Differences in Hip and Knee Landing Moments across Female Pubertal Development

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ABSTRACT

SAYER, T. A., R. S. HINMAN, K. L. PATERSON, K. L. BENNELL, K. FORTIN, A. TIMMI, P. PIVONKA, and A. L. BRYANT. Differences in Hip and Knee Landing Moments across Female Pubertal Development. *Med. Sci. Sports Exerc.*, Vol. 51, No. 1, pp. 123–131, 2019. **Purpose**: The higher prevalence of knee injuries among adolescent females may be related to female pubertal development. The aim of this study was to determine whether girls exhibit higher triplanar knee and hip moments with more advanced pubertal development during a single-limb landing. **Methods**: Lower-limb biomechanics of 93 females grouped according to prepubertal (n = 31), early/midpubertal (n = 31) and late/postpubertal (n = 31) development performed a single-limb drop lateral jump. Peak triplanar knee moments and hip moments at the time of peak knee moments were derived from a Vicon motion analysis system and concealed force plate. Joint moments were normalized to body mass ($N \cdot m \cdot kg^{-1}$), height ($N \cdot m \cdot kg^{-1} \cdot m^{-1}$) and body mass by height ($N \cdot m \cdot kg^{-1} \cdot m^{-1}$). Between-group differences were analyzed using a one-way ANOVA with Pearson correlations used to explore relationships between joint moments and anthropometrics. **Results**: Girls at latter stages of puberty landed with higher triplanar knee moments and hip flexion moment at time of peak knee flexion moment when normalized separately to body mass and to height ($P < 0.05$). In contrast, hip internal rotation moments at time of peak knee internal rotation moment normalized to body mass and to body mass by height were lower in late/postpubertal girls compared to their early/midpubescent ($P = 0.01$) and prepubescent ($P = 0.01$) counterparts. Positive correlations were identified between triplanar knee moments and body mass (r = 0.73–0.91, $P < 0.001$) and height (r = 0.61–0.89, $P < 0.001$) for all participants. **Conclusions**: Higher triplanar knee and sagittal plane hip moments with more advanced pubertal stage is attributed to growth-related increases in body mass and height. Given that growth is a crucial element of puberty, further research is required to quantify the impact of pubertal growth-related changes on risk of adolescent female anterior cruciate ligament injury. **Key Words:** BIOMECHANICS, ADOLESCENT, FEMALE, KINETICS, LANDING

Puberty is the transition from childhood to adulthood and typically involves a rapid rise in sex hormones driving substantial growth of the musculoskeletal system (1). During early adolescence when physical characteristics of puberty begin to emerge, the incidence of serious knee injuries, such as noncontact anterior cruciate ligament (ACL) rupture among females is reported to increase approximately fourfold (2). The onset of the menstrual cycle (menarche) leads to higher circulating estrogen levels which, in turn, may alter neuromuscular parameters related to ACL injury (3). Consequently, female pubertal and hormonal characteristics are suggested to influence aberrant knee biomechanics (3), a significant risk factor contributing to higher rates of ACL injury between early compared with late pubertal females (4–6). The external knee abduction moment (KAbM) is commonly evaluated in studies of female pubertal development given its association with ACL injury (6–8). Furthermore, higher sagittal and transverse plane knee moments (i.e., external knee flexion moment [KFM] and knee internal rotation moment [KIRM], respectively) in combination with KAbM are more likely to rupture the ACL via a triplanar mechanism of injury (9), rather than excessive force in one plane alone.

The majority of previous developmental biomechanics research has evaluated a bilateral drop vertical jump (DVJ), reporting higher KAbM and KFM in postpubertal females compared to pubertal counterparts (7,10,11). However, a recent study indicated that a bilateral DVJ may be a poor biomechanical screening tool for ACL injury (12). Thus, the use of single-limb landing tasks may be more appropriate at identifying aberrant biomechanical patterns, which might be useful in subsequent prospective studies related to pubertal noncontact ACL injury (12). The few relevant investigations that have included single-limb landing protocols (4,5,13) have reported contradictory findings with respect to KFM

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(5,13) and KAbM (4,5), whereas no study has reported KIRM between stages of female pubertal development. Differences may be partly due to the use of menarche to classify pubertal development, in which the time of onset can vary considerably and does not reliably categorize pubertal stage (14,15). By contrast, Tanner stages of development provide a more appropriate classification, as they are based on an individual's current stage of biological maturation (16). Hence, investigating whether girls at different Tanner stages exhibit altered triplanar knee moments during a single-limb landing task, will further help identify whether pubertal stage effects knee moments related to noncontact ACL injury.

Although higher triplanar knee moments are major contributors to ACL rupture (9), hip joint kinetics may also be important given that only the proximal kinetic chain has the capacity to influence knee joint mechanics (17). Studies investigating hip biomechanics across female pubertal development have, in general, reported higher sagittal plane external hip flexion moment (HFM) (13,18), knee/hip moment ratio (7) and lower hip adduction moments (HAM) (13) in postpubescent females compared with their prepubescent counterparts. However, it is difficult to interpret the influence of hip moments on triplanar knee moments from these studies given that only peak values were reported. Instead, characterization of triplanar hip moments (i.e., hip adduction, flexion and rotation) at the time of peak knee moments (i.e., KAbM, KFM and KIRM) may be more relevant to our understanding of hip joint contributions during landing (19). Indeed, aberrant hip biomechanics have been linked with ACL injury (20) and may contribute to alterations in peak knee moments via the kinetic chain (17).

Mixed findings of puberty studies investigating landing-related triplanar knee and hip joint moments may also be related to differences in normalization methods used to account for differences in body mass and height across developmental stages. In this respect, normalizing joint moments to body mass and height is typically advised to minimize the influence of differences in body size between pubertal groups (21). That being said, the growth-related changes associated with puberty (1) likely contribute to a higher incidence of adolescent female ACL ruptures between ages 12 and 17 yr (2). Hence, establishing if pubertal growth-related changes influence triplanar knee and hip moments via body mass, height and body mass by height normalized moments during single-limb landing, may provide further support that pubertal growth contributes to ACL biomechanical risk factors (3). Support for this notion was provided by Hewett et al. (22) who longitudinally investigated the female adolescent growth spurt and found that increased height was correlated with absolute (Nm) higher peak KAbM during a bilateral DVJ. Despite these findings, the study by Hewett et al. (22) performed a bilateral limb landing task which may not mirror single-limb landing tasks. Moreover, they do not report the effect of different normalization methods or correlate other anthropometrics, such as body mass to triplanar knee moments across female pubertal development, highlighting a gap in our current understanding of these growth-related changes.

Therefore, the aim of this study was to compare single-limb landing-related knee (triplanar) and hip (triplanar) moments (normalized to body mass, height and body mass by height) of prepubertal, early/midpubertal, and late/postpubertal girls. The primary hypothesis was that KAbM would be higher in the late/post pubertal group compared with the early/midpubertal and prepubertal groups, and in the early/midpubertal compared with prepubertal when normalized to body mass and to height but not when normalized to body mass by height. Similarly, higher KAbM would be accompanied by a higher HAM at time of peak KAbM when normalized to body mass and to height but not when normalized to body mass by height. The secondary hypotheses were that peak KFM, KIRM, HFM at time of peak KFM and hip internal rotation moment (HIRM) at time of peak KIRM would be higher in the late/postpubertal group compared with early/midpubertal and prepubertal groups, and in the early/midpubertal compared with prepubertal group when normalized to body mass and by height but not when normalized to body mass by height.

METHODS

Study population. Ninety-three recreationally active females (31 per pubertal group) were recruited based on our sample size calculation which assumed average KAbM for prepubertal, early/midpubertal and late/postpubertal females to be 0.15, 0.32, and 0.4 $N{\cdot}m{\cdot}kg^{-1}$, respectively, during single-limb landing (4). We used a within-group standard deviation of 0.15 based on previous studies (4,10) and set power at 0.8 and a P value of 0.05.

Participants were recruited from the student body at the University of Melbourne, local schools, community centers, and sporting facilities. Inclusion criteria were: (i) age 7 to 25 yr old, (ii) participating in regular physical activity (>30 min of moderate and/or vigorous activities daily), and (iii) healthy weight (BMI < 30 $kg{\cdot}m^{-2}$). Exclusion criteria were: (i) history of lower-limb injury, knee pain or medical condition affecting walking, running and jumping; (ii) previous ACL or meniscal injury; or (iii) biphasic or triphasic oral contraceptive pill (OCP) use. All participants, together with parents/guardians of those <18 yr of age, signed an informed consent form. This study was supported by an ARC linkage grant (LP150101041) with ethics approved by the University of Melbourne Human Research Ethics Committee (1442604). The funding body did not influence any of the study design, data collection, or analysis of results.

All 93 girls were categorized into one of three modified phases of puberty: (i) prepubertal (Tanner stage I), (ii) early/midpubertal (Tanner stage II-III and either growth spurt or menarche), and (iii) late/postpubertal (Tanner stage IV-V, both menarche and growth spurt essential) stages. Tanner staging was based upon self-rated breast development via an online, deidentified questionnaire containing pictures and modified diagrams (16,23). The questionnaire also ascertained if the adolescent growth spurt had occurred (yes or no response) using the question "The adolescent has grown 3 to 3.5 inches (7.5–9 cm) in the past 6 months or is past this growth spurt" and whether menarche had commenced via the statement "The adolescent has begun menarche (period)" taken from the modified pubertal maturation observational scale (10,24). For girls <12 yr of age, all pubertal assessment information was provided by a parent/guardian, whereas girls age ≥12 yr completed the questionnaire themselves to improve reliability and validity (25,26).

Physical activity. Although no association between physical activity and lower-limb joint moments has been established, time spent in moderate and vigorous physical activity is positively associated with motor skill development (i.e., jumping, throwing and balance tasks) (27). Hence, physical activity data were collected to ensure that i) participants met the inclusion criteria of being physically active, and ii) pubertal groups were participating in comparable levels of physical activity.

All girls >12 yr of age and parents/guardians of girls <12 yr of age were required to complete a self-reported physical activity questionnaire: a modified Children's Leisure Activity Study Survey (CLASS) (28,29). The CLASS classifies intensity levels of sport and physical activity participation throughout a typical week as "moderate" and "vigorous" using METs (28). The reliability (ICC = 0.71) and validity (r = 0.48) of the CLASS have been established as moderate (28,29).

Hormonal consideration. Because higher estrogen levels have the capacity to influence lower-limb biomechanics (3), we ensured that all girls were tested when estradiol levels were low. For the early/midpubertal and late/postpubertal girls who had indicated that their menstrual cycle had commenced, eumenorrheic girls were required to identify their early follicular phase (days 1–7 after menses) at which time biomechanical testing was performed. In contrast, monophasic OCP users were tested at any time, given consistency of estradiol levels. To confirm that all participants were indeed tested with low estradiol levels (including the prepubertal group), we measured saliva estradiol levels via a 5-mL sample at time of testing, whereby all participants were required to have <18 $pmol \cdot L^{-1}$ according to the reference ranges provided by the manufacturer (Nutripath Integrative Pathology, Melbourne, Australia). For analysis, saliva samples were stored at −20°C and subsequently analyzed via enzyme immunoassay according to the manufacturer's instructions.

Procedure. Three-dimensional motion analysis was recorded by a 12-camera Vicon motion analysis system (Oxford, UK) synchronized to a concealed force plate (AMTI, Inc., Watertown, MA). System calibration was performed using an MX calibration wand with five reflective markers and an L-shaped frame to define the X, Y, Z global coordinate system (30). After system calibration, 40 reflective markers (13 mm) were affixed to the skin using double-sided tape according to the Schache and Baker model (Fig. 1) (31). Limb dominance was determined using the footedness subscale of the Lateral Preference Inventory (LPI) (32). We tested the nondominant limb as previous literature indicates a higher rate of female ACL injury on this limb (12).

All participants were familiarized with a single-limb drop lateral jump (Fig. 2), after which three successful trials were recorded. For each participant, jump height was scaled to a relative box height (OEM Engineering Pty Ltd, Melbourne, Australia) of 30% of their lower-limb length, measured from the outermost lateral aspect of the greater trochanter to the floor. We normalized box height to individual lower-limb anthropometry to create similar neuromuscular demand between participants of different heights given that jump and subsequent landing height increases during adolescence (33). Hence, landing from a scaled box height is more reflective of the environmental demands imposed on the lower limb of girls of different sizes during sports participation.

In bare feet, participants stood on their nondominant limb and were instructed to align their foot to the center of the box 10 cm from a force plate with their toes on the edge and hands across their chest. Participants were required to hop down from the box and laterally hop as quickly as possible in the direction of their dominant side, landing on a marker placed on the ground at distance of 150% lower-limb length from the center of the force plate. Before data collection, each participant performed a static and dynamic knee swinger calibration to determine the anatomical and technical reference frames of the trunk, pelvis, thigh, shank, and foot (34).

FIGURE 1—Participant prepared for data collection. All 40 (13 mm) reflective markers were placed on the trunk, thigh, shank and foot. Participants were instructed to fold their hands across their chest (as pictured) for the static calibration.

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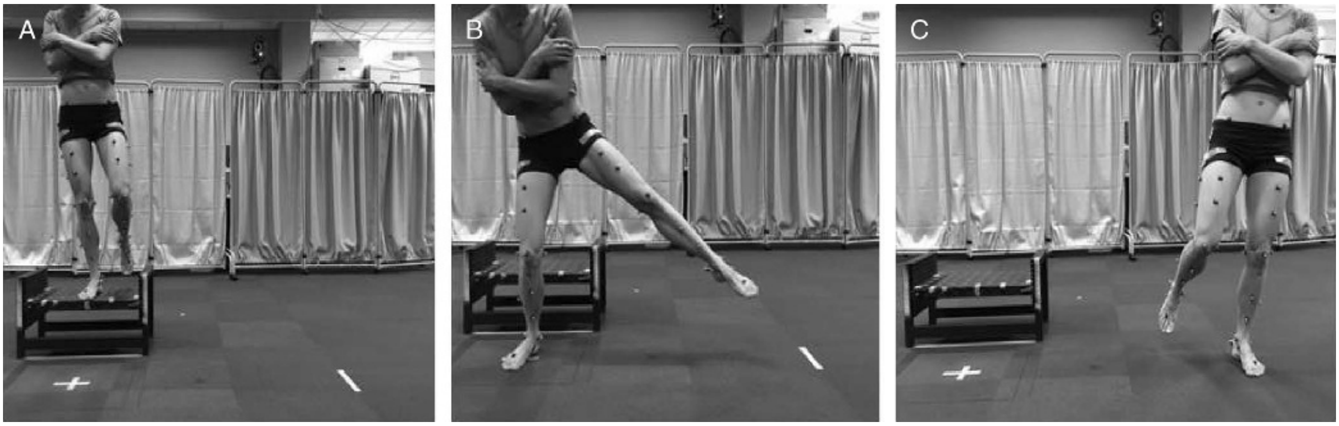

FIGURE 2—Single-limb landing task. The participant balanced on their nondominant test limb with hands folded across chest (A), hopped down toward the "X" marked on the ground (B), and then laterally hopped 90° as quickly as possible toward their dominant limb, landing and balancing for 5 s (C).

Data analysis. Marker trajectories (120 Hz) and ground reaction force data (2400 Hz) were then filtered using a fourth order zero-lag Butterworth filter at a frequency of 20 Hz (35) Peak external joint moments were derived using inverse dynamics and were expressed in the distal anatomical reference frame. Normally, joint moments are normalized to body mass and height to minimize the influence of anthropometrics, thereby allowing exploration of other factors, such as altered movement patterns (21). However, in the context of pubertal development, growth-related differences between developmental groups (i.e., body mass and height) may drive differences in knee moments and subsequently lead to joint injury (1,2). Hence, it is important to understand whether growth-related changes at various stages of puberty contribute to differences in knee and hip moments by normalizing to body mass ($N{\cdot}m{\cdot}kg^{-1}$), height ($N{\cdot}m{\cdot}m^{-1}$) and body mass by height ($N{\cdot}m{\cdot}kg^{-1}{\cdot}m^{-1}$) (31). Negative joint moment values indicate higher KAbM, KIRM and HIRM, whereas positive joint moment values correspond to higher KFM, HAM, and HFM. Joint moments were evaluated during the first 25% of stance as ACL injury typically occurs shortly after initial contact (22). Additional anthropometric segment lengths for the thigh and shank for each pubertal group were calculated from the kinematic model by estimating the distance (cm) from hip to knee joint center (thigh length) and knee to ankle joint center (shank length). Finally, ensemble curves for knee and hip moments across the three stages of pubertal development are provided (Figs. 3 and 4).

Statistical analysis. Means and standard deviations (SD) were calculated for all participant characteristics and biomechanical outcome measures. A one-way analysis of variance (ANOVA) was used to test for differences in participant

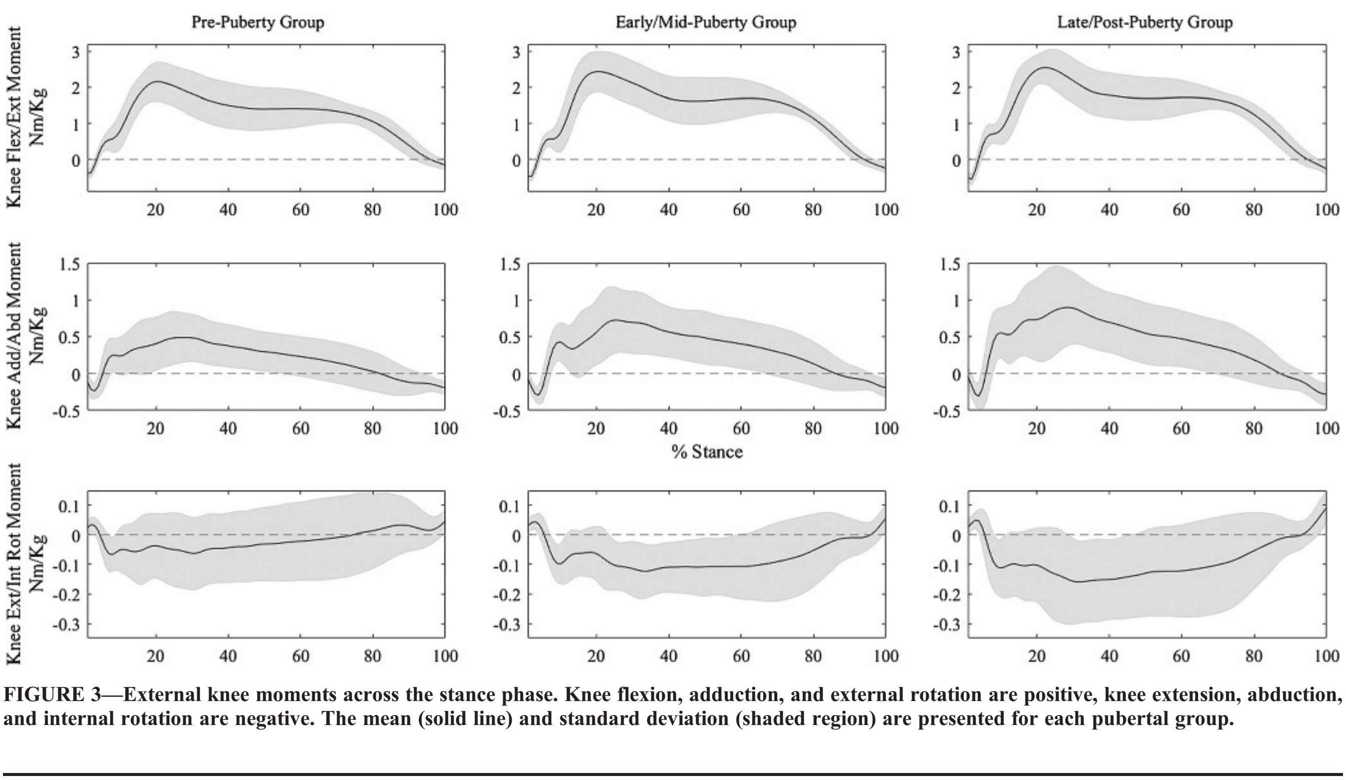

FIGURE 3—External knee moments across the stance phase. Knee flexion, adduction, and external rotation are positive, knee extension, abduction, and internal rotation are negative. The mean (solid line) and standard deviation (shaded region) are presented for each pubertal group.

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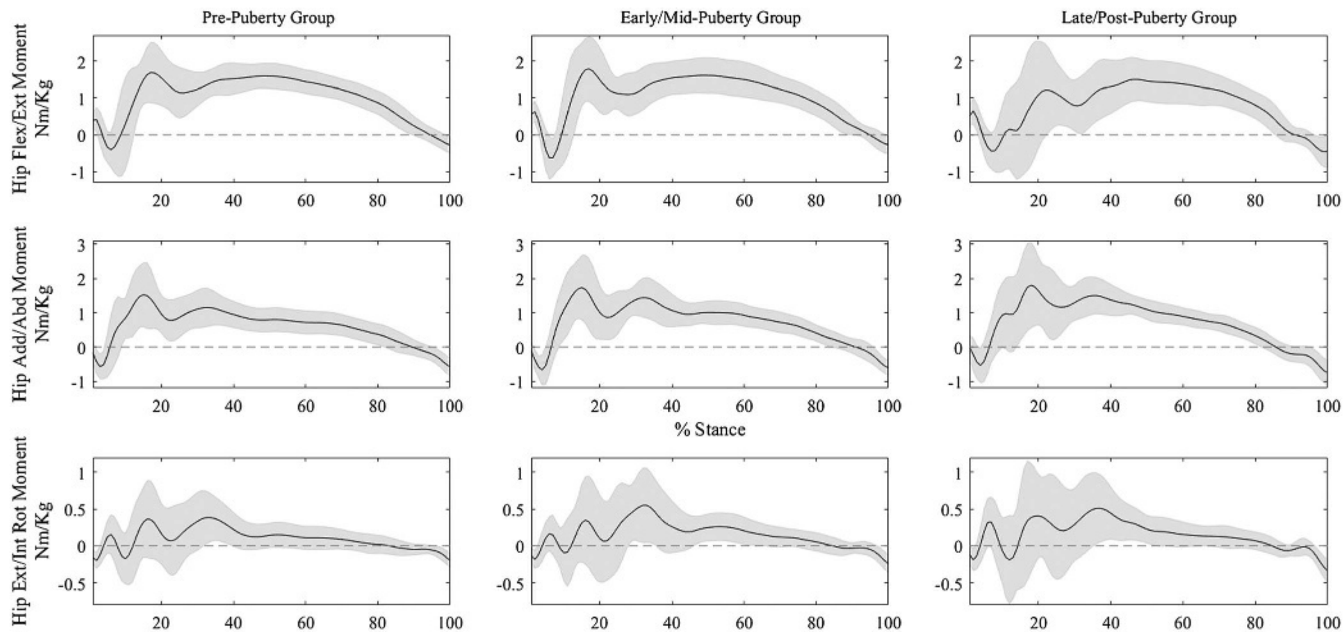

FIGURE 4—External hip moments across the stance phase. Knee flexion, adduction, and external rotation are positive, knee extension, abduction, and internal rotation are negative. The mean (solid line) and standard deviation (shaded region) are presented for each pubertal group.

descriptive characteristics and knee and hip moments between the three pubertal groups. In the event of a main effect, *post hoc* analyses were performed using Fisher's Least Significant Difference tests, with the mean difference (MD), and 95% confidence intervals (CI) reported. If differences in knee and hip moments for the various normalization methods were identified, Pearson product moment correlations were performed between joint moments (N·m) and anthropometrics (i.e., height and body mass). All data were analyzed using the Statistical Packages for Social Science (SPSS, version 23, IBM) and significance was set at 0.05.

RESULTS

Demographic results for the three groups are presented in Table 1. As anticipated, there was a difference between groups for age, weight, height and lower-limb segment lengths ($P < 0.05$). *Post hoc* analyses demonstrated that the late/postpuberty group was older, heavier and taller with longer thigh and shank segments than both the early/midpubertal and prepubertal groups ($P < 0.001$). There were no between-group differences in endogenous estrogen levels ($P > 0.05$) between prepubertal, early/midpubertal and late/postpubertal groups. In the late/postpubertal group, 11/31 girls (34%) had been using a monophasic OCP for >6 months. Moreover, no between-group differences were found for moderate (P = 0.66), vigorous (P = 0.22) or total (P = 0.46) physical activity (Table 1).

Knee and hip joint moments are shown in Table 2. In the frontal plane, a main group effect was found for peak KAbM (P = 0.036) normalized to body mass, from which subsequent *post hoc* analyses revealed higher peak KAbM for the late/postpubertal compared to the prepubertal group (MD, −0.09; 95% CI, −0.02 to −0.17 N·m·kg^{-1}; P = 0.015). There were no differences in peak KAbM between the early/midpubertal group and either the prepubertal or late/postpubertal groups (all $P > 0.05$). Likewise, a main group effect was found for peak KAbM normalized to height ($P < 0.001$). Peak KAbM

TABLE 1. Participant characteristics according to pubertal development.

Variables	Prepubertal	Early/Midpubertal	Late/Postpubertal
n	31	31	31
Age (yr)	9.4 ± 1.2	11.1 ± 1.4*	19.8 ± 4.0*,**
Weight (kg)	30 ± 5.7	38.4 ± 7.4*	60.5 ± 8.5*,**
Height (m)	1.4 ± 0.1	1.5 ± 0.1*	1.7 ± 0.1*,**
Estradiol (pmol·L^{-1})	7.1 ± 5.1	6.7 ± 4.6	9.5 ± 5.1
Thigh segment length (cm)	34.9 ± 2.7	38.7 ± 2.7*	43.7 ± 2.1*,**
Shank segment length (cm)	31.9 ± 2.5	34.9 ± 2.9*	38.8 ± 2.1*,**
Moderate physical activity (min)	445.5 ± 283.9	410.36 ± 216.7	474.0 ± 301.2
Vigorous physical activity (min)	195.0 ± 157.5	270.7 ± 210.1	286.5 ± 276.6
Total physical activity (min)	640.5 ± 344.1	659.1 ± 351.0	760.5 ± 505.9

All variables are reported as mean ± SD.
*Significantly different to pre-pubertal group ($P < 0.05$).
**Significantly different to early/midpubertal group ($P < 0.05$).

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TABLE 2. Knee and hip kinetics according to pubertal development.

Variable	Prepubertal	Early/Midpubertal	Late/Postpubertal
Peak KAbM (N·m·kg^{-1})	−0.34 ± 0.11	−0.37 ± 0.13	−0.43 ± 0.18*
Peak KAbM (N·m·m^{-1})	−7.27 ± 2.35	−10.05 ± 4.84*	−15.96 ± 7.62*,**
Peak KAbM (N·m·kg^{-1}·m^{-1})	−0.25 ± 0.08	−0.25 ± 0.08	−0.26 ± 0.11
Peak KFM (N·m·kg^{-1})	2.41 ± 0.41	2.69 ± 0.54*	2.86 ± 0.41*
Peak KFM (N·m·m^{-1})	52.80 ± 12.58	71.82 ± 16.81*	103.51 ± 19.32*,**
Peak KFM (N·m·kg^{-1}·m^{-1})	1.76 ± 0.31	1.83 ± 0.38	1.72 ± 0.25
Peak KIRM (N·m·kg^{-1})	−0.16 ± 0.07	−0.18 ± 0.06	−0.23 ± 0.10*,**
Peak KIRM (N·m·m^{-1})	−3.42 ± 1.71	−4.96 ± 2.31*	−8.49 ± 4.23*,**
Peak KIRM (N·m·kg^{-1}·m^{-1})	−0.11 ± 0.05	−0.12 ± 0.04	−0.14 ± 0.07
HAM at time of peak KAbM (N·m·kg^{-1})	−0.27 ± 0.70	−0.34 ± 0.78	−0.42 ± 0.70
HAM at time of peak KAbM (N·m·m^{-1})	−5.91 ± 14.84	−9.33 ± 19.89	−15.14 ± 26.75
HAM at time of peak KAbM (N·m·kg^{-1}·m^{-1})	−0.21 ± 0.51	−0.25 ± 0.50	−0.24 ± 0.41
HFM at time of peak KFM (N·m·kg^{-1})	1.80 ± 0.71	1.57 ± 0.63	1.69 ± 1.14
HFM at time of peak KFM (N·m·m^{-1})	38.89 ± 15.64	43.21 ± 21.38	62.42 ± 41.29*,**
HFM at time of peak KFM (N·m·kg^{-1}·m^{-1})	1.32 ± 0.51	1.05 ± 0.43	1.04 ± 0.70
HIRM at time of peak KIRM (N·m·kg^{-1})	0.48 ± 0.48	0.48 ± 0.46	0.16 ± 0.49*,**
HIRM at time of peak KIRM (N·m·m^{-1})	10.62 ± 11.36	12.04 ± 11.74	5.36 ± 16.58
HIRM at time of peak KIRM (N·m·kg^{-1}·m^{-1})	0.34 ± 0.34	0.32 ± 0.31	0.10 ± 0.30*,**

All variables are reported as mean ± SD within the first 25% of stance phase for each developmental group. KAbM, KIRM and HIRM correspond to negative values, whereas KFM, HAM, and HFM correspond to positive values.
*Significantly different to pre-pubertal group ($P < 0.05$).
**Significantly different to early/midpubertal group ($P < 0.05$).

for the late/postpubertal group was higher compared to early/midpubertal (MD, −5.90; 95% CI, −8.62 to −3.19 N·m·m^{-1}; $P < 0.001$) and prepubertal groups (MD, −8.69; 95% CI, −11.40 to −5.97 N·m·m^{-1}; $P < 0.001$). Moreover, peak KAbM for the early/midpubertal group was higher compared to the prepubertal group (MD, −2.78; 95% CI, −5.49 to −0.07 N·m·m^{-1}; $P = 0.045$). However, when normalized to body mass by height, no between-group differences were found ($P = 0.88$). At the hip, no between-group differences for HAM at time of peak KAbM were observed regardless of normalization method (all $P > 0.05$; Table 2).

In the sagittal plane, there was a main group effect for peak KFM normalized to body mass ($P = 0.002$, Table 2). *Post hoc* analyses revealed higher peak KFM in the late/postpubertal compared to the prepubertal group (MD, 0.44; 95% CI, 0.19–0.68 N·m·kg^{-1}; $P = 0.001$). In addition, the early/midpubertal group demonstrated higher peak KFM compared with the prepubertal group (MD, 0.28; 95% CI, 0.05–0.52 N·m·kg^{-1}; $P = 0.017$). A main group effect was also found when KFM was normalized to height ($P < 0.001$) with higher peak KFM in the late/postpubertal compared to early/midpubertal (MD, 31.69; 95% CI, 23.38–40.00 N·m·m^{-1}; $P < 0.001$) and prepubertal groups (MD, 50.71; 95% CI, 42.40–59.02 N·m·m^{-1}; $P < 0.001$). Moreover, KFM of the early/midpubertal group was higher (MD, 19.02; 95% CI, 10.71–27.33 N·m·m^{-1}; $P < 0.001$) than the prepubertal group. No between-group differences for peak KFM normalized to body mass by height ($P = 0.30$) were found and likewise, HFM normalized to body mass and to body mass by height at time of peak KFM ($P > 0.05$). However, a main group effect was evident for height normalized HFM at time of peak KFM ($P = 0.003$), whereby late/postpubertal girls exhibited higher KFM compared with the early/midpubertal (MD, 19.21; 95% CI, 4.91–33.50 N·m·m^{-1}; $P = 0.009$) and prepubertal girls (MD, 23.53; 95% CI, 9.24–37.82 N·m·m^{-1}; $P = 0.002$).

A main effect of group was also found for peak KIRM normalized to body mass ($P = 0.003$). *Post hoc* analyses revealed higher peak KIRM in the late/postpubertal group compared to both the early/midpubertal (MD, −0.05; 95% CI, −0.09 to −0.01 N·m·kg^{-1}, $P = 0.028$) and prepubertal groups (MD, −0.07; 95% CI, −0.12 to −0.03 N·m·kg^{-1}; $P = 0.001$). There was no difference between the early/midpubertal and prepubertal groups ($P > 0.05$). Between-group differences were found for peak KIRM normalized to height ($P < 0.001$). Once again, the late/postpubertal group exhibited higher KIRM than the early/midpubertal (MD, −3.53; 95% CI, −5.02 to −2.04 N·m·m^{-1}; $P < 0.001$) and prepubertal groups (MD, −5.07; 95% CI, −6.57 to −3.58 N·m·m^{-1}; $P < 0.001$); moreover, KIRM of the early/midpubertal group was higher compared to the prepubertal group (MD, 31.69; 95% CI, 23.38–40.00 N·m·m^{-1}; $P = 0.042$). No differences in peak KIRM normalized to body mass by height were found between groups ($P = 0.19$).

At the hip, a main group effect was found for HIRM at time of peak KIRM when normalized to body mass ($P = 0.01$) and to body mass by height ($P = 0.004$). The late/postpubertal group exhibited lower body mass normalized HIRM at time of peak KIRM compared to the early/midpubertal (MD, 0.32; 95% CI, 0.56–0.07 N·m·kg^{-1}; $P = 0.01$) and prepubertal groups (MD, 0.32; 95% CI, 0.56–0.07 N·m·kg^{-1}; $P = 0.01$). For body mass by height normalized HIRM, the late/postpubertal group demonstrated lower values compared with early/midpubertal (MD, 0.23; 95% CI, 0.39–0.07 N·m·kg^{-1}·m^{-1}; $P = 0.005$) and prepubertal groups (MD, 0.25; 95% CI, 0.40–0.09 N·m·kg^{-1}·m^{-1}; $P = 0.003$). No between-group differences were found for HIRM data normalized to height ($P = 0.13$).

Significant positive correlations were identified between absolute (N·m) peak KAbM, KFM, KIRM and HFM at time of peak KFM and body mass and height ($P < 0.05$). Strong positive correlations were found between body mass and peak KAbM ($r = 0.77$, $P < 0.001$), peak KFM ($r = 0.91$,

$P < 0.001$), peak KIRM ($r = 0.73$, $P < 0.001$), and HFM at time of peak KFM ($r = 0.56$, $P < 0.001$). Likewise, height was positively correlated with peak KAbM ($r = 0.61$, $P < 0.001$), peak KFM ($r = 0.89$, $P < 0.001$), peak KIRM ($r = 0.66$, $P < 0.001$) and HFM at time of peak KFM ($r = 0.42$, $P < 0.001$).

DISCUSSION

This is the first study to characterize single-limb landing-related triplanar knee and hip moments in females across stages of pubertal development. Notably, triplanar knee and sagittal plane HFM at time of peak KFM (normalized for body mass and/or height) of late/postpubertal girls were higher compared to those exhibited by their early/midpubertal and prepubertal counterparts. Moreover, increasing body mass and height were strongly correlated with higher absolute (N·m) peak KAbM, KFM, KIRM, and HFM at time of peak KFM.

Findings pertaining to the primary hypothesis of higher peak KAbM are partly supported, given that differences between late/postpubertal and prepubertal groups for peak KAbM (normalized to body mass and height) were found. By contrast, the hypothesis of higher peak KAbM in early/midpubertal compared to prepubertal girls and higher HAM at the time of peak KAbM is rejected as no between-group differences were found for any normalization method. From the available evidence, the body mass normalized data are consistent with those outlined by Kim and Lim in a smaller study across two stages of pubertal development (i.e., prepubertal and postpubertal), albeit testing the dominant limb during a drop and hold task (4). Specifically, postpubescent elite gymnasts exhibited higher peak KAbM (0.37 ± 0.11 N·m·kg^{-1}) compared with their prepubertal counterparts (0.19 ± 0.09 N·m·kg^{-1} (4)).

Moreover, our findings pertaining to peak KAbM normalized to body mass by height agree with previous single-limb landing studies by Hass and colleagues (5,13), that also found no differences in peak KAbM (normalized to body mass, height and landing height) between maturational groups in a sample of recreational girls age between 8 and 25 yr. However, these findings contradict those of Wild et al. (6) who performed a 12-month longitudinal study in which peak KAbM, normalized for body mass and height together, was higher ($P < 0.05$) in girls at the latter stages of their adolescent growth spurt (i.e., Tanner stage II; −0.13 vs 0.15 N·m·kg^{-1}·m^{-1}) during a single-limb landing task (6). Hence, these findings suggest that pubertal-related growth does not contribute to higher peak KAbM.

Given the findings of Wild et al. (6), we also examined the association between absolute peak KAbM and body mass and height, respectively. Strong positive correlations ($r = 0.61$–0.77) were identified between peak KAbM and pubertal-related growth (i.e., body mass and height). These findings agree with previous research by Hewett and colleagues (22) that reported a positive correlation between absolute peak KAbM during a bilateral DVJ and increasing tibial length (i.e., adolescent growth spurt) of pubescent females. Given that higher absolute joint moments have been linked with ACL rupture (36,37), the present study in combination with the aforementioned study by Hewett et al. suggest that female adolescent growth-related changes may indeed contribute to higher absolute joint loads that lead to injuries such as ACL rupture. Hence, further studies should examine whether these growth-related changes predict and/or increase risk of ACL injury among adolescent females.

With respect to the frontal plane HAM at time of peak KAbM, there were no differences between pubertal groups irrespective of the normalization method; in fact, girls demonstrated an external hip abduction moment at time of peak KAbM. This is surprising given that proximal frontal plane hip joint mechanics are recognized as a contributor to distal knee joint mechanics (17), however, no study has characterized the frontal plane HAM with respect to peak KAbM in a pubertal cohort. Hence, these findings may further suggest that growth-related changes (i.e., adolescent height) as previously discussed, rather than frontal plane hip moments contribute to differences in peak KAbM.

The secondary hypothesis was also partly confirmed, with higher peak KFM (normalized to body mass and to height) in the late/postpubertal and early/midpubertal girls compared to the pre-pubertal girls. However, no between-group differences were found for peak KFM normalized to body mass by height. Moreover, with respect to the HFM at time of peak KFM, between-group differences were only found for height normalized moments. Given our study design, causation between pubertal-related differences in biomechanics and ACL injury cannot be inferred; however, higher body mass and height normalized peak KFM and HFM at time of peak KFM may be clinically important. Indeed, Leppanen et al. (20) reported that of the 15 ACL ruptures sustained in their cohort of 171 adolescent females age 12 to 21 yr, higher absolute peak KFM and lower hip flexion excursion (i.e., stiffer landing) was associated with higher ACL injury risk (20). However, it is important to note that Leppanen et al. (20) used a bilateral DVJ and, as such, their findings may not be transferable to single-limb landing. Nonetheless, future studies should determine whether pubertal-related growth is associated with a higher risk of knee ligament injuries, particularly as strong correlations ($r = 0.89$–0.91) between peak KFM and body mass and height were identified in the present study.

Finally, the findings of higher peak KIRM and lower HIRM at time of peak KIRM (both normalized to body mass and to height) at the latter stages of puberty suggest that the HIRM may not contribute to higher peak KIRM given that external hip moments were found for each pubertal group. Similar to results pertaining to peak KAbM, these findings contradict the study by Wild et al. (6) that reported an increase in peak KIRM normalized to body mass by height. However, differences between study findings for peak KIRM may be attributed to variations in test movements (i.e., single-limb drop lateral jump vs single-limb horizontal forward hop) and study design (i.e., longitudinal vs cross-sectional), whereas the findings pertaining to the HIRM are likely related to rapid fluctuations between hip external and internal moments during early stance. Hence, further studies are required to confirm whether growth-related changes during puberty influence peak KIRM across a variety of tasks and whether hip rotation is associated with peak KIRM.

Despite this study providing novel insights between pubertal growth and lower-limb joint moments during single-limb landing, there are some limitations. First, the cross-sectional design of our study and use of healthy females does not enable us to elucidate whether these factors are indeed linked to higher risk of ACL injury. Furthermore, we used a single-limb landing task given that recent evidence suggests a bilateral DVJ lacks external validity (12). As studies linking aberrant biomechanics to adolescent ACL injury have all used a bilateral DVJ task (20,36,37), interpretation of single-limb landing studies with respect to ACL injury should be cautioned until further evidence is published.

CONCLUSIONS

Increases in triplanar knee and sagittal plane hip moments across pubertal stages are related to growth-related increases in body mass and height. Further research is required to determine whether increasing stature and body mass are important in the context of adolescent knee injuries including noncontact ACL rupture.

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REFERENCES

1. Faust MS. Somatic development of adolescent girls. *Monogr Soc Res Child Dev*. 1977;42(1):1–90.
2. Shea KG, Pfeiffer R, Wang JH, Curtin M, Apel PJ. Anterior cruciate ligament injury in pediatric and adolescent soccer players: an analysis of insurance data. *J Pediatr Orthop*. 2004;24(6): 623–8.
3. Wild CY, Steele JR, Munro BJ. Why do girls sustain more anterior cruciate ligament injuries than boys?: a review of the changes in estrogen and musculoskeletal structure and function during puberty. *Sports Med*. 2012;42(9):733–49.
4. Kim KW, Lim BO. Effects of menarcheal age on the anterior cruciate ligament injury risk factors during single-legged drop landing in female artistic elite gymnasts. *Arch Orthop Trauma Surg*. 2014;134(11):1565–71.
5. Hass CJ, Schick EA, Tillman MD, Chow JW, Brunt D, Cauraugh JH. Knee biomechanics during landings: comparison of pre- and postpubescent females. *Med Sci Sports Exerc*. 2005;37(1):100–7.
6. Wild CY, Munro BJ, Steele JR. How young girls change their landing technique throughout the adolescent growth spurt. *Am J Sports Med*. 2016;44(5):1116–23.
7. Sigward SM, Pollard CD, Powers CM. The influence of sex and maturation on landing biomechanics: implications for anterior cruciate ligament injury. *Scand J Med Sci Sports*. 2012;22(4): 502–9.
8. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med*. 2005;33(4):492–501.
9. Quatman CE, Quatman-Yates CC, Hewett TE. A 'plane' explanation of anterior cruciate ligament injury mechanisms: a systematic review. *Sports Med*. 2010;40(9):729–46.
10. Ford KR, Shapiro R, Myer GD, Van Den Bogert AJ, Hewett TE. Longitudinal sex differences during landing in knee abduction in young athletes. *Med Sci Sports Exerc*. 2010;42(10):1923–31.
11. Hewett TE, Myer GD, Ford KR, Slauterbeck JR. Preparticipation physical examination using a box drop vertical jump test in young athletes: the effects of puberty and sex. *Clin J Sport Med*. 2006;16(4): 298–304.
12. Krosshaug T, Steffen K, Kristianslund E, et al. The vertical drop jump is a poor screening test for ACL injuries in female elite soccer and handball players: a prospective cohort study of 710 athletes. *Am J Sports Med*. 2016;874–83.
13. Hass CJ, Schick EA, Chow JW, Tillman MD, Brunt D, Cauraugh JH. Lower extremity biomechanics differ in prepubescent and postpubescent female athletes during stride jump landings. *J Appl Biomech*. 2003;19(2):139–52.
14. Dorn LD, Sontag-Padilla LM, Pabst S, Tissot A, Susman EJ. Longitudinal reliability of self-reported age at menarche in adolescent girls: variability across time and setting. *Dev Psychol*. 2013;49(6):1187–93.
15. Dambhare DG, Wagh SV, Dudhe JY. Age at menarche and menstrual cycle pattern among school adolescent girls in Central India. *Glob J Health Sci*. 2012;4(1):105–11.
16. Tanner JM, Whitehouse RH, Marubini E, Resele LF. The adolescent growth spurt of boys and girls of the Harpenden growth study. *Ann Hum Biol*. 1976;3(2):109–26.
17. Mendiguchia J, Ford KR, Quatman CE, Alentorn-Geli E, Hewett TE. Sex differences in proximal control of the knee joint. *Sports Med*. 2011;41(7):541–57.
18. Ford KR, Myer GD, Hewett TE. Longitudinal effects of maturation on lower extremity joint stiffness in adolescent athletes. *Am J Sports Med*. 2010;38(9):1829–37.
19. Sasaki S, Koga H, Krosshaug T, Kaneko S, Fukubayashi T. Kinematic analysis of pressing situations in female collegiate football games: new insight into anterior cruciate ligament injury causation. *Scand J Med Sci Sports*. 2018;28(3):1263–71.
20. Leppanen M, Pasanen K, Krosshaug T, et al. Sagittal plane hip, knee, and ankle biomechanics and the risk of anterior cruciate ligament injury: a prospective study. *Orthop J Sports Med*. 2017;5(12): 2325967117745487.
21. Moisio KC, Sumner DR, Shott S, Hurwitz DE. Normalization of joint moments during gait: a comparison of two techniques. *J Biomech*. 2003;36(4):599–603.
22. Hewett TE, Myer GD, Kiefer AW, Ford KR. Longitudinal increases in knee abduction moments in females during adolescent growth. *Med Sci Sports Exerc*. 2015;47(12):2579–85.
23. Tanner JM. Normal growth and techniques of growth assessment. *Clin Endocrinol Metab*. 1986;15(3):411–51.
24. Davies PL, Rose JD. Motor skills of typically developing adolescents: awkwardness or improvement? *Phys Occup Ther Pediatr*. 2000;20(1):19–42.

25. Chan NP, Sung RY, Kong AP, Goggins WB, So HK, Nelson EA. Reliability of pubertal self-assessment in Hong Kong Chinese children. *J Paediatr Child Health*. 2008;44(6):353–8.
26. Pereira A, Garmendia ML, Gonzalez D, et al. Breast bud detection: a validation study in the Chilean growth obesity cohort study. *BMC Womens Health*. 2014;14:96.
27. Fisher A, Reilly JJ, Kelly LA, et al. Fundamental movement skills and habitual physical activity in young children. *Med Sci Sports Exerc*. 2005;37(4):684–8.
28. Telford A, Salmon J, Jolley D, Crawford D. Reliability and validity of physical activity questionnaires for children: the Children's Leisure Activities Study Survey (CLASS). *Pediatr Exerc Sci*. 2004;16(1):64–78.
29. Huang YJ, Wong SH, Salmon J. Reliability and validity of the modified Chinese version of the Children's Leisure Activities Study Survey (CLASS) questionnaire in assessing physical activity among Hong Kong children. *Pediatr Exerc Sci*. 2009;21(3):339–53.
30. Winter DA. *Biomechanics and Motor Control of Human Movement*. Fourth ed. NY: John Wiley & Sons; 2009.
31. Schache AG, Baker R. On the expression of joint moments during gait. *Gait Posture*. 2007;25(3):440–52.
32. Coren S. The lateral preference inventory for measurement of handedness, footedness, eyedness and earedness: norms for young adults. *Bull Psychon Soc*. 1993;31(1):1–3.
33. Temfemo A, Hugues J, Chardon K, Mandengue SH, Ahmaidi S. Relationship between vertical jumping performance and anthropometric characteristics during growth in boys and girls. *Eur J Pediatr*. 2009;168(4):457–64.
34. Schache AG, Baker R, Lamoreux LW. Defining the knee joint flexion–extension axis for purposes of quantitative gait analysis: an evaluation of methods. *Gait Posture*. 2006;100–9.
35. Bisseling RW, Hof AL. Handling of impact forces in inverse dynamics. *J Biomech*. 2006;39:2438–44.
36. Myer GD, Ford KR, Di Stasi SL, Foss KD, Micheli LJ, Hewett TE. High knee abduction moments are common risk factors for patellofemoral pain (PFP) and anterior cruciate ligament (ACL) injury in girls: is PFP itself a predictor for subsequent ACL injury? *Br J Sports Med*. 2015;49(2):118–22.
37. Hewett TE, Myer GD, Ford KR. Decrease in neuromuscular control about the knee with maturation in female athletes. *J Bone Joint Surg Am*. 2004;86-a(8):1601–8.