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

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Abstract

Introduction—Females have been reported to have a 3-5 times greater incidence of non-contact ACL injury when compared to 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—To determine if lower extremity biomechanics differ between male and female soccer athletes during a cutting maneuver across different stages of maturational development.

Methods—One hundred and fifty six soccer players (76 male and 80 females) between the ages of 9 and 23 participated. Subjects were classified based on maturation as pre-pubertal, pubertal, post-pubertal or young adult. Lower extremity kinematics, kinetics and ground reaction forces (GRF) were obtained during a 45 degree side-step cutting maneuver. Differences between sex and maturation were assessed for peak knee valgus angle, knee adductor moments and GRF's (vertical, posterior and lateral) during weight acceptance using a 2 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. Pre-pubertal athletes demonstrated greater knee adductor moments and GRFs than all other groups.

Conclusion—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.

Keywords

puberty; cutting; locomotor skills; kinematics; kinetics

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Introduction

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 and colleagues 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 14-18. Only 10% of claims were made for children under the age of 14. (12, 31) This is consistent with data from the American Board of Orthopaedic Surgery's database that found the majority of ACL reconstructions were performed on high school aged patients between the ages of 14 and 18. (12, 31) In this group, high school and college age, females have been reported to have a 3-5 times greater incidence of non-contact ACL injury when compared to their male counterparts.(1, 24, 26)

Sex related differences in lower extremity biomechanics during the performance of athletic tasks is one factor thought to contribute to the disproportionate incidence of ACL injury in females.(13) While 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 (39) as well as smaller knee flexion angles (20, 22, 39) when compared to their males counterparts during tasks that require deceleration and change of direction. This differences may be particularly important as a prospective study found that females who tore their ACL had significantly greater knee abduction angles, adductor moments and vertical ground reaction forces during a drop land task when compared to those who were not injured.(16) Additionally, reduced knee flexion combined with a greater posteriorly directed GRF during the deceleration phase of landing are 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 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, while males have larger increases in lean muscle mass. (2, 35) A marked acceleration in strength occurring approximately one year after peak height and weight velocities in males magnifies the relatively small pre-adolescent 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 to 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 pre-pubertal females. These differences however, have not been noted between pre-pubertal 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 as 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 re-orientation and re-direction 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 if lower extremity kinematics and kinetics differ between male and female soccer athletes during a cutting maneuver across different stages of maturational development. Based on 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 post-pubertal group. More specifically, we hypothesized that post-pubertal females would exhibit higher knee adductor moments, greater knee valgus angles, and greater ground reaction forces when compared to post-pubertal males.

Materials and methods

Subjects

One hundred and sixty soccer players participated in this study. An *a prior* power analysis using previously collected kinematic and kinetic data for males and females indicated that between 18-20 subjects per group were needed to detect differences between sexes with a power level of 80% and an alpha of 0.05. Data from four subjects were excluded from the analysis due to incomplete kinematic data from poor marker visualization throughout the task. As such, one hundred and fifty six participants (76 male and 80 females) between the ages of 9 and 23 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 days a week. 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 effect lower extremity biomechanics including : 1) history of previous ACL injury, 2) history of any ankle, knee or hip surgery 3) 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 based on their stage of maturational development: pre-pubertal, pubertal, post-pubertal or young adult (Table 1). As 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 generally used to classify pubertal stages. While 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 under the age of 18 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 pre pubertal, 2-4 as pubertal, and 5 as post-pubertal or young adult. Post-pubertal and young adult groups were further differentiated by age. Participants over the age of 18 (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 Pubertal Maturation Observational Scale (PMOS).(9) The PMOS categorization is based on an unobtrusive observation of 8 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. Based on the number of items identified on the PMOS questionnaire, subjects were classified as follows: 1 or less: pre-pubertal; 2-5 with growth spurt: pubertal; 6 or greater with growth spurt completed: post-pubertal. A growth spurt was defined as an increase in height 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 Health Sciences Institutional Review Board of the University of Southern California. Parental consent and youth assent were obtained for all subjects under the age of 18.

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) where used to quantify segment motion. Ground reaction forces were obtained using an AMTI force platform at a rate of 1500 Hz (Model #OR6-61, Advanced Mechanical Technologies, Inc., Newton, MA, USA).

Reflective markers were placed bilaterally over the following anatomical landmarks: 1st and 5th 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 following a static calibration trial. To control for the potential influence of varying footwear, subjects were fitted with same style of cross-training shoe (New Balance Inc., Boston, MA, USA).

Each participant performed four trials of a randomly cued side-step cutting maneuver. Subjects were instructed to run seven meters at a speed of 4-5.5 m/s contact their dominant foot on the force platform and perform one of 3 tasks: change direction to the opposite side at 45° angle, 110° angle or continue straight ahead (Figure 1). A light signal was activated three meters prior to 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 pre-determined speed. Practice trials allowed subjects to become familiar with the procedures and instrumentation. Data from the 45° angle change of direction task was considered for analysis.

Data Analysis

Coordinate data were digitized using Vicon Workstation software and filtered using a fourth-order zero-lag Butterworth 12-Hz low-pass filter. Visual3D™ software (C-Motion, Inc., Rockville, MD, USA) 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 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 was determined from the segment's triad of reflective markers. The kinematics of the 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 as it the period of the in the cycle where the majority of non-contact 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 ANOVA's (sex × maturation). While all groups performed the task within the preset range of approach velocities; between subject differences have the potential to effect ground reaction forces and net joint moment calculations. Therefore, differences between sexes and across the different stages of maturation were evaluated using multiple 2 × 4 ANCOVA's (sex × maturation), co-varying 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 (LSD) post-hoc testing was performed. All statistical analyses were performed using SPSS statistical software (Chicago, IL, USA v.18) 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). While no sex differences in height and weight were noted in pre-pubertal and pubertal groups, post-pubertal 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 years older than females and had 1.3 years 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 pre-pubertal athletes performed the task at a slower approach velocity (4.6 ± 0.05 m/s) than pubertal (4.9 ± 0.05 m/s), post-pubertal (5.02 ± 0.05 m/s) and young adults (4.8 ± 0.05 m/s).

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 (Figure 2). When collapsed across maturation groups, females demonstrated significantly greater peak knee adductor moments than males (Figure 2B). When collapsed across sex, post-hoc testing revealed that pre-pubertal athletes exhibited greater peak knee adductor moments than the pubertal (P=0.01), post-pubertal (P<0.001) and young adult athletes (P<0.001; Figure 2C). Pubertal athletes exhibited greater moments than post-pubertal (P=0.01) and young adult athletes (P<0.001; Figure 2C). No significant interactions or main effects were found when the non-normalized knee adductor moment data were analyzed (Figure 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, Figure 4) and maturation (P=0.007, Figure 3) was found for the peak knee valgus angle. When collapsed across maturation groups, females demonstrated significantly greater peak knee valgus angles than males (Figure4B). When collapsed across sex, post-hoc testing revealed that young adult athletes exhibited smaller peak knee valgus angles than the pre-pubertal (P=0.01), pubertal (P=0.01) and post-pubertal athletes (P=0.01; Figure 4C).

No sex × maturation interactions were observed for vertical (P=0.36, power=0.29), posterior (P=0.67, power=0.15) 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, pre-pubertal athletes exhibited greater peak vertical, posterior and lateral ground reaction forces than the pubertal, post-pubertal and young adult athletes (Figure 5 A-C).

Discussion

While 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 to males. When collapsed across maturation groups, females exhibited 20% higher knee adductor moments and nearly twice the amount of knee valgus when compared to males.

Surprisingly, our results did not support the hypothesis that sex differences in cutting biomechanics would emerge post-puberty as 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) While 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 pre-pubertal athletes (Cohen's *d* effect size=0.76), with smaller sex differences noted in more mature athletes (Cohen's *d* effect size=0.001, 0.19, 0.47: pubertal, post-pubertal and young adult, respectively; Figure 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 appear to exist. During landing from a jump, pubertal and post-pubertal athletes have been shown to exhibit increased frontal plane knee loading and altered shock attenuation strategies during landing compared to pre pubertal athletes (11, 15, 32, 40). In the current study, an opposite pattern was noted in that pre-pubertal athletes exhibited larger knee adductor moments and GRF's when compared to the pubertal and post-pubertal groups.

In general, the pre-pubertal 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)

The discrepancy in maturation differences reported in the current study for side-step cutting compared to 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 re-direction of the body center or mass (17, 18). Previous studies have reported that when compared to young adults, children (9-11 years) utilize less efficient steering and re-orientation 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 to 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 pre-pubertal athletes performed the tasks with a slightly slower average approach velocity. However, this did not appear to affect the results as we found the same group differences when the data was 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 contribute to the differences in performance noted between maturation groups.

While 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 ground reaction forces suggest that pre-pubertal athletes utilize 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 to 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 pre-pubertal athletes may be warranted. However, this study design was cross-sectional, limiting our interpretation to 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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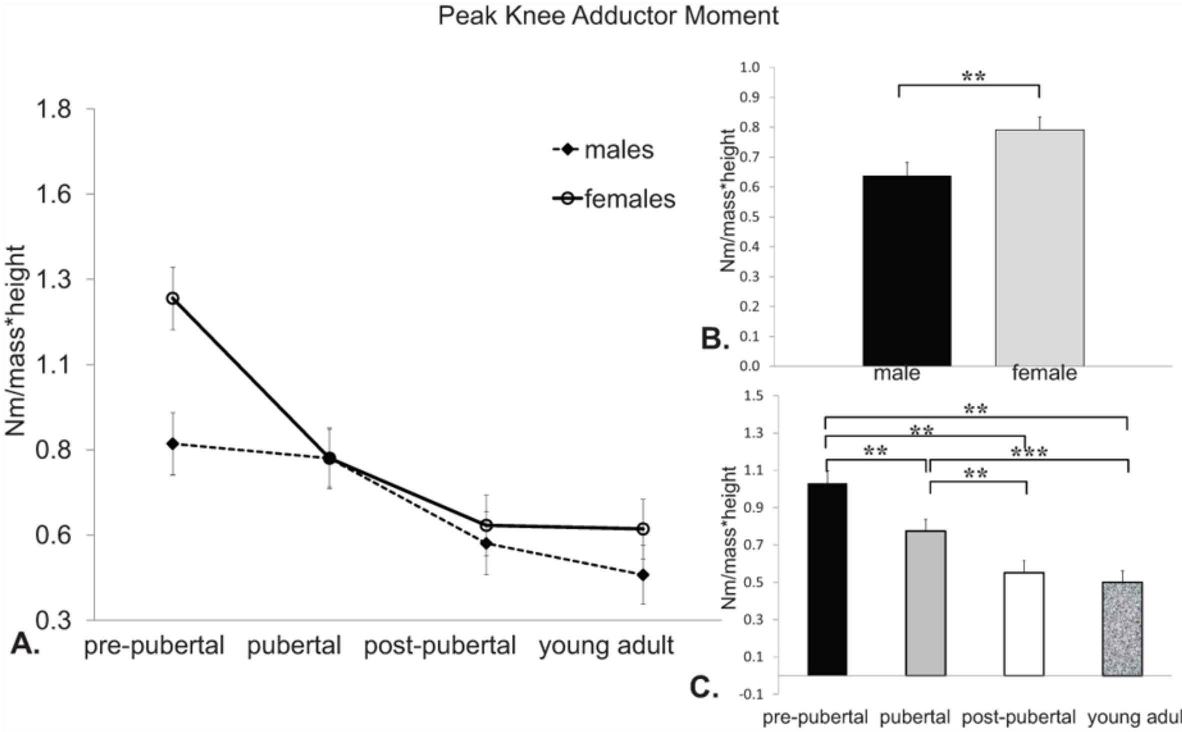

Figure 1.

Experimental set-up for side-step cutting. Open arrow indicates original plane of progression, the solid line indicates the direction of the 45° cut task. The light cue was triggered 3 meters prior to force plate contact.

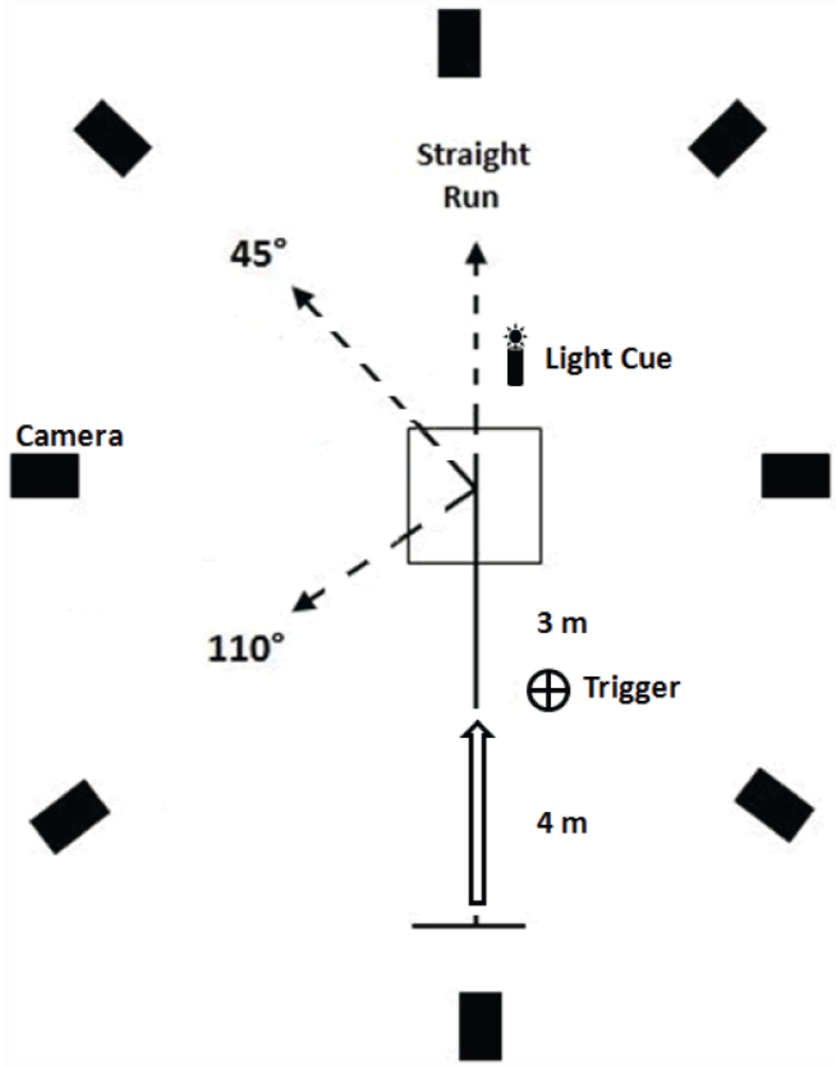

Figure 2.
Peak knee adductor moment (Nm/mass*height) during weight acceptance A) individual group data stratified by sex and maturation, B) data collapsed across maturation levels, C) data collapsed across sex. Data represents mean + standard error. ** P ≤ 0.01

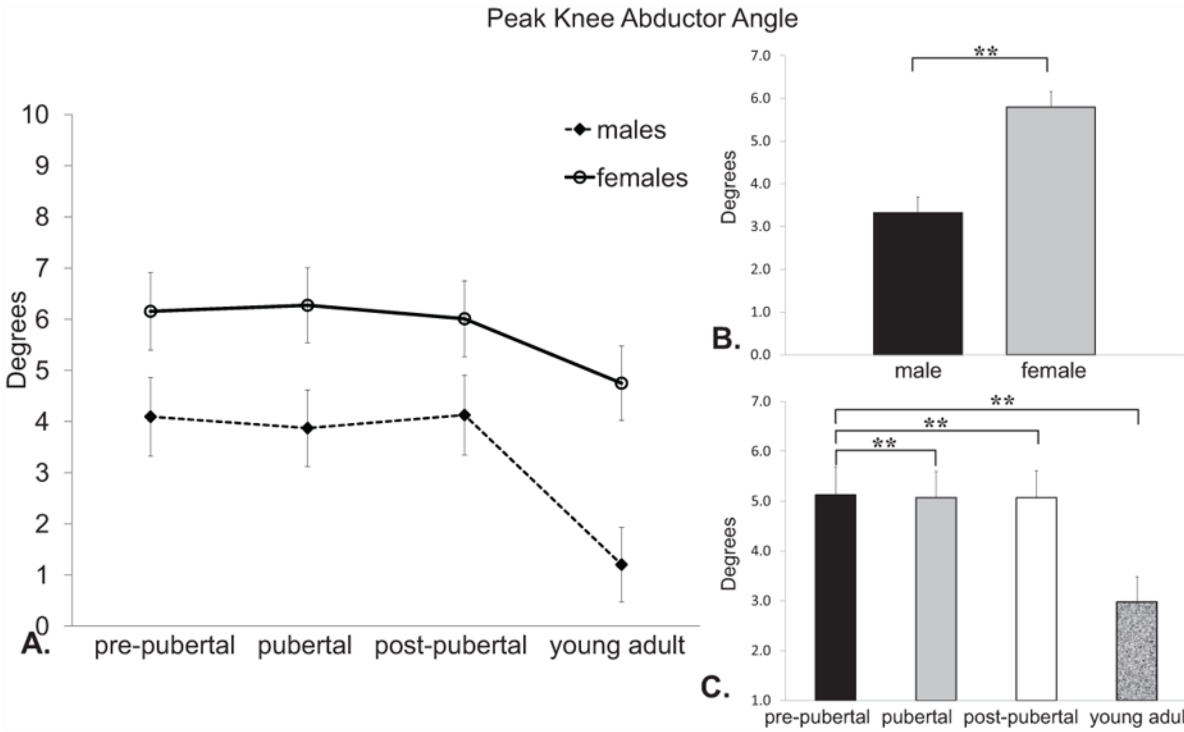

Figure 3.

Non-normalized peak knee adductor moment during weight acceptance. Individual group data stratified by sex and maturation. Data represents mean + standard error.

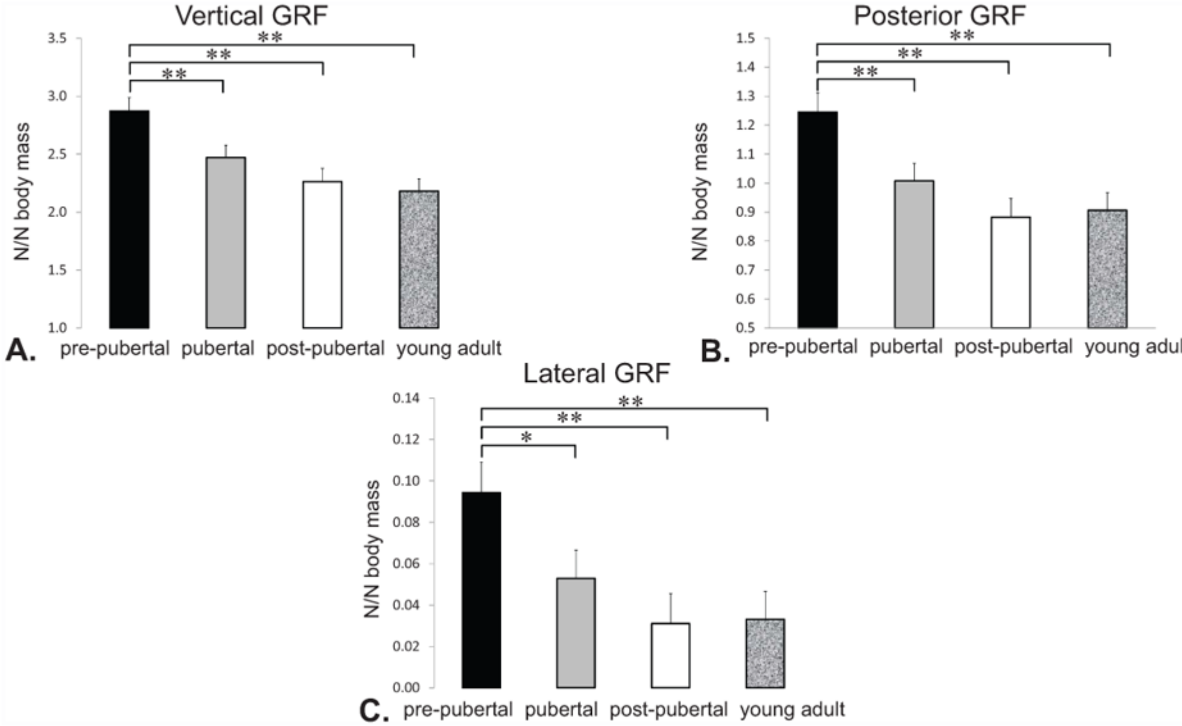

Figure 4.

Peak knee abductor angle (degrees) during weight acceptance A) individual group data stratified by sex and maturation, B) data collapsed across maturation levels, C) data collapsed across sex. Data represents mean + standard error. ** P ≤ 0.01

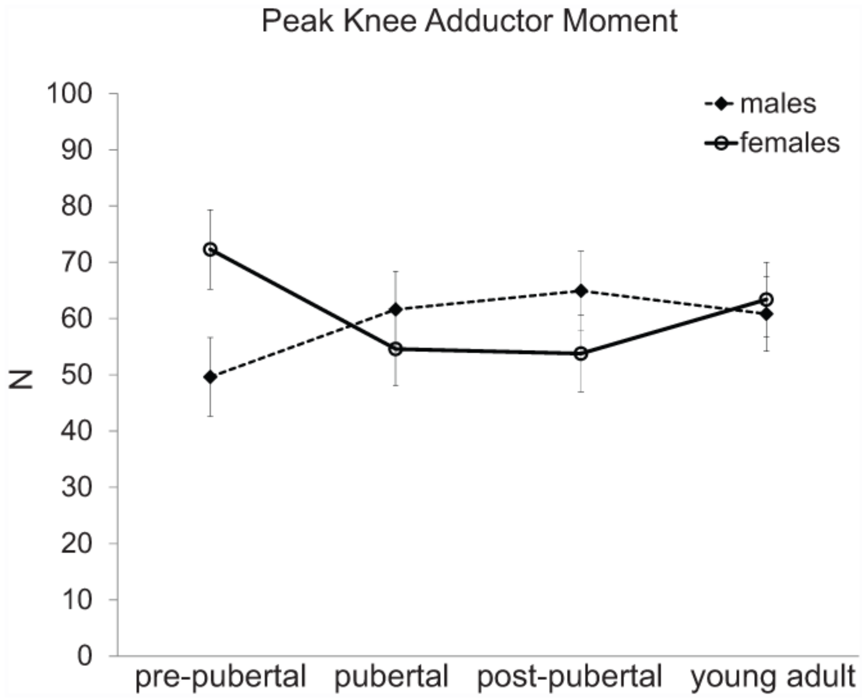

Figure 5.
Peak ground reaction forces during weight acceptance (N/N body mass). Data collapsed across sex. A) Vertical, B) Posterior, C) Lateral. Data represents mean + standard error. * P<0.05, ** P ≤ 0.01

Table 1

Subject Characteristics (Mean (SE))

	Female				Male			
	pre-pubertal (n=19)	**Pubertal (n=21)**	**post-pubertal (n=20)**	**young adult (n=20)**	**pre-pubertal (n=19)**	**Pubertal (n=19)**	**post-pubertal (n=18)**	**young adult (n=20)**
age (yrs)†‡	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)*	181.1 (1.6)*
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)*	78.6 (1.7)*
experience (yrs)†‡	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)

* =significant difference between males and females

† =significant main effects of sex

‡ = significant main effect of maturation