LONGITUDINAL INCREASES IN KNEE ABDUCTION MOMENTS IN FEMALES DURING ADOLESCENT GROWTH

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ABSTRACT

HEWETT, T. E., G. D. MYER, A. W. KIEFER, and K. R. FORD. Longitudinal Increases in Knee Abduction Moments in Females during Adolescent Growth. Med. Sci. Sports Exerc., Vol. 47, No. 12, pp. 2579–2585, 2015. Purpose: Knee abduction moment (KAM) is an injury risk factor for anterior cruciate ligament (ACL) injury that shows divergent incidence between males and females during adolescence. The objective of this study was to determine the relation between skeletal growth and increased KAM. The hypotheses tested were that females would demonstrate peak KAM during landing at peak height velocity (PHV) and that they would diverge from males at PHV. Methods: The subject pool consisted of 674 females and 218 males (1387 female and 376 male assessments) who participated in a preseason testing session before their basketball or soccer seasons. They were tested longitudinally for multiple years (2 ± 1 yr) to capture maturation via estimates of percent (%) adult stature and biomechanical analysis during a drop vertical jump maneuver. Data were analyzed using three-dimensional motion analysis that used a 37 retroreflective marker body model and inverse dynamics to calculate segment joint centers and peak KAM. Results: Mature females, as defined as 92% adult stature or greater, displayed increased peak KAM and knee abduction angles relative to growing (≤91% adult stature) adolescent females (P < 0.001). A significant sex-maturation (% adult stature) interaction (P < 0.001) in peak KAM was observed. Post hoc analyses showed consistent sex differences in groups greater than or equal to, but not less than, 92% adult stature, which is approximately at PHV. Hence, sex differences in peak KAM and PHV coincide. Conclusions: Increases in peak KAM during and after PHV seem to coincide with increased risk of ACL injury in females. KAM peaked in females at PHV. Tracking longitudinal increases in peak KAM may be useful for the identification of females at increased risk of ACL injury. Key Words: ACL injury, neuromuscular control, imbalance, injury prevention, sex differences

A
dolescent females who participate in landing, cutting, and pivoting sports experience anterior cruciate ligament (ACL) injuries at a two- to 10-fold greater rate than adolescent males who participate in these same high-risk sports. Since the passage of Title IX of The US Educational Assistance Act, male participation at the high school level has increased under 3% (from 3.7 to 3.8 million) whereas female participation has increased over ninefold, roughly doubling every 10 yr (from 0.3 to 3.4 million). This geometric growth in female sports participation, coupled with the two- to 10-fold higher injury rate, has led to a near-epidemic increase in the number of ACL injuries in female athletes. More than 125,000 ACL injuries occur in the United States annually. ACL surgery and rehabilitation costs well exceed $1 billion annually in varsity female sports in the United States, and this is accompanied by a more alarming 50%–100% prevalence of osteoarthritis in this high-risk population (15,18,26,33). Knee injuries frequently occur in the pediatric athlete. In children age 6–12 yr, 63% of sports-related injuries are classified as joint sprains, with most sprains occurring at the knee (13). However, ACL sprains are rarer in prepubescent children than in adolescents and ruptures do not present at significantly different rates in males and females before adolescence (1,4,5). After the onset of adolescence, which parallels the rise in the sex disparity in ACL injury incidence, both females and males experience rapid musculoskeletal
growth (27). During this adolescent growth spurt, the long bones of the lower extremity, the tibia and femur, grow at a rapid rate in both males and females (38). This growth of the tibia and femur leads to longer lever arms at the two longest boney levers in the human body, which translates into greater potential for increased torques on an athlete’s knee joint. Subsequent height and weight increases lead to a higher center of mass and greater body mass, and this makes muscular control of the body more challenging. In addition, as the height of the center of mass increases, the athlete’s ability to balance and dampen forces during high-velocity athletic movements becomes more difficult and injury risk increases.

After the onset of adolescence, males exhibit increases in power and strength with chronological age that correlate to maturational stage whereas females show little change in these neuromuscular parameters throughout adolescence (21,28). For example, Kellis et al. (21) performed a cross-sectional study on male and female basketball players, and results indicated that female basketball players did not significantly increase vertical jump performance with increasing age whereas male players showed significantly greater scores with age. Female athletes often demonstrate decreased dynamic knee stability compared with adolescent males after their rapid growth spurt (10,16,19,35). The increase in height and weight in the absence of corresponding increases in lower extremity bone length that occur during adolescence, in the absence of sufficient neuromuscular adaptation to dampen the increased forces and torques, may lead to increased dynamic knee stability. This study tested the hypothesis that the rapid increases in lower extremity bone length that occur during adolescence, in the absence of sufficient neuromuscular adaptation to dampen the increased forces and torques, are related to a decrease in dynamic knee stability in female athletes. The hypothesis tested was that growth, as measured by peak height velocity (PHV), would correlate to high joint load biomechanics that results in poor dynamic knee stability, as measured by peak KAM, in female athletes. To the authors’ knowledge, no previous studies have examined the relation of peak KAM to PHV, percent adult stature, maturational status, or age.

**METHODS**

**Subjects.** This investigation was a longitudinal/cross-sectional controlled laboratory study. Participants in this study were healthy male and female children and adolescents screened relative to predetermined inclusion/exclusion criteria. Subjects were excluded from the study if they were not enrolled in a school-sponsored basketball or soccer team. Athletes who had previous ACL injury were also excluded from the study. Female and male basketball and soccer players (892 subjects, 674 female participants and 218 male participants; 1763 visits, 1387 female and 376 male visits) (Table 1) from middle schools and high schools in a single county school district volunteered to participate in this study, with the range of repeat measures between one and six, with an average of two. Subjects ranged in age from 10 to 18 yr.

| % Adult Stature | Female | | Male | | |
|---|---|---|---|---|---|
| | Height (cm) | Mass (kg) | Height (cm) | Mass (kg) |
| 82 | 143.6 (141.9–145.3) | 36.3 (34.1–38.5) | 150.2 (148.5–152.0) | 41.8 (39.6–43.9) |
| 84 | 148.5 (147.5–149.4) | 40.8 (39.2–42.4) | 154.6 (153.0–156.2) | 44.2 (42.2–46.2) |
| 86 | 154.0 (153.0–155.0) | 46.6 (44.7–48.5) | 158.7 (156.2–161.1) | 47.3 (43.9–50.6) |
| 88 | 156.8 (155.8–157.6) | 48.4 (46.9–49.8) | 163.3 (161.1–165.5) | 54.3 (51.3–57.3) |
| 90 | 159.9 (159.0–160.8) | 52.9 (52.1–55.6) | 166.4 (165.2–169.0) | 57.0 (52.9–61.7) |
| 92 | 161.2 (160.3–162.0) | 54.6 (53.0–56.1) | 169.6 (168.8–172.5) | 57.1 (53.6–60.7) |
| 94 | 163.1 (162.3–164.0) | 57.6 (56.2–59.0) | 173.4 (171.6–175.2) | 63.4 (60.7–66.0) |
| 96 | 164.4 (163.5–165.2) | 59.5 (58.3–60.7) | 177.6 (175.5–179.6) | 69.1 (66.1–72.1) |
| 98 | 165.0 (164.2–165.8) | 60.8 (59.5–62.1) | 180.3 (178.1–182.6) | 70.7 (67.8–73.5) |
| 100 | 165.3 (164.1–166.4) | 61.6 (60.7–63.5) | 182.0 (179.1–185.0) | 75.5 (71.9–79.1) |

Data are presented as means (95% confidence interval).
An informed written consent was obtained from the parent or guardian, and assent was obtained from the subject. The data collection procedures were approved by the institutional review board. After informed consent was obtained, height and mass were recorded and anthropometric measures were recorded during the same laboratory evaluation.

**Percent adult stature and PHV.** Percent adult stature was estimated on the basis of the Khamis–Roche regression equation method developed from the Fels Longitudinal Study that collected data from families residing in southwestern Ohio: a similar geographic region to the one from which the current cohort was drawn (23). The subject’s stature, mass, midparental stature, and age were used to develop regression equations for boys and girls. Percent adult stature was then calculated and used as a somatic indicator of maturity (27). A regression technique has been developed to estimate PHV on the basis of additional measurements (23). The Khamis–Roche method of PHV was developed from the Fels Longitudinal Study that collected data from families residing in southwestern Ohio (23). The subject’s stature, mass, midparental stature, and age were used to develop regression equations for boys and girls. These authors demonstrated that PHV occurs at 91% to 92% adult stature.

**Three-dimensional kinematic and kinetic motion analysis.** Three-dimensional (3D) hip, knee, and ankle kinematic and kinetic data were quantified for the contact phase of three drop vertical jump (DVJ) tasks. Each subject was instrumented by a single investigator with 37 retroreflective markers placed on the sacrum, left posterior superior iliac spine, and sternum and bilaterally on the shoulder, elbow, wrist, ASIS, greater trochanter, midthigh, medial and lateral knee, tibial tubercle, midshank, distal shank, medial and lateral ankle, heel, dorsal surface of the midfoot, lateral foot (fifth metatarsal), and toe (between the second and third metatarsals). As indicated previously, a static trial was conducted, in which the subject was instructed to stand still with foot placement standardized to the laboratory coordinate system. This static measurement was used as each subject’s neutral (zero) alignment; subsequent kinematic measures were referenced in relation to this position (9). The DVJ involved the subject starting on top of a box (31 cm high) with their feet positioned 35 cm apart. They were instructed to drop directly down off the box and immediately perform a maximum vertical jump, raising both arms while jumping for a basketball rebound (8).

All trials were collected by a single investigator with EvaRT (version 4; Motion Analysis Corporation, Santa Rosa, CA) using a motion analysis system consisting of 10 digital cameras (Eagle Cameras; Motion Analysis Corporation, Santa Rosa, CA) positioned in the laboratory and sampled at 240 Hz. Before data collection, the motion analysis system was calibrated on the basis of the manufacturer’s recommendation. Two force platforms (AMTI, Watertown, MA) were sampled at 1200 Hz and time-synchronized with the motion analysis system. The force platforms were embedded into the floor and positioned 8 cm apart, so that each foot would contact a different platform during the stance phase of the DVJ (9).

**Data analysis.** After data collection, the motion and force data were further analyzed in Visual3D (version 4.0; C-Motion, Inc.). The procedures within Visual3D first consisted of the development of a static model customized for each subject (9). 3D marker trajectories from each trial were filtered at a cutoff frequency of 12 Hz, and the data from the three trials were averaged (9). 3D knee joint angles were calculated according to the Cardan/Euler rotation sequence (6). Kinematic and force platform data were used to calculate knee joint moments using inverse dynamics (41). The ground reaction force data were filtered through a low-pass fourth-order Butterworth filter at a cutoff frequency of 12 Hz to minimize possible impact peak errors (3,40). Net external knee moments were described in this article and represent the external load on the joint. Although abduction motion and moments were calculated as negative values, these are presented in the tables and figures as positive values for angles for clarity of presentation. Lower extremity kinetics and kinematics were calculated during the deceleration phase of landing from the stance phase of the DVJ. The deceleration phase was operationally defined from initial contact (vertical ground reach on force first exceeded 10 N) to the lowest vertical position of the body center of mass. The left side data were used for statistical analysis. The goal of the investigation was to assess peak values. The left side data were used because peak KAM was observed in this population to be higher on the left side. The described biomechanical landing analysis techniques and measures, including peak KAM, have demonstrated to be reliable measurements (9).

**Statistical analysis.** Statistical means and SEM values for each variable were calculated for each subject group. Subjects were grouped into 10 maturational groups from 81% to 100% of adult stature (e.g., 81–82, 83–84, ..., 99–100). A two-way ANOVA was used, with sex (male and female) and maturation (10 levels) as the independent variables. The dependent variables were knee abduction load and knee angle. A Pearson correlation coefficient was used to determine the relation between segment length (femur and tibia) and knee abduction (moment and angle) in male and female subjects. An $\alpha \leq 0.05$ indicated statistical significance. Statistical analyses were conducted in SPSS version 16.0 (SPSS Inc., Chicago, IL). The post hoc comparisons between the females and males at the 10 individual time points were controlled for multiple testing using the least significant difference technique in SPSS.

**RESULTS**

A significant interaction between sex and maturation was observed for peak KAM ($P = 0.025$). Figure 1 demonstrates that maturation resulted in greater KAM in female but not in male athletes. Post hoc analyses indicated consistent sex differences in groups after 92% of adult stature, which is just
after PHV and occurs near 91% of adult stature, in KAM (Table 2).

A significant interaction between sex and maturation was also observed for knee abduction angle (KAA) ($P = 0.001$). Figure 2 shows that with maturation, there was greater KAA observed in females than that in males. Post hoc analyses showed consistent sex differences in groups greater than 92% of adult stature in KAA (Table 3). Hence, sex differences in peak KAM and KAA also coincide with PHV.

Figure 3 demonstrates that an association was observed between increased tibia length and increased KAM in females. Significant correlations were observed between peak KAM and tibia ($r = 0.431$, $P < 0.001$) and between peak KAM and femur length ($r = 0.254$, $P < 0.001$) in females. This relation indicates that as segment lengths are increased, knee abduction magnitude is also increased in females. Significant, though weaker, correlations were observed in males between peak KAM and in tibia ($r = 0.276$, $P < 0.001$) and femur ($r = 0.119$, $P < 0.05$) length.

With increased lower extremity bone length that accompanies maturation, associations with greater KAM were observed in female but not in male participants. Statistically significant correlations were observed between KAM and tibia ($r = 0.232$, $P < 0.001$) and femur ($r = 0.115$, $P < 0.001$) length in female athletes. Male athletes did not demonstrate significant correlations between KAA and tibia ($r = 0.035$, $P = 0.05$) and femur ($r = -0.093$, $P = 0.05$) length.

**DISCUSSION**

Increases in dynamic knee load in adolescent athletes. The current study findings demonstrate that peak KAM increases in both females and males after the onset of adolescence. However, after the neuromuscular spurt at 91% adult stature (the time point of the occurrence of PHV), males regain dynamic knee control whereas dynamic knee stability in females continues to decrease. These observations support the more general hypothesis that rapid increases in lower extremity bone length that occur during adolescence, in the absence of sufficient neuromuscular adaptation, are related to decreased dynamic knee stability and increased joint torque loads in female athletes. Females also displayed valgus load of similar amounts to those of males at preadolescence and early adolescence but greater valgus load compared with that of males at late adolescence. This study indicates that biomechanical changes during adolescence are

### TABLE 2. KAM during DVJ landing.

| % Adult Stature | Female (Nm) | Male (Nm) | Post Hoc ($P$ Value) |
|-----------------|-------------|-----------|----------------------|
| 82              | 13.3 (16.1–10.5) | 13.3 (16.1–10.5) | 0.88 |
| 84              | 12.4 (14.8–9.9)  | 15.8 (18.6–13.1) | 0.07 |
| 86              | 18.2 (20.3–16.1) | 17.5 (21.4–13.5) | 0.75 |
| 88              | 20.1 (22.9–17.9) | 19.0 (22.9–15.1) | 0.63 |
| 90              | 21.8 (23.9–19.7) | 18.8 (23.9–13.6) | 0.25 |
| 92              | 22.6 (24.6–20.5) | 20.5 (28.4–12.0) | 0.47 |
| 94              | 24.9 (27.3–22.5) | 18.4 (23.4–13.5) | 0.022 |
| 96              | 25.8 (28.1–23.6) | 16.6 (21.3–11.9) | 0.002 |
| 98              | 23.6 (25.7–21.5) | 17.8 (23.5–12.1) | 0.031 |
| 100             | 25.2 (28.7–21.7) | 16.8 (24.3–9.3)  | 0.037 |

Data are presented as means (95% confidence interval).

### TABLE 3. KAA during DVJ landing.

| % Adult Stature | Female (°) | Male (°) | Post Hoc ($P$ Value) |
|-----------------|------------|----------|----------------------|
| 82              | 9.4 (11.1–7.7) | 8.4 (10.1–6.6) | 0.41 |
| 84              | 7.4 (9.0–5.9)  | 9.1 (10.6–7.5) | 0.16 |
| 86              | 9.7 (10.8–6.6) | 9.0 (11.1–6.8) | 0.55 |
| 88              | 10.5 (11.7–9.4) | 8.2 (10.4–6.1) | 0.07 |
| 90              | 9.8 (10.8–8.8) | 8.0 (10.5–5.5) | 0.15 |
| 92              | 10.4 (11.4–9.5) | 8.0 (11.1–5.5) | 0.10 |
| 94              | 10.6 (11.4–9.7) | 6.2 (7.9–4.6)  | <0.001 |
| 96              | 10.4 (11.2–9.5) | 6.3 (8.0–4.6)  | <0.001 |
| 98              | 8.9 (9.7–8.0)  | 5.1 (6.7–3.4)  | <0.001 |
| 100             | 9.0 (10.1–7.8) | 3.6 (5.8–1.8)  | <0.001 |

Data are presented as means (95% confidence interval).
likely to underlie changes in dynamic knee stability and potentially contribute to the increased risk of ACL injury that is present after the onset of maturation.

**Mechanisms of ACL injury in adolescent female athletes.** The findings of the current study indicate that females demonstrated increased peak KAM during adolescence, which is likely indicative of altered neuromuscular control of lower extremity motion in the coronal plane. This may reflect changes in contraction patterns of the adductors and abductors of the hip and knee (24), and muscular contraction can decrease the valgus laxity of the knee threefold (29). The present findings support the hypothesis that growth and development decrease dynamic stability of the female’s knee. Specific sprains such as injuries to the ACL are relatively rare and do not represent sex differences in children before their growth spurt (1,4,5). However, after the growth spurt, female athletes have higher rates of knee sprains, and this trend continues into maturity (39). In addition to increased injury prevalence that peaks at age 16, female athletes also demonstrate incremental increases in peak KAM as they increase in chronological age. Interestingly, the knee abduction loads that are related to increased knee injury risk also peak concurrently at age 16 in female athletes (7,37). These data demonstrate a relation between maturational development and the tendency for high-risk female athletes to demonstrate a preferential, increased frontal plane load strategy as opposed to a sagittal plane load absorption strategy via increased muscle activation in flexion–extension during dynamic sport-related activities. Preferential loading in the frontal plane and increased peak KAM during competitive play limit desirable sagittal plane mechanics, destabilize the knee, load the ACL, and increase knee injury risk in adolescent female athletes (8,11,12,17,20,22,25,30–32).

**Need for injury prediction measures in adolescent female athletes.** We now have the measurement capabilities to measure differences in knee load in the high-risk adolescent and mature female sports populations. The data show that peak KAM knee load can be reliably measured with 3D kinetic analysis (10). Such an analysis may be used as a measure of dynamic knee stability, as 3D analysis of valgus peak KAM provides an objective screening technique for biomechanical loading and control of the knee joint. It has been suggested that there is a need for the implementation of neuromuscular and proprioceptive testing before participation to allow the identification of at-risk female athletes (14). A very timely and appropriate question that needs to be answered then is whether it is possible to delineate a high-risk female subgroup among adolescent females. The high-risk biomechanics detailed previously may be especially prevalent in a subgroup of females who are more susceptible to knee injury than other female athletes.

Other factors such as age, height, and body mass index have been reported to correlate with injury (2,4). Specifically, a study at West Point demonstrated that height, weight, and body mass index were significant indicators of ACL injury risk in female Army recruits (36). Other preliminary studies indicate that height and weight are predictors of knee injury risk in adolescent females (4), and Beynnon et al. (2) reported that thigh length was a predictor of ACL injury risk in skiers. The biomechanical alterations we have demonstrated with growth and maturation in the present study, combined with the biomechanical indicators implicated in epidemiologic studies such as those mentioned previously, may provide the foundation for an algorithm that could prove highly predictive of relative injury risk. The current findings demonstrate that after the onset of the adolescent growth spurt, increases in tibia and femur length in the absence of increased knee...
flexor strength and recruitment lead to high joint load biomechanics and decreased dynamic knee stability in female athletes.

**Limitations.** This musculoskeletal disorder is likely multifactorial with unmeasured factors influencing outcome, as injury data demonstrate that many physical and psychological parameters affect injury rates. There are several possible contributing and confounding variables that were not controlled for in the study design. These included school, team, age/grade, aggressiveness, foot pronation, quadriceps angle, femoral notch width, and blood hormone levels. Regardless, neuromuscular parameters seem to be a major determinant of injury risk and are the only potential factor that is readily alterable. Another limitation was with the observed significant effects of maturity status on active knee stability. The expected differences were of a magnitude outside of the protocol’s measurement error. The inclusion of only soccer and basketball players is a limitation to the generalizability of the findings of this study. However, gender differences in injury incidence have been demonstrated in several sports, including basketball, soccer, lacrosse, team handball, and volleyball. Differences in neuromuscular control measures likely exist in most gender-paired sports. Therefore, the associations between adolescent stage, neuromuscular control measures, and injury in adolescent basketball and soccer players should be comparable with those found in adolescent athletes participating in other sports.

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**CONCLUSIONS**

The findings demonstrate that growth plays an important role in the mechanism of increased dynamic peak KAM—a potentially important predictor of ACL injury. Methods to identify the female athletes who exhibit increased dynamic peak KAM are outlined. It is likely that a significant proportion of the female sports population demonstrates increased dynamic peak KAM and may require intervention. Prevention of female ACL injury from two to 10 times, to equal the rate of males, would allow tens of thousands of young females to continue the health benefits of sports and avoid the long-term complications of osteoarthritis, which occurs at a tenfold greater incidence than in the uninjured population.

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