abstract]. *J Athl Train.* 2001;36(suppl):S-9.
28. Larkin D, Parker HE. Teaching landing to children with and without developmental coordination disorder. *Pediatr Exerc Sci.* 1998;10:123–136.
29. Lees A. Methods of impact absorption when landing from a jump. *Eng Med.* 1981;10:207–211.
30. Pittenger VM, McCaw ST, Thomas DQ. Vertical ground reaction forces of children during one- and two-leg rope jumping. *Res Q Exerc Sport.* 2002;73:445–449.
31. Sigg JA, Belyea BC, Ives JC. Jumping impact force in elementary schoolage children. *Med Sci Sports Exerc.* 2001;33(5 suppl):S-238.
32. Ayalon A, Ben-Sira D, Leibermann D. Characteristics of landing from different heights and their relationships to various fitness and motor tests. In: *Physical Fitness and the Ages of Man: Proceedings of the Symposium of the International Council for Physical Fitness Research.* Jerusalem, Israel: Academon Press; 1987.
33. Hass C, Schick E, Chow J, et al. Lower extremity biomechanics differ in prepubescent and postpubescent female athletes during stride jump landings. *J Appl Biomech.* 2003;19:139–152.
34. Tanner J. Human growth: a comprehensive treatise. In: Falkner F, Tanner J, eds. *Postnatal Growth Neurobiology.* 2nd ed. New York, NY: Plenum Press; 1986.
35. Gallahue D, Ozmun J, *Understanding Motor Development.* 4th ed. Boston, MA: WCB McGraw-Hill; 1998.
36. Wickstrom R. *Fundamental Motor Patterns.* Philadelphia, PA: Lea & Febiger; 1983.
37. Richards J. The measurement of human motion: a comparison of commercially available systems. *Hum Mov Sci.* 1999;18:589–562.
38. Rozzi SL, Lephart SM, Gear WS, Fu FH. Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players. *Am J Sports Med.* 1999;27:312–319.
39. Dufek JS, Bates BT. The evaluation and prediction of impact forces during landings. *Med Sci Sports Exerc.* 1990;22:370–377.
40. McNitt-Gray JL. Kinetics of the lower extremities during drop landings from three heights. *J Biomech.* 1993;26:1037–1046.
41. James CR, Bates BT, Dufek JS. Classification and comparison of biomechanical response strategies for accommodating landing impact. *J Appl Biomech.* 2003;19:106–118.
42. Decker M, Torry M, Sterett W. Functional adaptations affect landing performance after ACL reconstruction. *Biomechanics.* July 2000;29–40.
43. Cohen J. *Statistical Power Analysis for the Behavioral Sciences.* 2nd ed. Hillsdale, NJ: L. Erlbaum Associates; 1988:xxi,567.
44. McNitt-Gray JL, Yokoi TMC, Millward C. Landing strategy adjustments made by female gymnasts in response to drop height and mat composition. *J Appl Biomech.* 1993;9:173–190.
45. Prapavessis H, McNair PJ. Effects of instruction in jumping technique and experience jumping on ground reaction forces. *J Orthop Sports Phys Ther.* 1999;29:352–356.
46. Chappell JD, Yu B, Kirkendall DT, Garrett WE. A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. *Am J Sports Med.* 2002;30:261–267.