Decrease in Neuromuscular Control About the Knee with Maturation in Female Athletes

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Background: Compared with male athletes, female athletes demonstrate increased dynamic valgus angulation of the knee during landing from a jump, although prior to maturation male and female athletes have similar forces and motions about the knee when they land from a jump. Our hypothesis was that musculoskeletal changes that accompany maturation result in poor neuromuscular control of the knee joint in female athletes.

Methods: One hundred and eighty-one middle-school and high-school soccer and basketball players—100 girls and eighty-one boys—participated in the study. Dynamic control of the knee joint was measured kinematically by assessing medial knee motion and the lower-extremity valgus angle and was measured kinetically by assessing knee joint torques; the values were then compared between female and male athletes according to maturational stage. Lower-extremity bone length was measured with three-dimensional kinematic analysis.

Results: Following the onset of maturation, the female athletes landed with greater total medial motion of the knees and a greater maximum lower-extremity valgus angle than did the male athletes. The girls also demonstrated decreased flexor torques compared with the boys as well as a significant difference between the maximum valgus angles of their dominant and nondominant lower extremities after maturation.

Conclusions: After girls mature, they land from a jump differently than do boys, as measured kinematically and kinetically.

Clinical Relevance: Following the onset of the pubertal growth spurt, female athletes change the way that they land from a jump. This change may be due to decreased neuromuscular control of the knee and may explain why the risk of anterior cruciate ligament injury is higher in girls than it is in boys. The measures of neuromuscular control of the knee used in this report may be employed to monitor athletes and to direct appropriate new interventions to athletes at high risk for injury.

Although girls and boys have an equal number of ligament sprains prior to adolescence, girls have a higher rate immediately following their growth spurt and into maturity[1]. Michaud et al. reported that the Tanner stage of maturation of girls was associated with the occurrence of sports injuries[2]. Adolescent girls who participate in pivoting and jumping sports have a four to sixfold greater rate of injuries of the anterior cruciate ligament than do adolescent boys participating in the same sports[3-5]. In contrast, an analysis of the published literature[6-9] demonstrated no evidence of a difference in the rates of anterior cruciate ligament injury between prepubertal male and female athletes.

Neuromuscular patterns in males and females diverge substantially during maturation. Males demonstrate increases in power, strength, and coordination with age that correlate with their maturational stage, whereas, on the average, girls show little change throughout maturation[10,11]. For example, the vertical jump height demonstrated by boys increases steadily during maturation, but that demonstrated by girls does not[10,11].

One of us (T.E.H.) and colleagues[4] tracked the occurrence of anterior cruciate ligament injuries in 1263 athletes through their soccer, volleyball, and basketball seasons. Untrained girls had significantly higher rates of anterior cruciate ligament injury than did trained girls and boys ($p < 0.05$), whereas the rates in trained girls were not different from those in untrained boys. That prospective study demonstrated that neuromuscular training has the potential to decrease rates of anterior cruciate ligament injury in adolescent female athletes. Intensive neuromuscular training may induce a so-called neuromuscular spurt that would otherwise be absent in adolescent girls[12-14].

Neuromuscular control of the knee can be defined as the unconscious response to an afferent signal concerning dynamic knee joint stability[15]. The absence of neuromuscular control of the knee joint may be responsible for the increased

TABLE I Data on the Study Subjects

Maturational Stage	No. of Subjects	Age* (yr)	Height* (cm)	Weight* (kg)
Female prepubertal	14	11.5 ± 0.7	148.7 ± 5.9	38.9 ± 5.9
Female early pubertal	28	12.6 ± 1.1	158.5 ± 6.1	46.8 ± 5.5
Female late or postpubertal	58	15.5 ± 1.5	168.3 ± 6.5	63.4 ± 10.9
Male prepubertal	27	12.0 ± 0.6	151.3 ± 6.7	41.9 ± 8.3
Male early pubertal	24	14.2 ± 1.4	169.7 ± 9.9	59.4 ± 11.8
Male late or postpubertal	30	15.8 ± 1.7	179.2 ± 8.4	70.8 ± 10.9

*The values are given as the mean and standard deviation.

rates of knee injury in females[14,16], but it is not normally measured in athletes prior to participation in sports. Standard preparticipation physical examinations assess static measures of joint stability. Few if any dynamic measures are assessed, and intervention is rarely implemented. Although musculoskeletal disorders are observed during approximately 10% of preparticipation examinations of athletes, intervention is carried out for 1% to 3%[15-18]. No method for the accurate and practical screening and identification of athletes at increased risk for anterior cruciate ligament injury is currently available.

Our long-term objectives are to determine how female athletes become more susceptible to anterior cruciate ligament injury and to prospectively identify those who are more susceptible in order to optimize the effectiveness of interventions designed to prevent anterior cruciate ligament injuries. The objectives of this study were to determine what role growth and development play in the mechanism of decreased neuromuscular control of the knee and to test methods to identify female athletes with decreased dynamic control of the knee. We tested the hypothesis that musculoskeletal changes that accompany maturation are associated with poor neuromuscular control of the knee in female athletes.

Materials and Methods

Subjects

We performed a cross-sectional controlled laboratory study of eighty-one healthy male and 100 healthy female preadolescent and adolescent athletes (Table I). The subjects were male and female basketball and soccer players from area middle schools and high schools who had volunteered to participate in the study. Acceptance into the study was based on predetermined inclusion and exclusion criteria: the subjects had to be on a school-sponsored basketball or soccer team, and athletes who had had a previous anterior cruciate ligament injury were excluded. In each case informed written consent was obtained from both the child and a parent, and the study was approved by the institutional review board of the Cincinnati Children's Hospital Medical Center. After the informed consent was obtained, the height, weight, and dominant lower limb were recorded. The dominant lower limb was determined for each subject by asking which limb he or she would use to kick a ball as far as possible. The tibial and thigh lengths of each subject were measured with the three-dimensional kinematic system described below and were recorded during the same laboratory evaluation.

Table I provides data on the six subject groups based on gender and stage of pubertal development[19]. A modified Pubertal Maturation Observational Scale (PMOS) was used to classify subjects into maturational categories: prepubertal (equivalent to Tanner[20,21] Stage 1), early pubertal (equivalent to Tanner Stages 2 and 3), or late or postpubertal (equivalent to Tanner Stages 4 and 5). The categories were then analyzed both as groupings and as a continuous variable. The scale is based on several indicators of pubertal maturation (growth spurt, menarchal status, body hair, sweating, and muscular definition)[19]. It can be used to reliably classify subjects into developmental stages on the basis of a parental report and the observations of an investigator[22]. The reliability of the scale has been demonstrated to be high[19].

Three-Dimensional Kinematic Analysis

A three-dimensional kinematic test was utilized as a measure of neuromuscular control of the knee[23]. Each subject had twenty-three retroreflective markers placed on the sacrum and bilaterally on the shoulder, anterior superior iliac spine, greater trochanter, midpart of the thigh, medial and lateral aspects of the knee, midpart of the shank, medial and lateral aspects of the ankle, and heel and toe (between the second and third metatarsals). The motion analysis system consisted of eight digital cameras (Eagle Cameras; Motion Analysis, Santa Rosa, California) connected through an Ethernet hub to the data collection computer (Dell Computer, Round Rock, Texas) and sampled at 240 Hz. Two force platforms (AMTI, Watertown, Massachusetts) were sampled at 1200 Hz and time synchronized to the motion analysis system. Data were collected with EVaRT (version 3.21; Motion Analysis) and were imported into KinTrak (version 6.2; Motion Analysis) for data reduction and analysis. Prior to each data collection session, the motion analysis system was calibrated to manufacturer recommendations.

A static trial was performed to align the joint coordinate system to the laboratory. Subjects were instructed to stand still and were aligned as closely with the laboratory coordinate system as possible. The medial knee and ankle markers were subsequently removed prior to the drop vertical jump trials. The drop vertical jump started with the subject standing on top of a 31-cm-high box with the feet positioned 35 cm apart, as measured between the toe markers. The subject was instructed to drop directly down off the box and immediately perform a maximum vertical jump, raising both arms as if he or she were jumping for a basketball rebound (see Appendix)[24]. The two force platforms were embedded into the floor and positioned 8 cm apart so that each foot came into contact with a different platform during the maneuver. The first contact on the platforms (i.e., the drop from the box) was used for analysis. Three successful trials were recorded for each subject.

The three-dimensional Cartesian marker trajectories from each trial were estimated with use of the direct linear transformation method and were filtered through a low-pass Butterworth digital filter at a cutoff frequency (9 Hz) determined with residual analysis[25]. Varus-valgus knee-joint angles of the right and left limbs were calculated from an embedded joint coordinate system[26]. A positive lower-extremity varus-valgus angle represented valgus, and a negative angle represented varus. Vertical ground reaction force was used to identify the time of the initial contact with the ground and of toe-off during take-off from the jump. The lower-extremity knee angle at initial contact and the maximum lower-extremity angle during stance (from initial contact to toe-off) were recorded.

Medial knee motion was calculated bilaterally on the basis of the coronal plane distance between the right and left lateral knee markers during the drop vertical jump. The knee distance was recorded 0.03 second prior to the initial contact and then as the minimum knee distance during the stance phase (maximum medial motion)[23]. The difference between the knee distance prior to the initial contact and the minimum medial knee distance was calculated as the total medial knee motion (in centimeters) and as the medial knee motion normalized to body height (in centimeters). All kinematic data were ensemble averaged from three trials.

Isokinetic Dynamometer Strength Measures

An isokinetic dynamometer was utilized to measure peak isokinetic torque production of the hamstrings and quadriceps muscles in order to assess knee flexion and extension strength. Subjects were seated on the dynamometer with the trunk perpendicular to the floor, the hip flexed to 90°, and the knee flexed to 90°. They performed a five-repetition knee extension-flexion warm-up with each lower limb at 300°/sec prior to the test. The test session consisted of ten repetitions of knee extension-flexion with each limb at 300°/sec. Maximum knee flexion and extension torques were recorded.

Reliability Measurements

Studies of the reliability of the measurements of the limb-segment lengths, the three-dimensional kinematic testing, and the dynamometric measurements were conducted. All measures demonstrated high day-to-day reproducibility in the laboratory. The three test sessions were one or two days apart and were held at approximately the same time of day. The testing order was randomized for each subject. The three-dimensional system has a marker tracking error of approximately 0.2 mm. The reliability of all measurements was high. The intraclass correlation coefficients were high for the lengths of the dominant and nondominant shanks and thighs measured over three different days (five subjects, intraclass correlation coefficient = 0.964 for the shank measurements and 0.954 for the thigh measurements). The between-day reliability of the three-dimensional motion analysis and isokinetic dynamometer measurements was assessed in the same sample of subjects. The intraclass correlation coefficient was 0.916 for the reliability of the measurement of the knee distance at the time of maximum medial motion, 0.893 for total medial motion, and 0.848 and 0.968 for isokinetic dynamometer measures of peak hamstrings and quadriceps torque.

Statistical Analysis

The means and standard error of the mean for each variable were calculated for each subject group. An analysis of variance test was used to compare means between the different groups, and a Fisher least-significant-difference post hoc test was used to determine significant differences between groups ($p < 0.05$). A paired t test was used to determine significant differences between the dominant and nondominant sides ($p < 0.05$). For measures of relative correlation between parameters, the Pearson correlation coefficient was calculated. Statistical analyses were conducted with SPSS for Windows software (release 10.0.7; SPSS, Chicago, Illinois).

Results

Increases in Lower-Limb-Segment Lengths in Female and Male Athletes

The shank and thigh lengths of the girls and boys in the early pubertal and late or postpubertal stages were increased relative to those of their prepubertal counterparts ($p < 0.01$; see Appendix). In addition, the shank and thigh lengths of the girls and boys in the late or postpubertal stage were increased relative to those of the girls and boys in the early pubertal stage ($p < 0.01$). Height and weight increased in these populations in a similar fashion, although the increases were smaller in girls than in boys. In order to correct for the potentially confounding effects of height and weight differences between groups, neuromuscular measures were normalized to height and weight.

Increases in Medial Knee Motion in Female Athletes with Growth and Development

Three-dimensional motion analysis demonstrated no differences in medial knee motion between boys and girls prior to the onset of maturation (Fig. 1). The maximal medial knee motion demonstrated by the girls in the prepubertal and early pubertal stages was similar to that demonstrated by the boys in those stages. However, the girls in the late or postpubertal stage displayed significantly more medial knee motion than did the boys in that stage ($p < 0.01$) and the girls and boys in

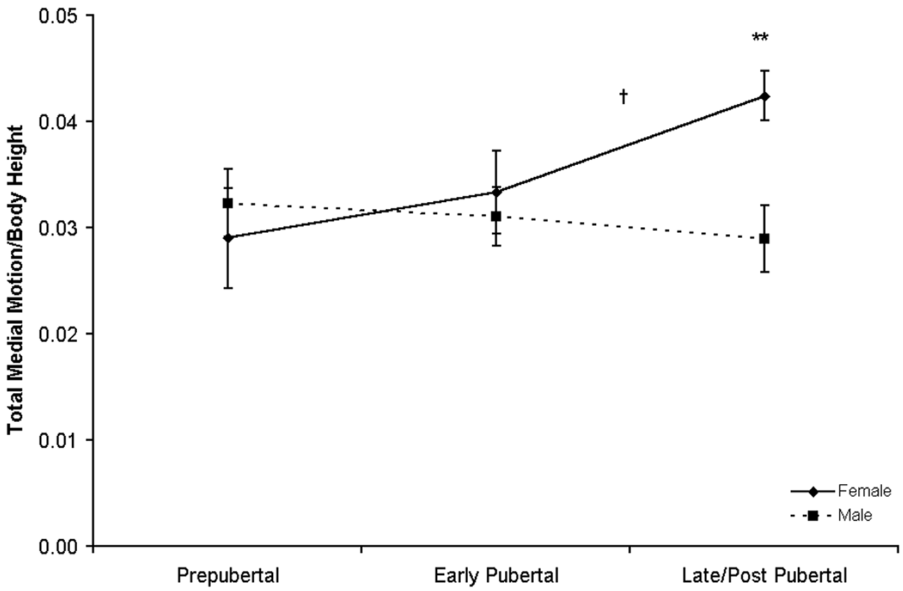


Fig. 1
Total medial knee displacement in female and male athletes in the prepubertal, early pubertal, and late or postpubertal stages. **Significant difference between genders ($p < 0.01$). †Significant difference between female maturational stages ($p < 0.05$).

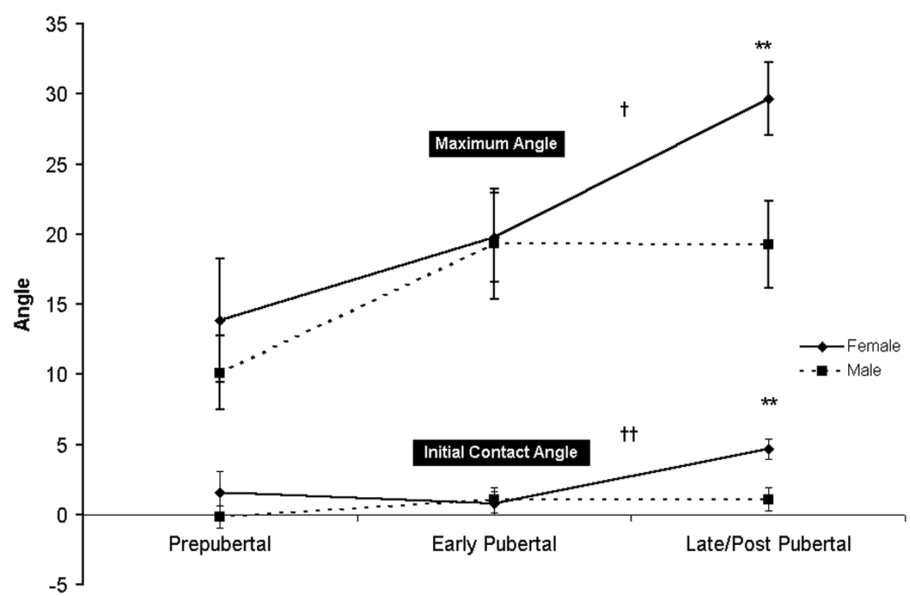
the prepubertal and early pubertal stages ($p < 0.05$). Medial motion of the knees correlated with shank (tibial) length in the female athletes ($r = 0.37$, $p < 0.001$) but not in the male athletes ($r = 0.07$, $p = 0.53$).

The lower-extremity valgus angle at initial contact and the maximum angle during landing are displayed in Figure 2. The girls in the late or postpubertal stage displayed a greater lower-extremity valgus angle than did the boys in that stage, both at initial contact (5° ± 1° compared with 1° ± 1°; $p < 0.01$) and at maximum during landing (30° ± 3° compared with 19° ± 3°; $p < 0.01$). Girls in the late or postpubertal stage also displayed a greater lower-extremity valgus angle at initial contact than did both the prepubertal girls (2° ± 2°; $p < 0.05$) and the girls in early puberty (1° ± 1°; $p < 0.01$), and they displayed a greater maximum angle than did the prepubertal girls (14° ± 4°; $p < 0.01$) and the girls in early puberty (20° ± 3°, $p < 0.05$).

Side-to-Side Differences in Valgus Angle in Female Athletes at Landing

The maximum lower-extremity valgus angle during landing was significantly lower on the nondominant side than it was

Fig. 2
Lower-extremity valgus angle at initial contact (lower graph) and maximum lower-extremity valgus angle during landing (upper graph) in female and male athletes in the prepubertal, early pubertal, and late or postpubertal stages. **Significant difference between genders ($p < 0.01$). †Significant difference between female maturational stages ($p < 0.05$). ††Significant difference between female maturational stages ($p < 0.01$).



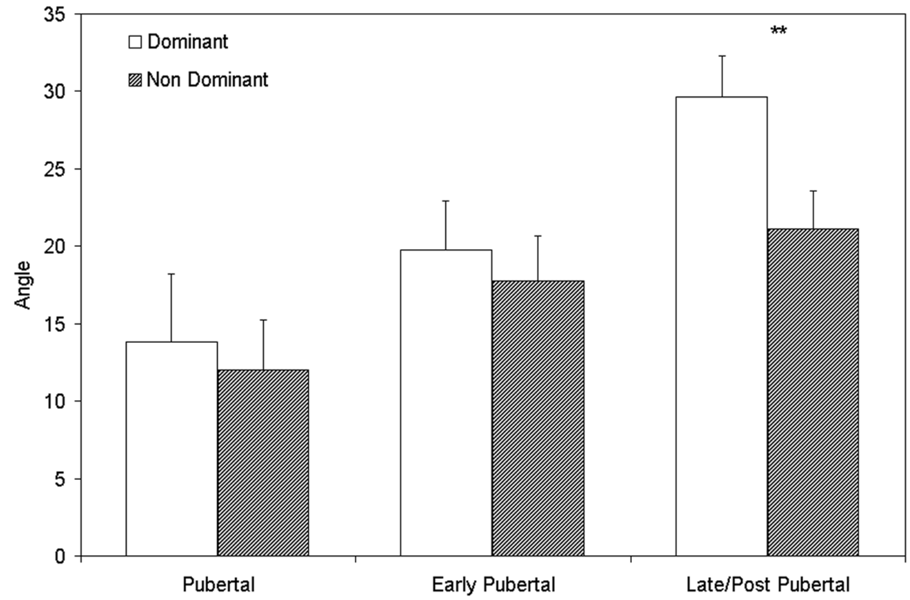


Fig. 3
Comparison of the lower-extremity maximum valgus angles during landing between the dominant and nondominant sides in female athletes in the prepubertal, early pubertal, and late or postpubertal stages. **Significant difference between maturational stages ($p < 0.01$).

on the dominant side in the girls in the late or postpubertal stage ($p < 0.01$, Fig. 3).

Increases in Knee Muscle Peak Torque with Maturation in Male but Not Female Athletes

After normalization to body weight, isokinetic dynamometer measurements demonstrated that male athletes had significantly greater hamstrings peak torques with increasing maturity, whereas peak torque remained steady with increasing maturational stage in female athletes. Boys demonstrated significantly higher hamstrings peak torque in the late or postpubertal stage than they did in the early and prepubertal stages ($p < 0.05$), whereas, with the numbers available, girls demonstrated no differences in hamstrings peak torque across maturational stages (Fig. 4). Hamstrings peak torque correlated with femoral length in both male ($r = 0.69$, $p < 0.001$) and female athletes ($r = 0.57$, $p < 0.001$). However, hamstrings peak torque was significantly lower in the girls in

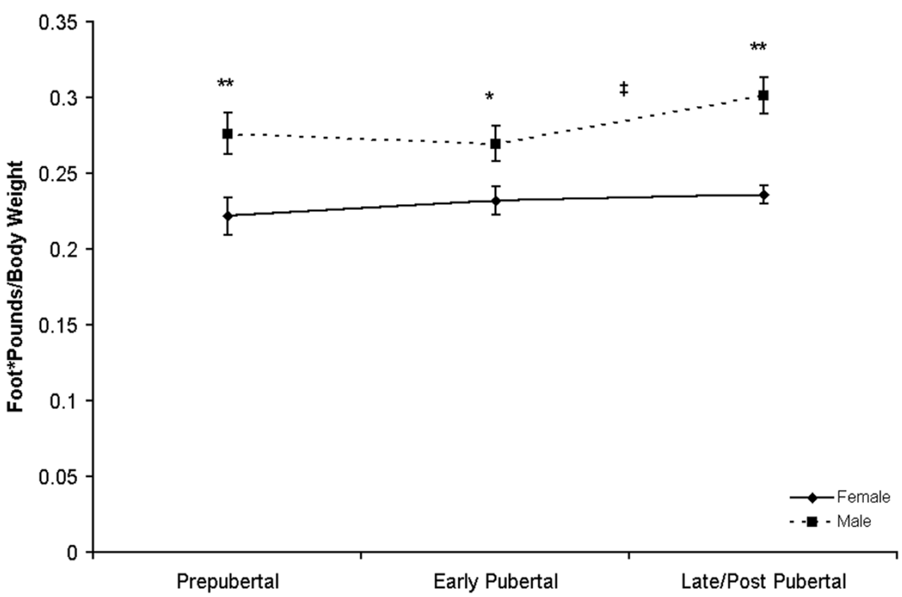


Fig. 4
Comparison of the isokinetic dynamometer measurements of the hamstrings peak torque normalized to body weight in female and male athletes in the prepubertal, early pubertal, and late or postpubertal stages. *Significant difference between genders ($p < 0.05$). **Significant difference between genders ($p < 0.01$). †Significant difference between male maturational stages ($p < 0.05$).

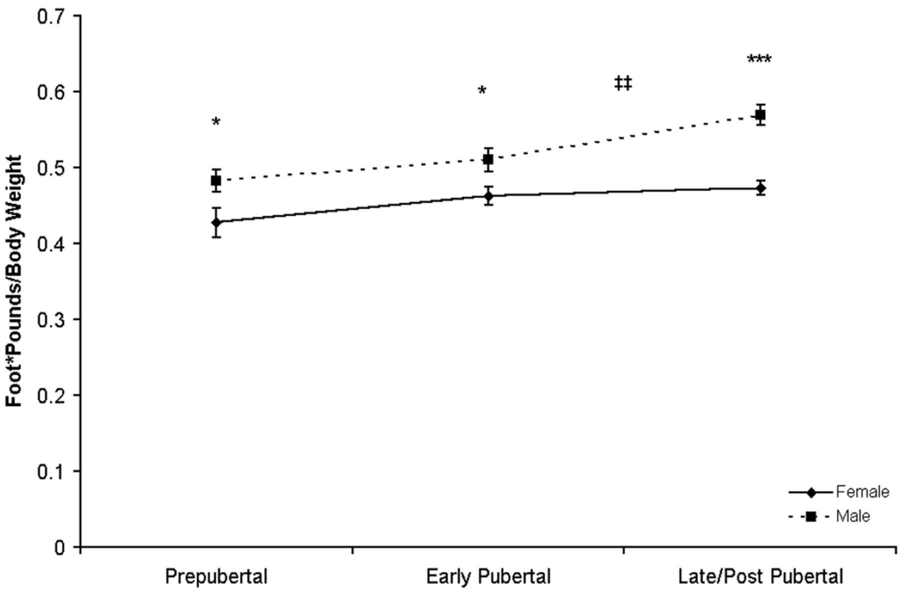


Fig. 5
Comparison of the isokinetic dynamometer measurements of the quadriceps peak torque normalized to body weight in female and male athletes in the prepubertal, early pubertal, and late or postpubertal stages. *Significant difference between genders (p < 0.05). ***Significant difference between genders (p < 0.001). ‡‡Significant difference between male maturational stages (p < 0.01).

the prepubertal ($p < 0.01$), early pubertal ($p < 0.05$), and later or postpubertal ($p < 0.01$) stages than it was in the boys in the same stages.

Male athletes also demonstrated significantly greater quadriceps peak torque (normalized to body weight) with increasing maturity, whereas girls did not (Fig. 5). The male athletes demonstrated significantly higher quadriceps peak torque in the late or postpubertal stage than they did in the early and prepubertal stages, whereas, with the numbers available, the girls demonstrated no differences in quadriceps peak torque across maturational stages. Quadriceps peak torque correlated with femoral length in both male ($r = 0.78$, $p < 0.001$) and female athletes ($r = 0.57$, $p < 0.001$). However, compared with boys in the same maturational stage, girls had a 12% deficit in quadriceps peak torque (normalized to body weight) in the prepubertal stage ($p < 0.05$), an 11% deficit in the early pubertal stage ($p < 0.05$), and an 18% deficit in the late or postpubertal stage ($p < 0.001$).

Discussion

Changes in Neuromuscular Control of the Knee in Adolescent Athletes

Several authors have documented a substantial increase in neuromuscular strength and coordination following the growth spurt in adolescent boys but not in the average adolescent girl[27-30]. Gender differences have been documented for grip strength, pulling strength, vertical jumps, long jumps, sprint speed, and balance in both longitudinal and cross-sectional studies. In a recent cross-sectional study by Kellis et al.[10], female basketball players did not increase vertical jump performance with increasing age, whereas male players improved their scores with age.

The data in the literature demonstrate that the genders diverge with regard to neuromuscular performance and injury rate following peak height velocity, which occurs at the age of eleven to twelve years in girls[20,21]. Differences in knee injury rates have been reported to occur at the age of twelve. The observed changes in neuromuscular measures across maturational boundaries were very different between the boys and girls in the present study. Girls demonstrated decreased neuromuscular control of the knee from early to late puberty, whereas boys demonstrated better neuromuscular control of the knee in late puberty than they had in early puberty.

Changes in Landing from a Jump by Adolescent Athletes

This study supports the hypothesis that musculoskeletal changes that accompany maturation are associated with poor neuromuscular control of the knee in female athletes. We documented changes, following the onset of maturation, in how girls and boys land from a jump. Boys regain neuromuscular control following their so-called neuromuscular spurt, whereas girls do not appear to make a similar neuromuscular adaptation. This potentially leads to decreased dynamic knee stability in female athletes. In the prepubertal and early pubertal stages, girls and boys displayed similar amounts of lower-extremity valgus motion, but girls demonstrated more valgus motion than boys at maturity. This study indicates that biomechanical changes during maturation are likely to underlie the changes in neuromuscular control of the knee.

Neuromuscular control indices in female athletes decreased with the onset of puberty, and the decreases continued into the late or postpubertal stage. This decrease may occur just prior to or coincident with the increase in injury risk. Although one cannot predict the exact stage of development at which the risk of injury will increase, it most likely does so subsequent to the period of peak height velocity and decreased neuromuscular control of the knee. Neuromuscular adaptation and coordination may lose pace with skeletal growth at this time[31,32]. The timing of this transition should be the subject of careful, longitudinal study.

Mechanisms of Anterior Cruciate Ligament Injury in Adolescent Female Athletes

The findings of the current study suggest that boys use a more efficient strategy for muscular damping of forces, through greater muscular cocontraction. The observed increases in valgus motion of the knees of postpubertal girls suggest altered muscular control of the lower extremities in the coronal plane. This probably reflects changes in contraction patterns of the adductors and abductors of the hip and the flexors and extensors of the knee[33,34]. Muscular contraction can decrease the valgus laxity of the knee threefold[35]. The present findings support the hypothesis that growth and development decrease a female's neuromuscular control of the knee.

It has been estimated that >70% of all anterior cruciate ligament injuries occur at landing from a jump[36]. Jump takeoff and landing movements were evaluated biomechanically in the current study. One of us (T.E.H.) and colleagues previously demonstrated that valgus torques about the knee are significant contributors to landing forces from a jump ($p < 0.01$)[14]. Biomechanical differences in the net knee-joint torques, landing forces, and muscle strength were found between male and female athletes during the sports-specific, non-contact activities of jumping and landing[14]. Landing with the knee in valgus can potentially injure the knee, and athletes should avoid excessive valgus or varus forces at the knee to minimize the risk of knee injury[34].

An athlete may be at risk for injury if the lower extremity is not properly aligned or if the foot is in an unusual position when he or she lands from a jump[37]. A multiple regression analysis incorporating flexion angles, flexion and extension moments, and valgus torque at the knee, hip, and ankle demonstrated that valgus torques at the knee were the sole significant predictors of peak landing forces ($p < 0.01$)[14]. It is likely that more equal distribution of forces transmitted across both the medial and the lateral compartment of the knee joint would lead to decreased landing forces[14,38]. In addition, a decreased valgus or varus moment would decrease the risk of femoral condylar lift-off from the tibial plateau. Biomechanical studies have established the relationship between femoral condylar lift-off and injury risk[33,35].

Limitations of This Study

Several limitations of this study should be considered. Several possible contributing and confounding variables, including school, team, age/grade, aggressiveness, foot pronation, quadriceps angle, femoral notch width, and blood hormone levels, were not controlled for in the study design. In addition, the study was cross-sectional and, as such, could not assay for changes over time; it was only a snapshot of one time-point. The hypotheses of this study must be tested in future, prospective longitudinal studies to better answer the questions raised by this investigation.

The fact that we included only soccer and basketball players in our study limits the generalizability of its findings. However, gender differences in injury incidence have been demonstrated in several sports, including basketball, soccer, lacrosse, team handball, and volleyball. There are probably differences in neuromuscular control measures in most gender-paired sports. Therefore, the associations between pubertal stage and neuromuscular control measures and injury in adolescent basketball and soccer players should be comparable with those found in adolescent athletes participating in other sports.

Future Directions

In conclusion, the findings of this study support our hypothesis that musculoskeletal changes that accompany maturation are associated with poor neuromuscular control of the knee in female athletes. These changes in height, weight, and bone length, in the absence of neuromuscular adaptation to these changes, may lead to dynamic knee instability in female athletes.

Our findings may lead to advances in the prevention and treatment of anterior cruciate ligament injuries in young female athletes. We demonstrated that growth and development play a role in the mechanism of decreased neuromuscular control of the knee. Future research should focus on controlled prospective longitudinal studies of defined populations of female athletes followed through multiple sports seasons to correlate neuromuscular profiles to injury risk. Only then can the relative injury risk be predicted with high sensitivity.

Appendix

eA Figures showing tibial and femoral length measurements in the athletes and a video of adolescent male and female athletes landing from a jump are available with the electronic versions of this article, on our web site at www.jbjs.org (go to the article citation and click on "Supplementary Material") and on our quarterly CD-ROM (call our subscription department, at 781-449-9780, to order the CD-ROM). ■

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References

1. **Tursz A, Crost M.** Sports-related injuries in children. A study of their characteristics, frequency, and severity, with comparison to other types of accidental injuries. *Am J Sports Med.* 1986;14:294-9.
2. **Michaud PA, Renaud A, Narring F.** Sports activities related to injuries? A survey among 9-19 year olds in Switzerland. *Inj Prev.* 2001;7:41-5.
3. **Arendt E, 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.
4. **Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR.** The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. *Am J Sports Med.* 1999;27:699-706.
5. **Malone TR, Hardaker WT, Garrett WE, Feagin JA, Bassett FH.** Relationship of gender to anterior cruciate ligament injuries in intercollegiate basketball players. *J South Orthop Assoc.* 1993;2:36-9.
6. **Andrish JT.** Anterior cruciate ligament injuries in the skeletally immature patient. *Am J Orthop.* 2001;30:103-10.
7. **Buehler-Yund C.** A longitudinal study of injury rates and risk factors in 5 to 12 year old soccer players [dissertation]. Cincinnati: University of Cincinnati; 1999.
8. **Clanton TO, DeLee JC, Sanders B, Neidre A.** Knee ligament injuries in children. *J Bone Joint Surg Am.* 1979;61:1195-201.
9. **Gallagher SS, Finison K, Guyer B, Goodenough S.** The incidence of injuries among 87,000 Massachusetts children and adolescents: results of the 1980-81 Statewide Childhood Injury Prevention Program Surveillance System. *Am J Public Health.* 1984;74:1340-7.
10. **Kellis SE, Tsitskaris GK, Nikopoulou MD, Mousikou KC.** The evaluation of jumping ability of male and female basketball players according to their chronological age and major leagues. *J Strength Cond Res.* 1999;13:40-6.
11. **Beunen G, Malina RM.** Growth and physical performance relative to the timing of the adolescent spurt. *Exerc Sport Sci Rev.* 1988;16:503-40.
12. **Kraemer WJ, Mazzetti SA, Nindl BC, Gotshalk LA, Volek JS, Bush JA, Marx JO, Dohi K, Gomez AL, Miles M, Fleck SJ, Newton RU, Hakkinen K.** Effect of resistance training on women's strength/power and occupational performances. *Med Sci Sports Exerc.* 2001;33:1011-25.
13. **Tropp H, Odenrick P.** Postural control in single-limb stance. *J Orthop Res.* 1988;6:833-9.
14. **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;24:765-73.
15. **Lephart SM, Riemann BL, Fu FH.** Introduction to the sensorimotor system. In: Lephart SM, Fu FH, editors. *Proprioception and neuromuscular control in joint stability.* Champaign, IL: Human Kinetics; 2000. p xvii-xxiv.
16. **Huston LJ, Wojtys EM.** Neuromuscular performance characteristics in elite female athletes. *Am J Sports Med.* 1996;24:427-36.
17. **McKeag DB.** Preseason physical examination for the prevention of sports injuries. *Sports Med.* 1985;2:413-31.
18. **Smith J, Laskowski ER.** The preparticipation physical examination: Mayo Clinic experience with 2,739 examinations. *Mayo Clin Proc.* 1998;73:419-29.
19. **Davies PS.** Assessment of cognitive development in adolescent motor performance by a means of neuropsychological assessments [dissertation]. Laramie, WY: University of Wyoming; 1995.
20. **Biro FM, Lucky AW, Huster GA, Morrison JA.** Pubertal staging in boys. *J Pediatr.* 1995;127:100-2.
21. **Biro FM, McMahon RP, Striegel-Moore R, Crawford PB, Obarzanek E, Morrison JA, Barton BA, Falkner F.** Impact of timing of pubertal maturation on growth in black and white female adolescents: The National Heart, Lung, and Blood Institute Growth and Health Study. *J Pediatr.* 2001;138:636-43.
22. **Davies PL, Rose JD.** Motor skills of typically developing adolescents: awkwardness or improvement? *Phys Occup Ther Pediatr.* 2000;20:19-42.
23. **Ford KR, Myer GD, Hewett TE.** Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc.* 2003; 35:1745-50.
24. **Myer GD, Ford KR, Hewett TE.** A comparison of medial knee motion in basketball players when performing a basketball rebound. *Med Sci Sports Exerc.* 2002;34(Suppl 1):S247.
25. **Winter DA, editor.** *Biomechanics and motor control of human movement.* 2nd ed. New York: Wiley-Interscience; 1990. p 41-5.
26. **Grood ES, Suntay WJ.** A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *J Biomech Eng.* 1983; 105:136-44.
27. **Espenschade AS.** *Motor performance in adolescence including the study of relatonships with measures of physical growth and maturity.* Monographs of the Society for Research in Child Development 5 (serial no. 24). Washington, DC: Society for Research in Child Development, National Research Council; 1940.
28. **Jones HE.** *Motor performance and growth: a developmental study of static dynamometric strength.* Berkeley, CA: University of California Press; 1949.
29. **Kellis E, Unnithan VB.** Co-activation of vastus lateralis and biceps femoris muscles in pubertal children and adults. *Eur J Appl Physiol Occup Physiol.* 1999;79:504-11.
30. **Hewett TE, Paterno MV, Myer GD.** Strategies for enhancing proprioception and neuromuscular control of the knee. *Clin Orthop.* 2002;402:76-94.
31. **Watkins J, Peabody P.** Sports injuries in children and adolescents treated at a sports injury clinic. *J Sports Med Phys Fitness.* 1996;36:43-8.
32. **Backous DD, Friedl KE, Smith NJ, Parr TJ, Carpine WD Jr.** Soccer injuries and their relation to physical maturity. *Am J Dis Child.* 1988;142:839-42.
33. **Tibone JE, Antich TJ, Fanton GS, Moynes DR, Perry J.** Functional analysis of anterior cruciate ligament instability. *Am J Sports Med.* 1986;14:276-84.
34. **Lloyd DG, Buchanan TS.** Strategies of muscular support of varus and valgus isometric loads at the human knee. *J Biomech.* 2001;34:1257-67.
35. **Markolf KL, Graff-Radford A, Amstutz HC.** In vivo knee stability. A quantitative assessment using an instrumented clinical testing apparatus. *J Bone Joint Surg Am.* 1978;60:664-74.
36. **Boden BP, Dean GS, Feagin JA Jr, Garrett WE Jr.** Mechanisms of anterior cruciate ligament injury. *Orthopedics.* 2000;23:573-8.
37. **Steele JR, Milburn PD.** Ground reaction forces on landing in netball. *J Hum Mov Stud.* 1987;13:399-410.
38. **Crenshaw SJ, Pollo FE, Calton EF.** Effects of lateral-wedged insoles on kinetics at the knee. *Clin Orthop.* 2000;375:185-92.