AJSM PreView, published on December 28, 2005 as doi:10.1177/0363546505281916

Maturation Leads to Gender Differences in Landing Force and Vertical Jump Performance

A Longitudinal Study

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Background: Female athletes have increased risk of anterior cruciate ligament rupture after the onset of puberty.

Hypotheses: Male athletes would demonstrate a longitudinal increase in vertical jump height compared with female athletes. There would be longitudinal gender differences in ground-reaction forces and loading rates.

Study Design: Cohort study; Level of evidence, 2.

Methods: Sixteen female and 17 male adolescent athletes were evaluated for 2 consecutive years. Subjects were included if they were classified as pubertal during the first year of testing and postpubertal during the second year. As subjects performed a drop vertical jump, ground-reaction force, and vertical jump height were measured. Data analysis consisted of a mixed design analysis of variance with post hoc analysis (paired *t* tests).

Results: The male athletes demonstrated increased vertical jump height with maturation ($P < .001$); female athletes did not. Boys significantly reduced their landing ground-reaction force ($P = .005$), whereas girls did not. Takeoff force decreased in girls ($P = .003$) but not in boys. Both boys and girls had decreased loading rates with maturation ($P < .001$); however, girls had higher loading rates than did boys at both stages of maturation ($P = .037$).

Conclusion: Male athletes demonstrated a neuromuscular spurt as evidenced by increased vertical jump height and increased ability to attenuate landing force. The absence of similar adaptations in female athletes may be related to the increased risk of anterior cruciate ligament injury.

Keywords: puberty; vertical jump height; ACL; landing forces; gender; neuromuscular

As children increase in biologic age, body height and weight increase, and subsequent maturation of the nervous, endocrine, muscular, and cardiovascular systems leads to alterations in neuromuscular performance.[5,43,45] With approximately half of all US children aged 5 to 18 years participating in organized sports programs[1] and an estimated one third of youths requiring medical attention for sports-related or physical activity–related injuries,[22] it is important to understand the effects of growth and development on sports performance and sports injuries. Equally important is the need to identify gender-related physical and physiologic differences that occur as a result of maturation, as these differences may help explain gender differences in strength, power, and coordination after the onset of puberty.[33] Because pubertal stages may be associated with both the occurrence and type of sports injury,[1,37,51] examination of the gender differences in neuromuscular performance during growth and maturation may help identify risk factors that lead to injury rate differences between the genders and may play an important role in the development of injury-prevention strategies.[25]

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Presented at the interim meeting of the AOSSM, Washington, DC, February 2005.

No potential conflict of interest declared.

The American Journal of Sports Medicine, Vol. 34, No. 5
DOI: 10.1177/0363546505281916

Epidemiologic evidence suggests that as adolescents mature, they experience a decreased likelihood of fracture and an increased rate of ligament sprain in the lower extremity.[1] Several studies have linked pubertal stage to type and incidence of injury sustained by children and adolescents. Michaud et al[37] reported that as children progressed through the stages of puberty, both boys and girls showed an increase in the occurrence of sports injuries. Tursz and Crost[51] noted that before puberty, both genders experience equal numbers of ligament sprains; however, at the age of 12 years, there is a distinct shift to girls demonstrating a higher incidence of ligament sprain than boys. More specifically, adolescent female athletes suffer anterior cruciate ligament (ACL) injury at a 4-fold to 6-fold higher rate compared with their male counterparts.[3,24,35] Also, ACL injuries are less frequent in prepubescent children than in adolescents, and no gender-related differences in ACL ruptures have been demonstrated before puberty.[2,9,19]

Most ACL injuries in female athletes are a result of noncontact mechanisms during landing or deceleration maneuvers.[8,49] Three theories have been identified as potential mechanisms underlying the gender differences in ACL injury rate: (1) anatomical, (2) hormonal, and (3) biomechanical.[27] Anatomical risk factors for ACL injury include narrow femoral notch, increased Q angle, and increased joint laxity.[20] Cyclic fluctuations in female hormones may be possible contributors to the gender disparity in ACL injury rates.[30,47,52] Biomechanical or neuromuscular differences between genders during sports-specific maneuvers have been identified, and these differences are considered to be ACL risk factors for female athletes.[15,17,26,28,48] In contrast to male athletes, adolescent female athletes demonstrate measurable neuromuscular imbalances in ligament dominance, quadriceps dominance, and dominant-to-nondominant leg differences, which lead to decreased dynamic knee stability.[27] High loading rates (high ground-reaction forces during a short period of time) combined with decreased lower extremity neuromuscular control are related to increased ACL injury risk in female athletes.[26] As adolescents mature, their anatomy, hormonal milieu, and movement biomechanics are dramatically altered, with boys and girls experiencing significantly different maturational effects.[5,33]

During the maturation process, both girls and boys undergo rapid growth. The long bones grow rapidly during puberty. This rapid growth leads to a significant increase in height for both genders. This pubertal height increase leads to longer levers and potential increases in torque at the knee joint. Peak growth in body mass for both genders generally occurs after peak height growth. Fat mass remains relatively stable for boys, with skeletal tissue and muscle mass gains primarily responsible for the observed mass increase.[5,33] In contrast, girls experience less dramatic gains in skeletal tissue and muscle mass compared with boys but demonstrate a continuous rise in fat mass during puberty.[5,33] The higher center of mass that results from skeletal growth and subsequent mass gain during adolescence makes muscular control of body position more difficult and may translate into larger joint forces at the knee.[25]

Although the anthropometric measures of growth and development show very similar trends between genders, male and female force production capabilities diverge significantly during and after puberty. Neuromuscular performance can be measured by static and dynamic strength, neuromuscular coordination, and balance using dynamometer tests, jumping tasks,[33,41] and landing and balancing tasks, respectively.[25,33,44] Boys demonstrate a neuromuscular spurt, whereas girls, on average, show little change throughout puberty.[5,33] The neuromuscular spurt may be defined as increased power, strength, and coordination that occur with increasing chronologic age and maturational stage in adolescent boys.[5,40] No similar correlations between height, weight, and neuromuscular performance are consistently demonstrated in pubescent girls. For example, vertical jump height increases steadily in boys during puberty but not in girls.[5,31,33] No gender differences in peak leg power are noted before age 14; however, boys demonstrate significantly greater power after that age.[36]

A plateau in girls' peak power occurs around 16 years of age.[36] The musculoskeletal growth during puberty, in the absence of sufficient neuromuscular adaptation to control the longer bony levers and greater mass, may increase neuromuscular imbalances. The lack of adaptation in female athletes may lead to inappropriate force attenuation strategies and limit force production capability during dynamic tasks.[23,25,40] The differences in neuromuscular performance between genders during and after puberty may be important contributors to forces on the knee, and altered biomechanics could potentially explain the increased risk of ACL injury in female athletes after the onset of puberty[46] and may help identify the optimal time to implement injury-prevention programs.[29,39]

The objectives of this study were to determine if vertical jump height and landing forces change during specific pubertal stages in male and female athletes. The first hypothesis was that boys would demonstrate a longitudinal increase in vertical jump height compared with girls. The second hypothesis was that longitudinal gender differences would be observed in ground-reaction forces and loading rates, with girls exhibiting higher ground-reaction forces and higher loading rates than boys.

MATERIALS AND METHODS

Subjects

This study was a prospective, controlled, longitudinal laboratory study. Subjects for this study comprised healthy preadolescent and adolescent male and female athletes from a local middle school and high school in a county school district just before the start of their competitive basketball seasons. An informed consent form was signed by a guardian of each subject and approved by the Institutional Review Board before screening. After informed consent was obtained, height and mass were recorded. Subjects were included in the study if they were classified as pubertal during the first year of testing and postpubertal during the second year of testing. No subjects had significant lower extremity injuries before the first year of testing or during the intervening year between testing. Sixteen female and

18 male adolescent athletes fulfilled the criteria for this study. One male athlete was excluded from the study because of a data collection error. No athletes dropped out of the study. All subjects listed basketball as their primary sport. Secondary sports listed by subjects included the following: 3 track, 9 soccer, 6 softball, 6 baseball, 4 football, 1 tennis, 1 swimming, and 1 golf. There were no differences in neuromuscular training experience between the female and male groups during either testing year. Ten of 16 girls had no prior training experience; 9 of 17 boys had no prior training experience during either testing year. Only 1 boy and 1 girl had jump training experience before testing.

The modified Pubertal Maturational Observational Scale (PMOS) was used to classify subjects into the 3 maturational categories, prepubertal (equivalent to Tanner stage 1), early pubertal (equivalent to Tanner stages 2 and 3), or postpubertal (equivalent to Tanner stages 4 and 5), and was assessed during each screening session using parental questionnaires and investigator observations. Only subjects classified as pubertal during the first year who transitioned to postpubertal during the second year were included in this study. In other words, all subjects were in Tanner stages 2 or 3 during the first year of the study and in Tanner stages 4 or 5 in the second year of the study. The PMOS was developed by Davies and Rose[11] to differentiate between prepubertal, early pubertal, and postpubertal stages based on indicators of pubertal maturation (growth spurt, menarchal status, body hair, sweating, and muscular definition). The reliability of the PMOS has been demonstrated to be high, and it can be used to classify subjects into developmental stages based on a parental report and investigator observation.[11,12,25]

Procedures

Each subject was instrumented as previously described for the drop vertical jump maneuver.[17] The subject was instructed to drop off the box, leave both feet at the same time, land, and then immediately perform a maximum vertical jump (Figure 1). Three trials were performed from a wooden box 31 cm high. Retroreflective markers placed bilaterally on the greater trochanter were used to calculate maximum jump height. The maximum vertical jump height was calculated as the difference in the vertical axis between the standing height and the maximum height during the vertical jump and averaged for each side. The 3 trials were averaged for analysis.

Two force platforms (AMTI, Watertown, Mass) were positioned 8 cm apart to ensure that each foot contacted a separate force platform. A 3D motion analysis system (Eagle cameras, Motion Analysis Corp, Santa Rosa, Calif) was used to record video and force data simultaneously.[17] Video was collected at 240 Hz, and force was collected at 1200 Hz. The first contact onto the platforms to the peak of the jump was used for analysis (Figures 1 B-D).

The entire stance phase was determined from initial contact to toe-off and further divided into the landing and takeoff phases.[18] Stance phase was subdivided into landing and takeoff phases based on estimation of the center of mass from double integration of the ground-reaction forces.

Figure 1. Representative photographs of the box drop vertical jump maneuver. A, subject's starting position; B, drop off the box; C, landing phase from initial contact to toe-off; D, maximum vertical jump height calculated as the difference in the vertical axis between the standing height and maximum height during the vertical jump; E, landing from vertical jump.

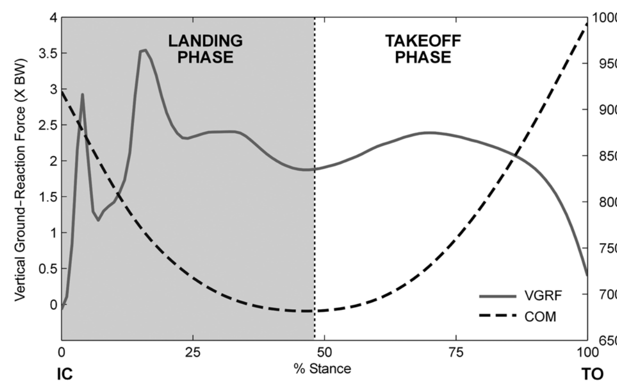

Figure 2. The landing and takeoff phases during the drop vertical jump maneuver. The 2 phases are divided by the lowest point of the center of mass.

Landing phase was defined as the portion of the maneuver from when the center of mass was moving downward, and the takeoff phase was defined as the center of mass moving upward until takeoff occurred (Figure 2).[7] Maximum vertical ground-reaction force was calculated during each phase and normalized to percentage of body weight (BW). Maximum force loading rate was calculated as the maximum landing force divided by the time from initial contact.[29] Data were analyzed with KinTrak software (Motion Analysis Corp).

Reliability Study

Five subjects participated in a 3-session between-day reliability assessment of the testing procedure. The sessions were held at approximately the same time of day and no more than 2 days apart. The reliability of the measurements of maximum vertical ground-reaction force at landing (intraclass correlation coefficient [ICC] = 0.899), maximum vertical ground-reaction force at takeoff (ICC = 0.983), and maximum vertical jump height (ICC = 0.986) was high.

TABLE 1
Subject Demographics (mean ± SD)

	Boys (n = 17)		Girls (n = 16)	
	Pubertal (Year 1)	Postpubertal (Year 2)	Pubertal (Year 1)	Postpubertal (Year 2)
Age, y	13.8 ± 1.4	14.8 ± 1.4	12.6 ± 1.0	13.6 ± 1.0
Height, cm	173.0 ± 9.2	177.0 ± 7.9	162.0 ± 7.9	165.7 ± 8.4
Mass, kg	62.6 ± 7.6	67.9 ± 5.5	47.5 ± 6.0	53.2 ± 6.2

Statistical Analysis

Statistical means and standard deviations were calculated for each subject. A repeated measures (pubertal stage × gender) analysis of variance (ANOVA) test to determine statistical significance was used to longitudinally compare vertical jump height between boys and girls ($P < .05$). A repeated measures ANOVA (pubertal stage × gender × side) was used to determine statistical significance between vertical ground-reaction force variables. Although overall significance was observed, follow-up post hoc paired t tests ($P < .05$) were employed. Statistical analyses were conducted in SPSS (SPSS Science Inc, Chicago, Ill).

RESULTS

Subject Characteristics

There were no significant differences between male and female groups with regard to mass and height changes from year 1 to year 2 (Table 1).

Vertical Jump Height

There was a significant pubertal stage by gender interaction in maximum vertical jump height, with a 7.3% increase in vertical jump height in boys and no increase in girls (boys: pubertal 43.6 ± 5.7 cm, postpubertal 46.8 ± 4.1 cm; girls: pubertal 35.0 ± 4.9 cm, postpubertal 35.0 ± 3.2 cm) ($F_{1,31}$ = 6.3, P = .018) (Figure 3). Post hoc paired t tests revealed that as boys progressed from the pubertal stage to the postpubertal stage, they significantly increased the height of their vertical jump (T_{16} = –4.0, P < .001) (Figure 3). Girls were not significantly different between the 2 stages (T_{15} = –0.1, P = .965).

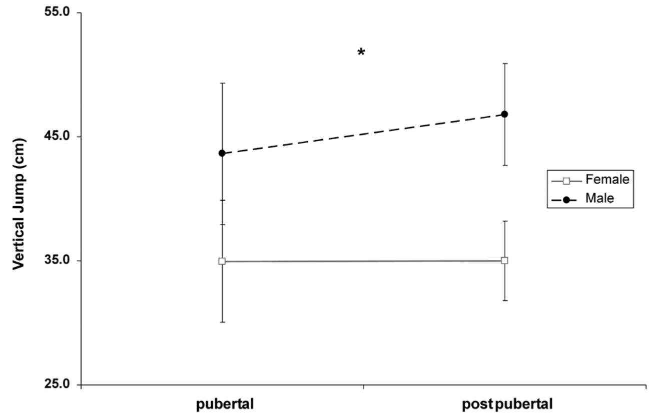

Figure 3. Comparison of maximum vertical jump height between boys and girls for year 1 (pubertal) and year 2 (postpubertal). *Significant pubertal stage × gender interaction, P = .018. Depicted values are mean ± 1 standard deviation.

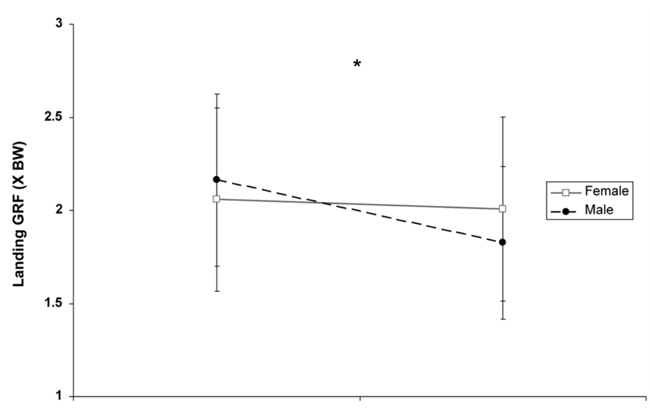

Figure 4. Comparison of maximum landing vertical ground-reaction force between boys and girls for year 1 (pubertal) and year 2 (postpubertal). Dominant and nondominant sides averaged; no differences between sides. *Significant pubertal stage × gender interaction, P = .046. Depicted values are mean ± 1 standard deviation.

Maximum Ground-Reaction Force

Maximum vertical ground-reaction force was identified for the landing and takeoff phases during the drop vertical jump. A significant pubertal stage by gender interaction was found for maximum landing vertical ground-reaction force ($F_{1,31}$ = 4.3, P = .046) (Figure 4). Post hoc paired t tests showed that boys significantly reduced their landing ground-reaction force on both the dominant (pubertal, 2.1BW ± 0.4BW; postpubertal, 1.9BW ± 0.5BW; T_{16} = 2.6; P = .021) and nondominant sides (pubertal, 2.2BW ± 0.5BW; postpubertal, 1.8BW ± 0.4BW; T_{16} = 3.3; P = .005) by 9.5% and 18.2%, respectively. Girls had no significant change during the landing phase on either the dominant (pubertal, 2.2BW ± 0.6BW; postpubertal, 2.2BW ± 0.4BW; T_{15} = 0.5; P = .63) or nondominant side (pubertal, 1.9BW ± 0.4BW; postpubertal, 1.9BW ± 0.5BW; T_{15} = 0.3, P = .75).

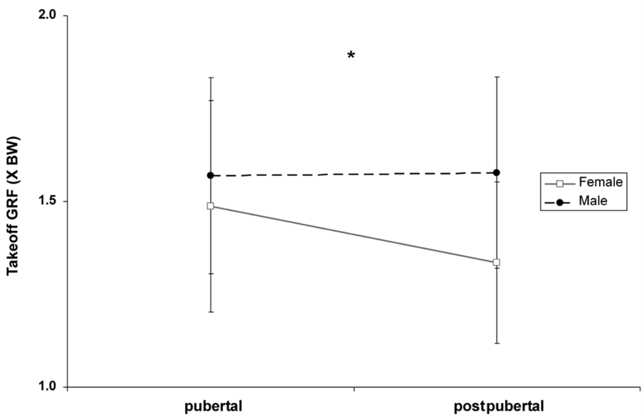

Figure 5. Comparison of maximum takeoff vertical ground-reaction force between boys and girls for year 1 (pubertal) and year 2 (postpubertal). Dominant and nondominant sides averaged; no differences between sides. *Significant pubertal stage × gender interaction, $P = .027$. Depicted values are mean ± 1 standard deviation.

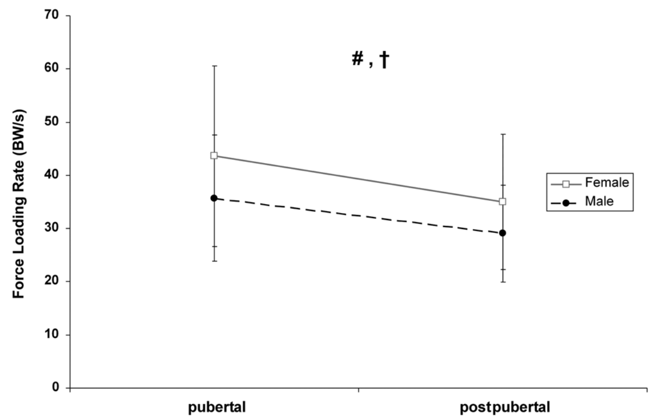

Figure 6. Comparison of force loading rate between boys and girls for year 1 (pubertal) and year 2 (postpubertal). Dominant and nondominant sides averaged; no differences between sides. #Significant main effect of pubertal stage, $P < .001$. †Significant main effect of gender, $P = .037$. Depicted values are mean ± 1 standard deviation.

A significant pubertal stage by gender interaction was also found during the takeoff phase ($F_{1,31} = 5.4$, $P = .027$) (Figure 5). In contrast to the landing phase, the female group showed a significant decrease in takeoff phase force with pubertal development. Post hoc analyses revealed that girls had significantly lower takeoff ground-reaction force on the dominant side (decrease of 6.7%) from the pubertal to the postpubertal stage (pubertal, 1.5BW ± 0.3BW; postpubertal, 1.4BW ± 0.3BW; $T_{15} = 3.5$; $P = .003$). The female nondominant side was not significantly different from the pubertal to the postpubertal stage (pubertal, 1.4BW ± 0.3BW; postpubertal, 1.3BW ± 0.2BW; $T_{15} = 2.1$; $P = .055$); however, a similar trend was found. There was no difference in normalized takeoff ground-reaction force in boys between the 2 stages of pubertal development (dominant side: pubertal, 1.6BW ± 0.3BW; postpubertal, 1.6BW ± 0.3BW; $T_{16} = –0.1$; $P = .91$; nondominant side: pubertal, 1.6BW ± 0.2BW; postpubertal, 1.6BW ± 0.2BW; $T_{16} = –0.2$; $P = .83$).

Ground-Reaction Force Loading Rate

A significant main effect of pubertal stage was found for the ground-reaction force loading rate ($F_{1,31} = 12.3$, $P < .001$) (Figure 6). Both boys and girls had decreased loading rates during the postpubertal stage compared with the pubertal stage. Girls, however, did show significantly greater loading rates during both stages compared with boys (gender main effect, $F_{1,31} = 4.7$, $P = .037$) (Figure 6).

DISCUSSION

Adolescent boys and girls demonstrate biomechanical and neuromuscular differences in lower extremity kinematics, kinetics, energy absorption, stiffness, and muscle strength during landing, cutting, and pivoting.[10,14,17,28,34] Adolescent girls demonstrate measurable neuromuscular imbalances of ligament dominance, quadriceps dominance, and dominant-to-nondominant leg differences, which lead to decreased dynamic knee stability.[17,27,28] Before puberty, lower extremity biomechanical neuromuscular differences are not apparent between genders.[5,25,33,44] Despite this divergence in neuromuscular patterns during maturation, only a small number of studies have compared the effects of maturation on gender differences in neuromuscular patterns and performance. Most of these reports are cross-sectional in nature.[13,31,45] The purpose of this study was to longitudinally compare changes in vertical jump height and landing ground-reaction forces in female and male athletes during maturation.

The results observed in this study confirmed the hypothesis that pubertal boys would experience longitudinal increases in vertical jump height during maturation, whereas girls would not (Figure 2). The pubertal stage by gender interaction was significant. Girls demonstrated no significant difference between year 1 and year 2 in vertical jump height, whereas boys showed a significant increase in vertical jump height between the 2 years. These data are consistent with previous studies that examined vertical jump height during maturation[6,31,33] and suggest that in contrast to boys, girls do not experience a neuromuscular spurt during puberty.

Boys maintained takeoff force during the jump despite their increased weight, and they increased their vertical jump height as they progressed through puberty. In contrast, girls significantly reduced their takeoff force as they matured. This gender-related difference further supports the hypothesis that male athletes generate greater lower extremity muscular power coincident with maturation, whereas female athletes do not. This finding suggests that neuromuscular spurt, which occurred naturally through puberty in boys in the current study, may be artificially induced through neuromuscular training in postpubertal girls.[28,41] Strong evidence demonstrates that movement biomechanics and lower extremity power can be altered in adolescent girls with neuromuscular training.[28,41]

The results of this study also confirmed the hypothesis that as they matured, female athletes would demonstrate higher ground-reaction forces and higher loading rates at landing compared with boys. Landing from jumps with high force or with inappropriate landing alignments likely places athletes at increased risk for injury.[15,26,28,48] A high ground-reaction force loading rate indicates that the athlete is subjected to high ground-reaction forces within a short period of time, making it difficult to adequately dissipate the forces reaching the knee joint.[29] Recent evidence demonstrates with high sensitivity and specificity that increased loading rates combined with decreased lower extremity coronal control are characteristic of athletes who are susceptible to an ACL injury.[26] Maturational development can lead to decreased lower extremity coronal plane control, which increases a female athlete's future risk of ACL injury.[25,26] Thus, the results of the current study indicate that female athletes' failure to improve neuromuscular performance in a manner similar to that of male athletes may be associated with puberty. The inability of female athletes to improve neuromuscular control in response to pubertal changes may be directly linked to the increased ACL injury risk that female athletes demonstrate in the adolescent years after the onset of puberty.[25,26,46]

The observed gender differences in lower extremity neuromuscular performance and landing mechanics associated with puberty support previously reported findings related to gender differences in growth and development. Studies of performance measures, such as vertical jump height, demonstrate steady increases in boys but not in girls during maturation.[5,31,33] Girls demonstrate decreased knee flexor torques, greater lower extremity valgus motion, and greater maximum valgus angle between each successive stage of maturation compared with boys.[25] Hass et al[21] showed that adult female recreational athletes land with greater knee extension, greater knee and hip extension moments and powers, and greater resultant forces at the knee compared with prepubescent female athletes. The biomechanical changes in female athletes that accompany puberty parallel the gender-specific biomechanical differences associated with increased ACL injury risk.[15,26,48]

The pubertal and postpubertal gender differences in landing mechanics, force absorption, muscle recruitment, and joint stability can be modified through neuromuscular training programs.[28,41,42,44] Because it appears possible to reduce ACL injury rates through neuromuscular training, neuromuscular factors are likely underlying mechanisms of increased risk for ACL injury.[24,26,42] A neuromuscular spurt in pubertal girls may be induced with neuromuscular training. Therefore, it may be important to identify high-risk female athletes before injury and to intervene with neuromuscular training targeted to their particular deficits.[38] Moreover, it is important to identify the optimal timing for intervention in young female athletes because it is unclear when training would be most efficacious and at what point female athletes become significantly more susceptible to ACL injury.

There are several limitations to the findings of the study. First, the pubertal classification system used for this study was not a gold standard measurement for determining maturational status. Although Tanner staging was not performed, the PMOS is considered to be a reliable approximation of pubertal status and a single rater performed all evaluations. The statistical differences found between maturational status and gender minimized this limitation of the study.[11,12,25] In addition, another limitation of the study was that the female and male groups were not height and weight matched. Although height-matched and mass-matched groups for each gender are preferred for comparison, both parameters are affected by the physical and physiologic changes that accompany puberty and vary significantly among persons at this age, making such groupings difficult. This limitation was minimized by the data normalization of height, mass, or both. Finally, although these data support the hypothesis that the neuromuscular differences between boys and girls shown in this study are related to knee injury risk, cause and effect cannot be established from this study. In spite of these limitations, the study was an accurate depiction of the gender differences in vertical jump height changes and relative landing forces that occurred during maturation.

We conclude that girls fail to demonstrate the neuromuscular spurt seen in boys during maturation. Increased relative landing forces in the absence of a neuromuscular spurt may be related to the peak incidence of ACL injuries in female athletes that occur close to the time of peak maturational development. Neuromuscular performance measures can increase within 6 weeks of training and may result in significant decreases in peak impact forces and abduction torques at the knee.[28,41] Dynamic neuromuscular training may reduce ACL injuries in adolescent[24] and mature female athletes.[42] In addition, neuromuscular training may increase measures indicative of a neuromuscular spurt in girls.[28,32,33,49] Intensive neuromuscular training significantly increases fat-free mass, vertical jump height, and balance measures in adolescent girls.[28,32,50]

Prepubertal athletes can improve lower extremity strength and power through short-term resistance training[16] and sport-specific training, respectively.[4] Targeted neuromuscular training, at or near the onset of puberty, may simultaneously improve lower extremity strength and power and reduce biomechanical parameters related to ACL injury risk.[26,38] These reports suggest the benefits of neuromuscular training for prepubertal and early pubertal children.

Because the athletic female population has a marked increase in ACL rupture after their growth spurt and into maturity, in contrast to the similar injury rates between genders in the pediatric population, changes that occur during puberty likely play a role in this injury disparity.[46] Although anatomical and hormonal changes during puberty may increase a female's risk for injury, the ability to change or develop intervention strategies based on these physiologic changes is both difficult and controversial. On the contrary, biomechanical and neuromuscular factors related to injury risk may provide the greatest opportunity for the identification of high-risk athletes and the development of optimal, targeted neuromuscular intervention training. Future studies should focus on the determination of the specific maturational stage when female athletes become more susceptible to ACL injury, prospective identification of female athletes who are more susceptible to injury, and optimization of the timing and effectiveness of ACL-prevention strategies.

ACKNOWLEDGMENT

The authors acknowledge funding support from National Institutes of Health grant R01-AR049735-01A1 (T.E.H.). The authors thank Boone County School District, Kentucky, especially School Superintendent Dr Brian Blavatt, for participation in this study. The authors also acknowledge Bob Mangine and Dr John Divine for their contributions to this study.

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