Influence of Sex and Maturation on Knee Mechanics during Side-Step Cutting

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ABSTRACT

SIGWARD, S. M., C. D. POLLARD, K. L. HAVENS, and C. M. POWERS. Influence of Sex and Maturation on Knee Mechanics during Side-Step Cutting. *Med. Sci. Sports Exerc.*, Vol. 44, No. 8, pp. 1497–1503, 2012. **Introduction**: Females have been reported to have a three to five times greater incidence of noncontact anterior cruciate ligament injury when compared with their male counterparts. Previous research suggests that physical maturation is one factor that is associated with the development of potentially injurious lower extremity biomechanics in female athletes. **Purpose**: The study's purpose was to determine whether lower extremity biomechanics differ between male and female soccer athletes during a cutting maneuver across different stages of maturational development. **Methods**: One hundred fifty-six soccer players (76 males and 80 females) between the ages of 9 and 23 yr participated. Subjects were classified on the basis of maturation as prepubertal, pubertal, postpubertal, or young adult. Lower extremity kinematics, kinetics, and ground reaction forces (GRFs) were obtained during a 45° side-step cutting maneuver. Differences between sex and maturation were assessed for peak knee valgus angle, knee adductor moments, and GRFs (vertical, posterior, and lateral) during weight acceptance using a two-factor ANCOVA (controlling for approach velocity). **Results**: No sex × maturation interactions were found for any variable of interest. On average, females exhibited greater knee abduction and adductor moments than males. Prepubertal athletes demonstrated greater knee adductor moments and GRFs than all other groups. **Conclusions**: Biomechanical differences between males and females were evident across all stages of maturation. On average, less mature athletes exhibit biomechanical patterns during cutting that may place them at greater risk for injury than their more mature counterparts. **Key Words:** PUBERTY, CUTTING, LOCOMOTOR SKILLS, KINEMATICS, KINETICS

Approximately 70% of anterior cruciate ligament (ACL) injuries result from situations that do not involve direct contact (5,23) and are associated with landing and evasive cutting maneuvers (27). The incidence of ACL injuries is disproportionately high in more mature and female athletes. Shea et al. (31) reported that the majority of claims made to a company that provides coverage to soccer leagues in the United States with the diagnosis of ACL injury were for children between the ages of 14 and 18 yr. Only 10% of claims were made for children younger than the age of 14 yr (12,31). This is consistent with data from the American Board of Orthopaedic Surgery's database that found that the majority of ACL reconstructions were performed on high school–age patients between the ages of 14 and 18 yr (12,31). In this group, high school– and college-age females have been reported to have a three to five times greater incidence of noncontact ACL injury when compared with their male counterparts (1,24,26).

Sex-related differences in lower extremity biomechanics during the performance of athletic tasks are one factor thought to contribute to the disproportionate incidence of ACL injury in females (13). Although not consistent across all studies, female collegiate and recreational athletes have been found to exhibit greater knee valgus angles (20,22), external knee valgus (or internal adductor) moments (7,21,33), and ground reaction forces (GRFs) (39) as well as smaller knee flexion angles (20,22,39) when compared with their male counterparts during tasks that require deceleration and change of direction. These differences may be particularly important because a prospective study found that females who tore their ACL had significantly greater knee abduction angles, adductor moments, and vertical GRFs during a drop land task when compared with those who were not injured (16). In addition, reduced knee flexion combined with a greater posteriorly directed GRF during the deceleration phase of landing is thought to increase ACL loading as a result of increased anterior tibial shear (38,39).

The development of potentially injurious movement strategies in females is thought to be associated with physical

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maturation. Increases in circulating hormones during puberty accelerate increases in body height and mass. Differences in skeletal growth, body composition, and muscle development between males and females are magnified during this phase of development as a result of distinct hormonal changes between the sexes (4,28). Females show signs of a greater distribution of subcutaneous fat, whereas males have larger increases in lean muscle mass (2,35). A marked acceleration in strength occurring approximately 1 yr after peak height and weight velocities in males magnifies the relatively small preadolescent sex difference (4,28,35). Smaller increases in strength are evident in females just before or after the growth spurt (4,10).

Concurrent with the changes in strength and body composition, males' performance improves noticeably compared with that of females. Males tend to perform better in tasks affected by strength and lean body mass such as running, long jump, and throwing (2,36). Recent studies suggest that the sex differences in lower extremity biomechanics emerge during puberty and may be related to the increased risk for ACL injury in female athletes (11,15,40). For example, pubertal females exhibit greater knee valgus angles, knee adductor moments, and smaller knee flexion angles during double-limb landing tasks than prepubertal females. These differences, however, have not been noted between prepubertal and pubertal males (11,15,40).

Research assessing movement strategies across various stages of maturation has been limited to the assessment of double-limb tasks such as landing from a jump. However, a large percentage of ACL injuries occur during single-limb maneuvers that involve deceleration and change of direction (5,8,27). Sex differences in lower extremity biomechanics have been identified during single-limb cutting maneuvers (20,21,33); however, it is not known how maturation influences the performance of such tasks. This is important because the biomechanical demands between double-limb landing and single-limb cutting tasks are inherently different. In contrast to landing from a jump, cutting requires horizontal deceleration along with reorientation and redirection of the body into a new direction. Currently, the effect of maturation on lower extremity mechanics during single-limb cutting tasks in males and females is not known.

The purpose of the current study was to determine whether lower extremity kinematics and kinetics differ between male and female soccer athletes during a cutting maneuver across different stages of maturational development. On the basis of epidemiological data showing the higher incidence of ACL injury in older, more mature female athletes, the sex differences in biomechanics observed in older athletes, and the unique effects of physical maturation between the sexes, we hypothesized that sex differences in cutting biomechanics would emerge in the postpubertal group. More specifically, we hypothesized that postpubertal females would exhibit higher knee adductor moments, greater knee valgus angles, and greater GRFs when compared with postpubertal males.

MATERIALS AND METHODS

Subjects. One hundred sixty soccer players participated in this study. An *a priori* power analysis using previously collected kinematic and kinetic data for males and females indicated that between 18 and 20 subjects per group were needed to detect differences between sexes with a power level of 80% and an α of 0.05. Data from four subjects were excluded from the analysis because of incomplete kinematic data from poor marker visualization throughout the task. As such, 156 participants (76 males and 80 females) between the ages of 9 and 23 yr were considered for analysis.

At the time of recruitment, all subjects were participating in organized soccer at the club or collegiate level. Training schedules typically required athletes to participate in practice or competition 3 to 5 $d \cdot wk^{-1}$. A medical history was obtained from the participants and their parents. Subjects were excluded from participation if they reported that they had participated in injury prevention training or had medical concerns that could potentially affect lower extremity biomechanics including 1) history of previous ACL injury; 2) history of any ankle, knee, or hip surgery; 3) a previous injury that resulted in persistent pain, limited function, or ligamentous laxity at the ankle, hip, or knee; 4) current lower extremity pain; or 5) presence of any medical or neurological condition that would impair their ability to perform the cutting task. If the athlete reported previous lower extremity injury, a licensed physical therapist obtained a detailed injury history and performed a clinical assessment of joint stability when applicable.

Subjects were divided into four groups on the basis of their stage of maturational development: prepubertal, pubertal, postpubertal, or young adult (Table 1). Because stages of pubertal development generally coincide with changes in physical characteristics (2), the presence or absence of secondary sex characteristics (i.e., stage of pubic hair development) is

TABLE 1. Subject characteristics (mean ± SE).

	Female				Male			
	Prepubertal (*n* = 19)	Pubertal (*n* = 21)	Postpubertal (*n* = 20)	Young Adult (*n* = 20)	Prepubertal (*n* = 19)	Pubertal (*n* = 19)	Postpubertal (*n* = 18)	Young Adult (*n* = 20)
Age (yr)[b,c]	10.1 ± 0.3	12.7 ± 0.2	15.2 ± 0.2	19.7 ± 0.2	11.3 ± 0.3	13.3 ± 0.3	15.7 ± 0.3	20.2 ± 0.2
Height (cm)	144.6 ± 1.7	155.8 ± 1.6	164.6 ± 1.6	167.0 ± 1.6	147.1 ± 1.7	161.9 ± 1.7	175.8 ± 1.7[a]	181.1 ± 1.6[a]
Weight (kg)	36.5 ± 1.7	47.3 ± 1.6	58.6 ± 1.7	65.9 ± 1.7	36.7 ± 1.7	51.8 ± 1.7	69.2 ± 1.8[a]	78.6 ± 1.7[a]
Experience (yr)[b,c]	5.2 ± 0.3	7.1 ± 0.4	9.1 ± 2.0	13.7 ± 2.1	5.7 ± 1.3	8.5 ± 0.4	10.6 ± 0.6	15.4 ± 2.0

[a] Significant difference between males and females.
[b] Significant main effects of sex.
[c] Significant main effect of maturation.

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generally used to classify pubertal stages. Although observational evaluation of these characteristics is considered the gold standard, less intrusive methods of self-report have been validated (19,29,30). The classification of subjects was based on scores obtained from a self-report of Tanner stages for pubic hair development from figured drawings (29,30) and the modified Pubertal Maturation Observational Scale (PMOS) (9). For improved accuracy, parents assisted participants younger than the age of 18 yr in identifying Tanner stage and completing the PMOS. In cases where scores from the PMOS and the Tanner scale did not match, subjects were excluded from the study.

For both males and females, a self-reported Tanner staging for pubic hair of 1 classified individuals as prepubertal, 2–4 classified individuals as pubertal, and 5 classified individuals as postpubertal or young adult. The postpubertal and young adult groups were further differentiated by age. Participants older than the age of 18 yr (close to or past the age of skeletal maturity) were admitted to the young adult group.

Tanner stage classification was supported with items identified on the modified PMOS (9). The PMOS categorization is based on an unobtrusive observation of eight secondary sex characteristics such as muscle development, increased perspiration with physical activity, acne, facial or body hair, deepening of the voice, menarche, and breast development, in addition to parent report of less obvious characteristics such as growth spurt. On the basis of the number of items identified on the PMOS questionnaire, subjects were classified as follows: one or less, prepubertal; two to five with growth spurt, pubertal; and six or greater with growth spurt completed, postpubertal. A growth spurt was defined as an increase in height of 3 to 4 inches in the past year.

Procedures. Testing took place at the Jacquelin Perry Musculoskeletal Biomechanics Research Laboratory at the University of Southern California. All procedures were explained to each subject, and informed consent was obtained as approved by the institutional review board for the University of Southern California Health Sciences Campus. Parental consent and youth assent were obtained for all subjects younger than the age of 18 yr.

Kinematic data were collected using an eight-camera motion analysis system at a sampling frequency of 250 Hz (Vicon, Oxford Metrics, Ltd., Oxford, England). Reflective markers (10-mm spheres) placed on specific boney landmarks (see below for details) were used to quantify segment motion. GRFs were obtained using an AMTI force platform at a rate of 1500 Hz (model #OR6-61; Advanced Mechanical Technologies, Inc., Newton, MA).

Reflective markers were placed bilaterally over the following anatomical landmarks: first and fifth metatarsal heads, medial and lateral malleoli, medial and lateral femoral epicondyles, greater trochanters, iliac crests, and a single marker on the joint space between the fifth lumbar and the first sacral spinous processes. In addition, reflective markers secured to rigid plates were placed bilaterally on the lateral surfaces of the subject's thigh, leg, and heel counter of the shoe. The rigid plates, iliac crest markers, and lumbar marker remained on the subject during testing. All other markers were removed after a static calibration trial. To control for the potential influence of varying footwear, subjects were fitted with the same style of cross-training shoe (New Balance, Inc., Boston, MA).

Each participant performed four trials of a randomly cued side-step cutting maneuver. Subjects were instructed to run 7 m at a speed of 4–5.5 $m{\cdot}s^{-1}$, place their dominant foot on the force platform, and perform one of three tasks: change direction to the opposite side at a 45° angle or 110° angle or continue straight ahead (Fig. 1). A light signal was activated 3 m before foot contact to indicate which task the subject was to perform. Approach speed was calculated with the use of a photoelectric switch and force platform contact. A trial was considered acceptable if the subject approached the force platform at the predetermined speed. Practice trials allowed subjects to become familiar with the procedures and instrumentation. Data from the 45° angle change-of-direction task were considered for analysis.

Data analysis. Coordinate data were digitized using the Vicon Workstation software and filtered using a fourth-order zero-lag Butterworth 12-Hz low-pass filter. The Visual3D™ software (C-Motion, Inc., Rockville, MD) was used to calculate three-dimensional lower extremity kinematics and net joint moments. Lower extremity segments were modeled as a frustra of cones, and the pelvis was modeled as an ellipsoid. The local coordinate systems of the pelvis, thigh, leg, and foot were derived from the standing calibration trial. Six degrees of freedom of each segment were determined from the segment's triad of reflective markers. The kinematics of the

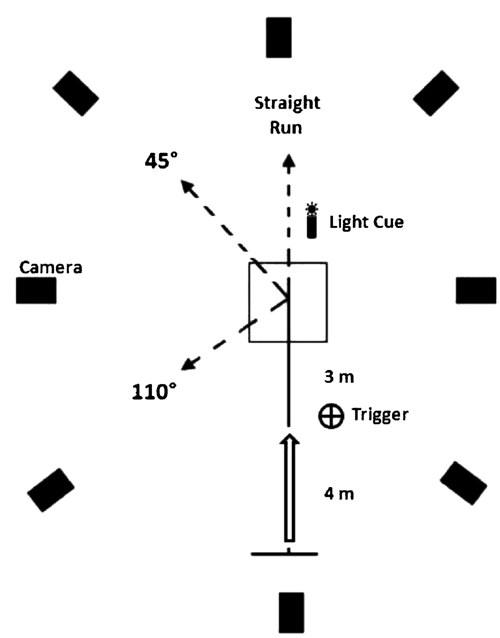

FIGURE 1—Experimental setup for side-step cutting. The *open arrow* indicates original plane of progression; the *solid line* indicates the direction of the 45° cut task. The light cue was triggered 3 m before force plate contact.

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model were calculated by determining the transformation from the triad of markers to the position and orientation of each segment determined from the standing calibration trial. Joint kinematics were calculated using a joint coordinate system approach (14). Internal net joint moments were calculated using inverse dynamics equations (6) and were normalized to body mass and height. The following conventions were used to report knee frontal plane data: positive = knee valgus/abduction angles and internal knee adductor moments and negative = knee varus/adduction angles and internal knee abductor moments.

For the purposes of this study, only data during the weight acceptance phase of the cutting task were considered. Weight acceptance was defined as the period from initial contact to the first local minima of the vertical GRF, as determined by the force plate recordings (3). This phase of the cutting cycle is considered important because it reflects the time during which the majority of noncontact ACL injuries are thought to occur (5). The variables of interest included the peak valgus angle, peak knee adductor (valgus) moment, and peak vertical, posterior, and lateral GRFs (normalized to body mass) during weight acceptance. The dependent variables were identified during each of the four trials and averaged for analysis.

STATISTICAL ANALYSIS

Differences in anthropometrics, soccer experience, and approach velocity between sexes and across stages of maturation were evaluated using multiple 2 × 4 ANOVAs (sex × maturation). Although all groups performed the task within the preset range of approach velocities, between-subject differences have the potential to affect GRFs and net joint moment calculations. Therefore, differences between sexes and across the different stages of maturation were evaluated using multiple 2 × 4 ANCOVAs (sex × maturation), covarying for approach velocity. This analysis was repeated for each dependent variable of interest. In the event of a significant main effect of maturation or a significant interaction between sex and maturation, least significant difference *post hoc* testing was performed. All statistical analyses were performed using SPSS statistical software (v.18; Chicago, IL) and a significance value of $P < 0.05$.

RESULTS

Significant sex × maturation interactions were observed for height and weight ($P = 0.003$ and $P = 0.001$, respectively). Whereas no sex differences in height and weight were noted in the prepubertal and pubertal groups, postpubertal and young adult males weighed more and were taller than females (Table 1). Significant main effects for sex and maturation were observed for age ($P < 0.00$ and $P < 0.001$, respectively; Table 1) and years of experience playing organized soccer ($P < 0.001$ and $P < 0.001$, respectively). On average, males were 0.67 yr older than females and had 1.3 more years of experience than females.

No main effect of sex ($P = 0.75$) or sex × maturation interactions ($P = 0.77$) were observed for approach velocity. However, a significant main effect of maturation was observed for approach velocity ($P < 0.001$). On average, prepubertal athletes performed the task at a slower approach velocity (4.6 ± 0.05 m·s^{-1}) than pubertal (4.9 ± 0.05 m·s^{-1}), postpubertal (5.02 ± 0.05 m·s^{-1}), and young adult athletes (4.8 ± 0.05 m·s^{-1}).

Although no sex × maturation interactions were observed for the peak knee adductor moment ($P = 0.08$, power = 0.58), a significant main effect of sex ($P = 0.01$) and maturation ($P < 0.001$) was found (Fig. 2). When collapsed across maturation groups, females demonstrated significantly greater peak knee adductor moments than males (Fig. 2B). When collapsed across sex, *post hoc* testing revealed that prepubertal athletes exhibited greater peak knee adductor moments than the pubertal ($P = 0.01$), postpubertal ($P < 0.001$), and young adult athletes ($P < 0.001$; Fig. 2C). Pubertal athletes exhibited greater moments than postpubertal ($P = 0.01$) and young adult athletes ($P < 0.001$; Fig. 2C). No significant interactions or main effects were found when the nonnormalized knee adductor moment data were analyzed (Fig. 3).

No sex × maturation interactions were observed for knee valgus angle ($P = 0.67$, power = 0.15). A significant main effect of sex ($P < 0.001$; Fig. 4) and maturation ($P = 0.007$; Fig. 3) was found for the peak knee valgus angle. When collapsed across maturation groups, females demonstrated significantly greater peak knee valgus angles than males (Fig. 4B). When collapsed across sex, *post hoc* testing revealed that young adult athletes exhibited smaller peak knee valgus angles than the prepubertal ($P = 0.01$), pubertal ($P = 0.01$), and postpubertal athletes ($P = 0.01$; Fig. 4C).

No sex × maturation interactions were observed for vertical ($P = 0.36$, power = 0.29), posterior ($P = 0.67$, power = 0.15),

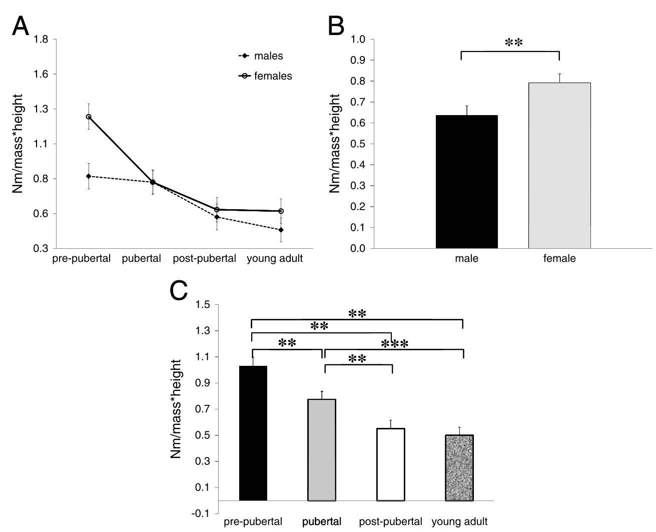

FIGURE 2—Peak knee adductor moment (N·m / mass × height during weight acceptance. A, Individual group data stratified by sex and maturation. B, Data collapsed across sex. C, Data collapsed across maturation levels. Data represent mean + SE. **$P \leq 0.01$. N/N body mass, newtons of force / newtons of body mass.

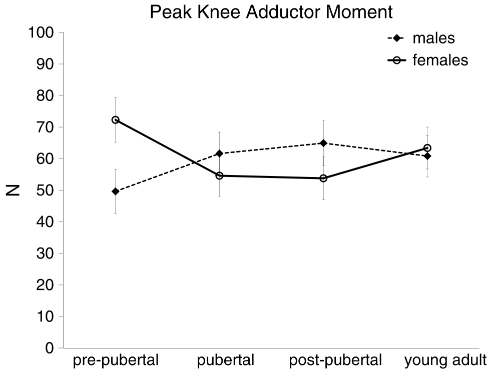

FIGURE 3—Nonnormalized peak knee adductor moment during weight acceptance. Individual group data stratified by sex and maturation. Data represent mean + SE.

or lateral GRFs ($P = 0.44$, power = 0.25). A significant main effect of maturation was found for the peak vertical ($P < 0.001$), posterior ($P = 0.001$), and lateral GRFs ($P = 0.01$). When collapsed across sex, prepubertal athletes exhibited greater peak vertical, posterior, and lateral GRFs than the pubertal, postpubertal, and young adult athletes (Figs. 5 A–C).

DISCUSSION

Although previous studies have considered the effects of sex and maturation on lower extremity mechanics during landing, this is the first study to evaluate the influence of maturation during a cutting task. Consistent with the previous literature examining young adults (21,33), the results of the current study indicate that female athletes exhibit greater knee valgus angles and knee adductor moments during cutting when compared with males. When collapsed across maturation groups, females exhibited 20% higher knee adductor moments and nearly twice the amount of knee valgus when compared with males.

Surprisingly, our results did not support the hypothesis that sex differences in cutting biomechanics would emerge after puberty because no significant interactions between sex and maturation were noted for any variable of interest. Previous studies have reported that sex differences in knee valgus angles and knee adductor moments emerge between early and late puberty during double landing tasks (11,15,40). Although a sex × maturation interaction for the knee adductor moment did not reach statistical significance in the current study ($P = 0.08$), the largest sex difference was evident in the prepubertal athletes (Cohen *d* effect size = 0.76), with smaller sex differences noted in more mature athletes (Cohen *d* effect size = 0.001, 0.19, 0.47: pubertal, postpubertal, and young adult, respectively; Fig. 2).

When comparing the results of the current investigation to studies that have evaluated the influence of maturation on lower extremity biomechanics during a bilateral landing task, several differences seem to exist. During landing from a jump, pubertal and postpubertal athletes have been shown to exhibit increased frontal plane knee loading and altered shock attenuation strategies during landing compared with prepubertal athletes (11,15,32,40). In the current study, an opposite pattern was noted in that prepubertal athletes exhibited larger knee adductor moments and GRFs when compared with the pubertal and postpubertal groups. In general, the prepubertal athletes in the current study adopted a cutting strategy that involved greater impact forces than their more mature counterparts, which likely contributed to greater knee frontal plane moments in this group (34).

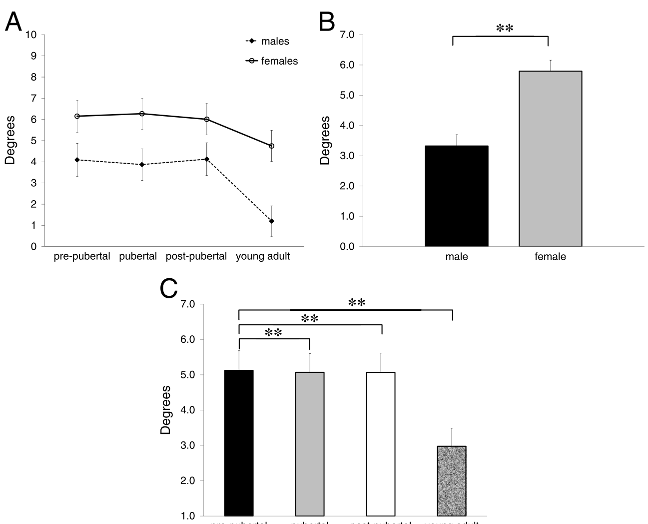

FIGURE 4—Peak knee abductor angle (°) during weight acceptance. A, Individual group data stratified by sex and maturation. B, Data collapsed across sex. C, Data collapsed across maturation levels. Data represent mean + SE. $^{**}P \leq 0.01$.

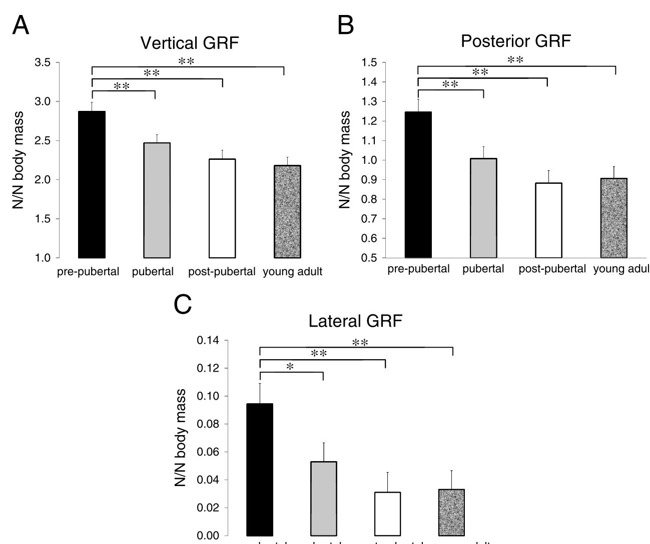

FIGURE 5—Peak GRFs during weight acceptance (N/N body mass). Data are collapsed across sex. A, Vertical. B, Posterior. C, Lateral. Data represent mean + SE. $^{*}P < 0.05$; $^{**}P \leq 0.01$.

The discrepancy in maturation differences reported in the current study for side-step cutting compared with the previous literature for landing may be related to task demand. During cutting, impact forces are generated by a single limb to control body rotation during deceleration and to facilitate redirection of the body center or mass (17,18). Previous studies have reported that when compared with young adults, children (9–11 yr) use less efficient steering and reorientation strategies when negotiating around environmental obstacles (37) and have more difficulty performing higher precision locomotor tasks (25). Therefore, it is likely that cutting may present additional challenges to younger athletes when compared with a landing task. Athletes in the current study also were required to respond to a random cue presented after the onset of movement. This may have presented an even greater challenge to young athletes who have not fully developed their perceptual motor processes (25). On average, prepubertal athletes performed the tasks with a slightly slower average approach velocity. However, this did not seem to affect the results because we found the same group differences when the data were analyzed without controlling for approach velocity. One must also consider that years of experience were generally proportional to age; the greater years of experience performing change-of-direction tasks in the older athletes may have contributed to the differences in performance noted between maturation groups.

Although our findings are consistent with the development of complex locomotor skills during early childhood, it is not clear how this information relates to injury risk. Greater knee adductor moments and larger GRFs suggest that prepubertal athletes use a cutting strategy that places them at increased risk for ACL injury. However, this finding is inconsistent with epidemiological data that suggests high school–age athletes incur a greater number of ACL injuries compared with younger athletes (12,31). Perhaps more immature athletes avoid performing more complex movement strategies during competition, thereby decreasing their exposure to these potentially injurious mechanics. It also should be noted that the older athletes in the current study may represent individuals with relatively good biomechanical profiles who have successfully participated in soccer throughout their developmental years without sustaining an ACL injury.

The results of this study suggest that less mature athletes exhibit biomechanical patterns during cutting that may place them at greater risk for injury than their more mature counterparts. The observed differences across maturation groups may be attributed to the development of complex locomotor skills in the older athletes. Implementation of prevention strategies in prepubertal athletes may be warranted. However, this study design was cross-sectional, limiting our interpretation to the difference between individuals at different stages of maturation. Longitudinal studies are needed to gain a better understanding of how complex locomotor skills develop through maturation.

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The authors report no conflicts of interest.

The results of this study do not constitute endorsement by the American College of Sports Medicine.

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