Knee-Muscle Activation during Landings: Developmental and Gender Comparisons

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ABSTRACT

RUSSELL, P. J., R. V. CROCE, E. E. SWARTZ, and L. C. DECOSTER. Knee-Muscle Activation during Landings: Developmental and Gender Comparisons. *Med. Sci. Sports Exerc.*, Vol. 39, No. 1, pp. 159–169, 2007. **Purpose:** This study determined anteroposterior knee-joint muscle activation differences among children and adult males and females landing from a self-initiated vertical jump (VJ) under normal and offset-target conditions to further understand physical maturation's influence on anterior cruciate ligament (ACL) injury risk. **Methods:** Fifty-five recreationally active volunteer subjects grouped by age (children = 9.5 ± 0.9 yr; adult = 23.9 ± 2.8 yr) and gender (females = 28; males = 27) completed motion analysis, ground reaction force, and surface electromyography (SEMG) data collection during a two-footed landing under straight (midline-target) and offset-target (adult = 45.7 cm; child = 30.5 cm) conditions. Target height was 50% of maximum VJ height. Cocontraction ratios (CCR) (hamstrings (HAMS)/vastus medialis (VM) activity) from normalized SEMG root mean squares were analyzed in the prelanding (PRE) (100 ms before initial contact (IC)), reflexive (REF) (100 ms after IC), and voluntary (VOL) (end of REF to maximum knee flexion) muscle activity phases. Repeated-measures statistical analyses determined significant gender, physical maturation, and target differences ($P < 0.05$) in CCR and associated HAMS and VM activity across landing phases. **Results:** A significant interaction ($P < 0.0001$) indicated similar CCR for children and adults during the REF and VOL phases, but during the PRE phase adult CCR (619.04 + 52.01) were two times greater than children's (308.32 ± 51.04). Significantly more HAMS activity, not less VM activity, increased adult PRE-CCR. Gender and target CCR differences were absent. **Conclusions:** Children's decreased preparatory cocontraction about the knee does not seem to be linked to increased ACL injury risk. Thus, adults may strive for preparatory cocontraction levels about the knee that permit adaptability to varied landing tasks. **Key Words:** ANTERIOR CRUCIATE LIGAMENT, JUMP LANDINGS, ELECTROMYOGRAPHY, COCONTRACTION RATIOS

Recent findings indicate that the incidence of noncontact anterior cruciate ligament (ACL) injury in females has remained consistent for more than a decade, despite training programs specific to ACL injury prevention and numerous research efforts into causative injury factors (1). Current data (1) indicate that collegiate female athletes continue to injure their ACL at rates 3.3 and 4.6 times greater than those of male athletes in soccer and basketball, respectively. The gender difference in ACL injury rates may range from 2.4 to 9.7 (7), with 70% of the injuries being noncontact (15). Numerous environmental, anatomical, hormonal, neuromuscular, and biomechanical factors contribute to this gender disparity (29), making the solution to the ACL injury puzzle clearly multifactorial. Influencing all of these factors is physical maturation. Maturation alters anatomical and hormonal characteristics, forcing neuromuscular and biomechanical adaptations in performance. Even environmental factors such as motivation, shoes, and playing surfaces may change with physical maturation as performers participate in settings that are more competitive. Thus, the impact of physical maturation or development on the risk factors for noncontact ACL injury warrants attention.

Many children, as young as 5 yr of age, participate in both instructional and competitive organized sport that requires them to jump and then land, plant, and pivot. These sport maneuvers are demanding of the ACL and are most likely to create injury (2), yet younger children do not injure their ACL at the same rate as older children (16). More than half of ACL injuries occur between 15 and 25 yr of age (16)—that is, during and subsequent to the anatomical and hormonal changes associated with puberty. Do younger participants, and those in the early stages of puberty, activate their muscles to move in ways protective of the ACL? Perhaps those in late and postpuberty move, particularly in landing, with strategies maladaptive to the structural changes of puberty, placing them at greater risk of injury (20).

Collegiate and adult populations have contributed much of the data for investigations into the causative factors of ACL injury risk. General findings suggest gender differences in the biomechanics of landing that may exacerbate ACL injury risk for females (29). Females tend to land in a more upright posture with less hip and knee flexion, greater internal hip rotation, tibial rotation, and knee valgus (29). Recent developmental research has tried to ascertain whether similar gender differences exist among younger age groups. If these differences exist, when during

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maturation do they appear? That is, when might the landing mechanics of young girls begin to differ from those of young boys and perhaps even adults (19,21,40,45). Because younger participants are not experiencing the same rate of ACL injury as older participants (16), this inquiry might highlight the timing and nature of gender differentiation in landing mechanics.

However, the presence of adult gender differences in landing mechanics may depend on the landing type (e.g., single leg, double leg) (18) and landing task (e.g., drop jump, vertical jump, stride jump, etc.) (29). Landing task demands may also influence the potential for gender differentiation in children. Typical explorations into landing biomechanics as related to ACL injury risk use pivot, planting, perturbation, and deceleration tasks that include mechanisms common to noncontact ACL injury (15). Laboratory studies attempt to replicate these mechanisms using varied drop or functional landing tasks. There are good experimental reasons to select either type of task. For example, use of drop-and-stop or drop-and-go landings from a standardized height (21) controls the velocity of the body's center of mass at entry into landing. Use of functional landing tasks, such as run-stop-go (19,45) or jump-stop (40), requires a normalization process to account for velocity differences at entry into landing, but this may represent a more realistic scenario, particularly for the neuromuscular system. The landing task should be selected with care, because different tasks may elicit varied neuromuscular demands, thus influence findings related to gender and physical maturation.

Findings from this study are associated with a functional landing task that allows performers to move within the limits of their own neuromuscular abilities. Performers land from a height that they can jump to—that is, representative of their neuromuscular "memory" (i.e., neuronal networks (e.g., fixed action patterns) that carry magnitude of force production and absorption data, among other data, and that respond selectively and quickly to well-defined environmental events, such as a typical landing height) (26). Drop-and-stop or drop-and-go landings done from a height specific to a subject's maximum vertical jump height (20) allow performance within a subject's neuromuscular "memory," but impact forces are then controlled with muscles just recently at rest as opposed to muscles that just shortened to generate some form of body propulsion. In functional landing tasks, subjects must control the landing with musculature just activated to move the body. This type of functional landing task may better assimilate neuromuscular system responsibilities in a scenario that has potential to injure the ACL.

When potential exists to injure the ACL during landing, the response of the neuromuscular system is critical. The ACL provides up to 86% of the resistance to anterior tibial translation (9), but external and internal forces incurred at the knee during landing often stress the passive ligament structures beyond their capacity, demanding additional active muscular forces to maintain joint stability (38,42). Increasing joint stiffness through cocontraction may augment the dynamic role of ligaments and shield them from excessive loads (24). *In vivo* exploration of hamstring and quadriceps cocontraction suggests that it doubles or even triples joint stiffness and decreases joint laxity by up to 50% (28). Because the ACL resists anterior tibial translation in a landing task, cocontraction of anteroposterior muscles (i.e., hamstrings and quadriceps) could reduce ACL loading and injury potential. The speed and amplitude of the anteroposterior neuromuscular response about the knee is critical to ACL protection (38), particularly given the demands and levels of perturbation within the dynamic tasks encountered in sport participation.

Despite the importance of the neuromuscular response, questions surrounding knee-joint muscular activity as related to ACL injury risk during landing have received little attention in the literature compared with questions seeking kinetic and kinematic gender differences in landing biomechanics. At the 2003 ACL injury retreat, participants agreed on few neuromuscular traits of knee stability: women compared with men tended towards quadriceps as opposed to hamstring dominance, produced less muscle stiffness, and responded to fatigue differently (29). These studies often used functional single-legged landing tasks or tests isolated from a landing scenario. Few investigations have used functional two-footed landing tasks (e.g., landing from a self-initiated vertical jump) to explore muscular activity gender differences. Moreover, most inquiries use college-aged and adult populations (8,14,36). A paucity of research addresses the neuromuscular traits of knee-muscle activation in children. Thus, as related to ACL injury risk, the influences of physical maturation and gender on the neuromuscular traits of anteroposterior knee-muscle activation remain unexplored.

Both McClay and Ireland (29) and Hass et al. (20) have advocated for further research into the effects of physical maturation on the biomechanical and neuromuscular factors associated with ACL injury risk. Recent findings from kinematic and kinetic data collected across gender for subjects spanning the pubertal years pointed to neuromuscular differences between males and females at the time of puberty (21,45) as a causative factor in ACL injury risk. Muscular activity must influence these mechanical differences associated with maturation. Knowledge of the age at which gender differentiation in the neuromuscular traits of landing may occur is important because muscular activity is partially responsible for dynamic knee stability and protection (42). In fact, the only aspect of dynamic knee stability that can be altered with some form of intervention is the influence of the neuromuscular response (42). Thus, information related to the neuromuscular aspects of physical development intertwined with the influence of gender may guide us in the initiation and development of training programs to increase dynamic knee stability and decrease ACL injury risk.

This study sought to determine neuromuscular differences in anteroposterior knee-joint muscle activation among prepubescent (children) and postpubescent (adult) males and females landing on two feet from a self-initiated vertical jump (VJ) under normal and perturbated (i.e., offset target) conditions. A cocontraction ratio (CCR) was calculated to assess the relative amount of posterior to anterior knee-muscle activation because cocontraction influences knee stiffness and the ability to stabilize the knee under dynamic loading scenarios, such as jump landing (24). From review of jump landing and related literature, four hypotheses were constructed. Compared with children, adults were expected to display a greater mean CCR, as evident in previous research (11). Adults were also expected to display higher CCR in preparation for landing compared with children, who were expected to have higher CCR during the landing (11). However, unlike previous research where gender-different CCR were absent when landing under normal target conditions (11), gender-different CCR were hypothesized for the current study, given the inclusion of the offset-target condition. Recent findings (42) from a similar task (i.e., landing on two feet from a functional task with variations) showed that females had greater CCR than males. Finally, higher CCR were anticipated in the offset-target condition because it was an attempt to challenge the neuromuscular system's ability to stabilize the knee during landing. A secondary purpose of this study was to observe knee-flexion differences associated with the initial muscle activity phase of landing, because preparatory cocontraction about the knee might influence knee motion immediately after landing. These kinematic observations could support the hypothesized gender and developmental differences.

METHODS

Subjects. Fifty-five subjects with no back or lower-extremity injuries volunteered to participate. Subjects were grouped by gender and age, that is, as either prepubescent or postpubescent. Because the onset of puberty correlates with a rapid gain in height at an average age of 10.5 yr for girls and 12.5 yr for boys, prepubescent subjects (i.e., children) included girls in the age range of 7–10 yr and boys in the age range of 8–11 yr. Prepubertal girls were screened for menarche, resulting in the exclusion of one subject. Puberty is complete at approximately 17 yr for females and 20 yr for males, and thus postpubescent subjects (i.e., adults) included 19- to 29-yr-old women and men. All children were current or recent past participants within a youth sports program that included jumping and landing activities (e.g., basketball, volleyball, and gymnastics). Adult subjects were currently active in recreational sport (i.e., at least 30 min of activity three times per week). Subject exclusion criteria included participation in a National Collegiate Athletic Association sport that included jumping and landing, or the inability to demonstrate a mature vertical jump (VJ) (41) (i.e., a preparatory crouch with almost 90° of knee flexion and a countermovement arm swing, followed by coordinated complete extension at the hips, knees, and ankles at take-off).

Subject preparation. On reporting to the biomechanics and motor control laboratory, adult subjects and a parent/legal guardian of each child read and signed a consent form approved by the university's institutional review board. Subjects dressed in form-fitting shorts, a tank top, socks, and received a new unused pair of sneakers to wear (New Balance Athletic Shoe Company, Lawrence, MA). Subject name, age, gender, height, weight, standing reach height, sport participation, and injury history were recorded. To determine limb dominance, each subject jumped up from two feet and landed on one foot (33). One trial was completed and the landing leg was labeled the dominant leg. Investigators also observed subjects complete a submaximal-effort VJ to confirm the existence of a mature VJ movement pattern (41) and, thus, determine study eligibility. Table 1 shows pertinent subject demographics.

Before data collection, target height and jump-start position were individualized for each subject. Target height was normalized to 50% of the maximum VJ height, previously assessed using a VERTEC (Sports Imports, Inc. Columbus, OH) and three maximal-effort VJ performed with a countermovement and without approach steps. Jump-start positions were determined as subjects practiced the jump-landing task used for data collection. This task required each subject to jump vertically off two feet, grab a suspended target (i.e., a 64-cm inflatable ball suspended from a retractable cord), and land on two feet facing forward, with only the dominant foot on the force plate. After six to eight practice trials, the jump-start position was marked on the floor for subsequent data collection.

To complete three-dimensional motion analysis, retro reflective markers (2.2-cm diameter) were applied bilaterally at each of the following sites: acromioclavicular joint, anterior–superior iliac spine, greater trochanter, anterior thigh, lateral femoral condyle, tibial tuberosity, middle tibia, distal tibia, superior navicular, lateral calcaneus, and base of the fifth metatarsal. A single marker was placed on the sacrum. Marker placement yielded an eight-segment model that included the head, arms, and thorax/abdomen as one segment, the pelvis, right and left upper legs, lower legs, and feet.

Bipolar surface electromyography (SEMG) determined the electrical activity of the vastus medialis (VM), medial hamstrings (semimembranosus and semitendinosus (MH)), and biceps femoris (BF) during the VJ. Silver/silver chloride pregelled surface electrodes (Blue Sensor Electrodes, Rugmarken, Denmark) were placed 2.5 cm apart and parallel to the muscle fibers over the longitudinal midline between the motor point and the tendon. A common reference electrode was placed over the head of the fibula. Thorough skin preparation for electrode placement included removal of dead epithelial cells with a razor,

TABLE 1. Subject characteristics (mean ± SD).

Group	Age (yr)	Height (cm)	Mass (kg)	Maximum VJ (cm)
Children (*N* = 28)	9.5 ± 0.9	136.5 ± 9.8	33.7 ± 8.1	29.2 ± 5.2
Girls (*N* = 14)	9.3 ± 0.9	136.6 ± 6.4	32.9 ± 8.4	27.0 ± 3.6
Boys (*N* = 14)	9.6 ± 1.0	136.3 ± 12.6	34.5 ± 8.1	31.4 ± 5.7
Adults (*N* = 27)	23.9 ± 2.8	170.6 ± 9.5	72.7 ± 15.0	48.8 ± 11.1
Women (*N* = 14)	24.2 ± 2.3	163.5 ± 6.2	62.4 ± 9.1	41.9 ± 4.6
Men (*N* = 13)	23.6 ± 3.4	178.1 ± 5.8	83.7 ± 11.9	56.2 ± 11.3

VJ, vertical jump.

isopropyl alcohol, and Nuprep abrasive pregel. Skin cleaning and abrasion achieved a skin impedance of < 5 kΩ after electrode application.

Data collection. After application of reflective markers and surface electrodes, subjects were instructed to jump from their start position, grab the target, and land facing forward on both feet with just the dominant foot on the force plate. Jumps included two-footed take-offs and landings. Under the normal condition, target placement was at the subject's midline. In the perturbated condition, the target offset from the dominant leg side was 45.7 cm for adults and 30.5 cm for children. The offset-target condition mimicked a functional dynamic task that forced lateral trunk movement, such as reaching for a ball while still in the air. Offset distances, determined through pilot work, elicited trunk movement (i.e., displacement of a large segmental mass) that appeared to require postural adjustments on landing but that allowed subjects to reach the target and land with control on two feet. Target condition was randomly assigned, and each subject completed four successful landings under one condition before attempting the second condition. Use of four successful landings allowed determination of mean data and kept the number of trials minimal, which discouraged learning in the offset-target condition and the potential for fatigue in both target conditions.

As subjects jumped, an external trigger synchronized the collection of all SEMG, force, and position–time data. The SEMG signal was amplified (gain setting of 1000, with a common mode rejection ratio of 90 dB) (EMG100, BIOPAC Systems Inc., Santa Barbara, CA), converted from analog to digital (MP100WSW, BIOPAC Systems Inc.), filtered (high- and low-pass Butterworth filters of 20 and 500 Hz, respectively), and digitized online with a sampling frequency of 1080 Hz. During the jumping and landing trials, raw SEMG signals were monitored online and stored using a DAS-16 Metrabyte data-acquisition card with a Gateway 2000 computer (San Diego, CA). Sampling rate and filter frequencies, along with skin preparation, were designed to achieve minimal signal attenuation and to remove potential movement artifacts and high-frequency noise.

Position–time data were collected with a six-camera (MAC Falcon High Resolution High Speed) three-dimensional motion-capture system (Motion Analysis, Inc. Santa Rosa, CA) that operated at 120 Hz. Data collection commenced as the self-initiated VJ started and lasted 5 s (i.e., through landing). Ground reaction force data were collected at 960 Hz with an Advanced Medical Technologies Incorporated (AMTI) force plate (Model OR6-7-2000, AMTI, Watertown, MA) interfaced with a six-channel signal amplifier (Model MSA-6, AMTI) set at a gain of 2000. Analog force data were converted (Model DT3002-16 bit, Data-Translation Inc., Marlboro, MA) to digital data at the Motion Analysis Inc., MIDAS system PC interface.

Before each data-collection session, a volume approximately equivalent to the space used by subject trials (3 × 3 × 7 m) was calibrated using a cube and wand technique. After collection of jumping and landing data for each subject, a static trial was collected to align the individual's joint coordinate system to the laboratory system. A 2.2-cm reflective marker placed on the patella permitted knee-joint center calculations after the subject stood still for 1 s during static position–time data collection.

Data reduction. A computer software program (BIOPAC Systems Inc., AcqKnowledge software, version 3.7.1) rectified the SEMG signal and calculated the mean amplitude of the root mean square (SEMGrms). The SEMGrms value, as determined by Basmajian and DeLuca (4), quantified the muscular activity for the BF, MH, and VL. SEMGrms values were extracted for each muscle for the three landing phases of interest (i.e., 100 ms before initial contact (IC) with the force plate, 100 ms after IC, and from 100 ms after IC to maximum knee flexion) in the four trials of each subject. In each trial, peak rectified SEMG values were determined from IC to maximal knee flexion for each muscle. After exporting these data to a spreadsheet, individual-muscle SEMGrms values for each landing phase where normalized to the within-trial peak rectified SEMG value. An EMG normalization process that uses a mean or peak value from the movement activity increases the reliability and sensitivity of the analysis and reduces intersubject variability (44). For these data, normalizing the SEMGrms values to within-trial peak SEMG values also negated unexpected, but potential, changes caused by fatigue. After normalization, subject means were determined from four trials, and then group means were calculated.

Motion Analysis EVa (version 6.01) software was used to track and smooth the three-dimensional position–time data. Smoothing employed a fourth-order low-pass Butterworth filter with a frequency cutoff of 10 Hz. Digitized position data were imported into the Motion Analysis Inc., Kintrak 6.02 software program, where an embedded right-hand Cartesian segment coordinate system was used in the calculation of joint centers. Knee flexion–extension was determined as the first rotation occurring about the medial–lateral axis. Knee-flexion angles were the amount of thigh rotation from a vertical axis extending from the ankle-joint center through the knee-joint center. Data were exported to a spreadsheet where knee-flexion means were determined from four trials for each subject, and group means were calculated for statistical analysis.

Dependent variables. Investigation of knee-joint muscle activation, particularly in the anteroposterior direction, was of primary importance to this study because excess quadriceps activity may increase ACL injury risk (25), particularly in the absence of corresponding hamstring muscle cocontraction that decreases the load on the ACL (25). Cocontraction of anteroposterior muscles may increase joint stiffness, unloading the knee ligaments and assisting dynamic joint stability (42). To quantify coupled anteroposterior muscle activity at the knee, CCR were calculated. The normalized activity of the knee flexors (i.e., averaged SEMGrms from the BF and MH (HAMS)) was divided by the normalized activity of a knee extensor (i.e., SEMGrms from the VM). Besier et al. (5) used a similar procedure to determine the relative activation of knee flexors and extensors. High CCR indicated greater HAMS activity relative to VM activity. Lower CCR indicated less HAMS activity relative to VM activity.

CCR were determined for three landing phases: a) 100 ms before IC with the force plate; b) 100 ms just after IC; and c) from 100 ms after IC to maximum knee flexion. Use of a 100-ms phase before landing allowed examination of muscle preactivation in preparation for landing. This time frame, consistent with other preactivation investigations (14,35), was used instead of a muscle-onset time because the muscles of most children displayed continual activity from maximal VJ height to the IC of landing. The continual muscle activity probably resulted from the use of a self-initiated VJ as opposed to a drop jump. During descent from a drop jump, muscles could remain relatively quiescent, because they were not just used to attain maximal jump height. In the self-initiated VJ, participants propelled themselves upward using muscular effort. Because the child participants had minimal air time, their muscles remained relatively active throughout descent as ascertained by visual inspection and specific offset/onset criteria (10). Thus, a preactivation time of 100 ms was used to indicate relative HAMS to VM activity (PRE-CCR) at entry into landing. A high PRE-CCR suggested that subjects preactivated or pretuned the hamstrings to increase stiffness before landing, using more of a feed-forward central nervous system (CNS) strategy in anticipation of the anterior knee stresses of landing (35).

The CCR determined 100 ms after IC was defined as the reflexive CCR (REF-CCR). After a stimulus such as jump landing, reflexive neuromuscular activity may occur as early as 20 ms or as late as 150 ms (35,37). The 20- to 150-ms range explains both monosynaptic and long-latency reflexive responses and includes estimated ranges of 20–60 ms (35,37), 35 or more ms (13), 30–70 ms (39), 50–60 ms (35,37), and 100–150 ms (35,37). From IC to 100 ms after, most of the muscle activity should be reflexive, and thus the CCR examined during this time were labeled REF-CCR. The amount of reflexive activity was not quantified, but the majority was assumed to occur within the first 100 ms after IC. Reflexive muscle activity precedes most of the voluntary activity (35,37), and depending on current joint-stiffness levels, reflexive activity preceding the earliest voluntary response may reduce injury potential (42). The CCR from 100 ms after IC to maximum knee flexion (mean time = 123 ms) was labeled the voluntary CCR (VOL-CCR) because voluntary muscle activity follows reflexive activity (35,37). The amount of voluntary activity was not quantified, but the majority was assumed to occur after the first 100 ms of landing. Higher REF-CCR and VOL-CCR would indicate greater reliance on the HAMS during these landing phases.

Knee angle at IC (KANG-IC) and the immediate amount of knee flexion during the reflexive phase (REF-%KFX) may relate to the potential for ACL injury (14). KANG-IC was recorded and REF-%KFX was determined as the amount of knee flexion during the first 100 ms after landing, expressed as a percentage of the total amount of knee flexion (i.e., from IC to maximum knee flexion). A small percentage of knee flexion during the REF phase could indicate that participants entered the task with a rigid or stiff lower extremity. Too much stiffness could impair adaptability and the modulation of impact forces (34), resulting in increased ACL injury risk. Thus, investigation of these knee kinematics supplemented the primary inquiry of anteroposterior knee-muscle activation during landing.

Data analysis. Completion of a power analysis before data collection established appropriate sample sizes. Before data collection, effect sizes were calculated from the limited available literature that had similar methods (10). For knee angle at IC (0.05) and the timing of neuromuscular events (0.5), effect sizes ranged from 0.05 to 0.5. For the other kinematic and kinetic variables collected, surveyed literature yielded effect sizes from 0.02 to 1.4. Using moderate to large effect statistics, an alpha level of 0.05, and power of 0.8, adequate sample sizes were estimated at 8–12. A sample of 14–15 subjects for each group established adequate power and accounted for subject mortality.

CCR differences were determined with a 2 × 2 × 3 × 2 (gender × developmental level × landing stage × target condition) repeated-measures analysis of variance (ANOVA). Landing stage (PRE, REF, and VOL) and target condition (straight or offset) were the repeated within-subjects factors. This analysis permitted comparison of coupled anteroposterior knee-muscle activation. To explain potential differences in CCR attributable to changes in HAMS and VM activity, a 2 × 2 × 3 × 2 × 2 (gender × developmental level × landing stage × target condition × muscle) repeated-measures ANOVA was used. In this analysis, landing stage, target condition, and muscle (HAMS and VM) were the repeated factors. Two separate ANOVAs determined differences in KANG-IC (2 × 2 × 2: gender × developmental level × target condition) and REF-%KFX (2 × 2 × 2: gender × developmental level × target condition). In all analyses, the conservative Greenhouse–Geisser adjustment factor indicated the significance of within-group F ratios. *Post hoc* comparisons consisted of planned orthogonal contrasts. Significance was established with $P < 0.05$.

RESULTS

CCR. Statistical analysis revealed significant (F (1, 51) = 14.64, $P < 0.0001$; effect size = 0.223) developmental-level differences in CCR. Children exhibited smaller CCR (177.83 ± 126.4) than adults (272.88 ± 333.82). Without regard to gender, landing phase, or target, adults had greater HAMS activity relative to VM activity compared with children. Also indicated was a significant landing phase difference (F (1.04, 53.1) = 94.71, $P < 0.0001$; effect

TABLE 2. Cocontraction ratios (CCR) for landing phases and developmental levels (mean ± SE).

	Landing Phase		
Developmental Level	PRE-CCR	REF-CCR	VOL-CCR
Children (*N* = 28)	308.32 ± 51.04	100.99 ± 2.56	124.17 ± 8.28
Adults (*N* = 27)	619.04 ± 52.01	86.06 ± 2.61	113.53 ± 8.44
Total mean (*N* = 55)	463.68 ± 36.44	93.53 ± 1.83	118.85 ± 5.91

CCR were derived using normalized values of the RMS from SEMG. HAMS activity values were divided by VM activity values.

Significant ($P < 0.05$) developmental level × landing phase interaction and landing phase differences.

size = 0.725). *Post hoc* analysis showed significant differences among the CCR for all three landing phases (Table 2). Perhaps most important, there was a significant developmental level by landing phase interaction (*F* (1.04, 53.1) = 19.32, $P < 0.0001$; effect size = 0.295). Children and adults had similar CCR during the REF and VOL phases, but during the PRE phase, adults had a CCR twice that of the children (Table 2).

There were no significant gender or target differences in the CCR (observed powers: gender = 0.054; target = 0.075). Across targets, landing phases, and developmental level, the males had a mean CCR of 227.64 ± 264.23, whereas the mean for the females was 223.06 ± 242.92. Across gender, developmental level, and landing phases, the mean target CCR were also incredibly similar (offset target = 228.22 ± 235.98; straight target = 222.48 ± 270.45).

HAMS and VM activity. Analysis of VM and HAMS activity normalized to respective peak trial values highlighted the source of CCR differences. Landing phase (PRE, REF, and VOL), muscle (HAMS and VM), and target (straight or offset) factors showed significant differences, but the most meaningful findings lay within interpretation of the two three-way interactions. The landing stage by muscle by developmental-level interaction (*F* (1.39, 71.06) = 9.65, *P* = 0.001) indicated that VM activity was similar to HAMS activity for both children and adults during REF and VOL phases, even though both muscles were slightly more active during the REF phase (Table 3). For both children and adults, PRE phase activity differed from REF and VOL phase activity. In the PRE phase, HAMS activity was 2.5 to 5.5 times greater than VM activity for children and adults, respectively (Table 3). The target by muscle by development interaction (*F* (1, 51) = 4.95, *P* = 0.03) indicated that mean HAMS activity was significantly greater for adults in the offset versus the straight-target condition (Table 4). For children, HAMS activity remained constant with changes in the target (Table 4). VM activity was slightly higher for both adults and children in the offset-target condition but was not significantly different from the straight target.

Reflexive-phase knee flexion. Knee-angle analyses revealed significant differences (*F* (1, 51) = 5.606, *P* = 0.022; effect size = 0.099) in KANG-IC between the offset and straight targets. The straight target elicited more knee flexion at IC (11.87 ± 5.71°) than the offset target (10.42 ± 5.63°). No gender or developmental differences were evident (observed powers: gender = 0.051; developmental level = 0.119). Analysis of the REF-%KFX (i.e., the first 100 ms) also showed significant target differences (*F* (1, 51) = 4.822, *P* = 0.033; effect size = 0.086). Subjects completed a greater percentage of their maximal knee flexion (80.94 ± 10.62%) when landing from the straight target compared with the offset target (79.34 ± 9.63%). In addition, children completed a significantly (*F* (1, 51) = 13.657, *P* = 0.001; effect size = 0.211) greater percentage of their maximal knee flexion (84.45 ± 6.33%) during the REF phase compared with adults (75.64 ± 11.37%).

DISCUSSION

Developmental-level comparisons. This study examined gender and developmental differences in dynamic knee-joint stabilization for a two-footed landing from a self-initiated vertical jump under normal and offset-target conditions. CCR described the coupled anteroposterior qualities of knee-joint muscle activation 100 ms before landing (preparatory phase (PRE)), 100 ms after landing (reflexive phase (REF)), and from the end of the REF phase to maximal knee flexion (voluntary phase (VOL)). Major findings indicated developmental differences in just the PRE-CCR and similarities in the REF and VOL-CCR (Table 2). Children and adults prepared for the landing differently regardless of gender and target location. Adults exhibited a PRE-CCR (619.0) twice that of children (308.3). Analysis of VM and HAMS activity in the PRE phase indicated the source of the CCR difference. Compared with children, adults used significantly more HAMS activity (adults = 39.1; children = 34.0) relative to VM activity (adults = 7.7; children = 12.2) (Table 3). These findings support the work of a previous paper (11) and our hypothesis that adults would enter the landing task with a greater CCR than children regardless of the target location. Thus, prepubescent children differed from adults in modulating knee-muscle cocontraction in preparation for a two-footed landing from a functional jumping task. As cocontraction improves joint stiffness (42), adults may have

TABLE 3. Muscle activity for landing phases and developmental levels (mean ± SE).

	PRE Landing Phase Muscle Activity		REF Landing Phase Muscle Activity		VOL Landing Phase Muscle Activity	
Developmental Level	HAMS	VM	HAMS	VM	HAMS	VM
Children (*N* = 28)	33.98 ± 2.55	12.23 ± 0.75	27.85 ± 0.70	27.90 ± 0.59	21.14 ± 1.18	18.21 ± 0.99
Adults (*N* = 27)	39.13 ± 2.60	7.74 ± 0.77	24.27 ± 0.72	28.51 ± 0.60	19.68 ± 1.14	19.09 ± 1.01

Muscle activity expressed as RMS values normalized to peak SEMG during landing. HAMS, average of medial and lateral hamstrings; VM, vastus medialis.

Significant ($P < 0.05$) landing phase × muscle × developmental level interaction.

TABLE 4. Muscle activity for each target by developmental level (mean ± SE).

Group	Straight-Target Muscle Activity		Offset-Target Muscle Activity	
	HAMS	VM	HAMS	VM
Children (N = 28)	27.83 ± 1.23	19.13 ± 0.68	27.48 ± 1.29	19.76 ± 0.61
Adults (N = 27)	25.46 ± 1.24	18.23 ± 0.70	29.93 ± 1.30	18.67 ± 0.62

Muscle activity expressed as RMS values normalized to peak SEMG during landing. HAMS, average of medial and lateral hamstrings; VM, vastus medialis. Significant ($P < 0.05$) target × muscle by developmental level interaction.

entered landing with a heightened level of knee-joint stiffness compared with children.

That children differ from adults is not surprising. In comparisons of pre- and postpubescent females, Hass and colleagues (19,20) highlighted both kinematic and kinetic differences in response to various drop-type and functional one-legged landings. As a child's body matures into its adult form, anatomical and hormonal changes necessitate adaptations in the neuromuscular system that may influence movement kinetics and, thus, kinematics. Maturation of neuromuscular control and growth-related strength gains may create differences in landing mechanics that distinguish prepubescent from postpubescent subjects (19). Comparisons with previous literature are difficult to make because few studies have quantified children's knee-muscle activity during landing (11). However, adult data are abundant.

Adults have shown preparatory muscle activity in isolated perturbation and landing studies (5,10). These studies have generally addressed the onset of muscular activity relative to IC, as opposed to the quantity of muscle activity before IC. As in this study, both knee-flexor and knee-extensor muscles were active before IC (10). Besier et al. (5) quantified the cocontraction of the three pairs of agonist and antagonist muscle groups about the knee during one-footed landings from functional tasks. Comparison of our adult CCR with their CCR was not possible because they calculated the ratios with slightly different equations. However, current findings support their results; that is, in both planned and unanticipated landing tasks, adult hamstring activation was greater than quadriceps activation during the PRE phase (5). Adults seem to generate high CCR about the knee in anticipation of landing by using significantly more HAMS activity relative to VM activity. This PRE-phase cocontraction may influence ACL injury potential.

Muscle cocontraction is important to joint stiffness and, thus, to dynamic knee stability and the ability to resist sudden and unexpected destabilizing loads (42). Before loading, increased joint stiffness through cocontraction may augment the dynamic role of ligaments, shielding them from excessive load. Cocontraction of the hamstrings assists the ACL in preventing excessive anterior tibial translation and internal rotation (25), so higher HAMS activity before landing may be protective of the ACL. A portion of this anticipatory muscle activity seems to be preprogrammed (3,10), perhaps even specifically to muscle groups that oppose the direction(s) of the anticipated load (5). Adults may ready the knee for impact with an anticipatory or feed-forward mechanism that uses higher HAMS activity compared with VM activity (11). Target location (straight or offset) and gender did not significantly alter this preparatory activity for adults. In contrast, children prepared for landing differently.

Children demonstrated significantly smaller CCR than adults during the PRE phase. As in previous findings (11), children used less HAMS activity relative to VM activity in preparation for landing (Table 3). Compared with adults, children were expected to have higher CCR in the REF and VOL phases immediately after and during landing, indicating reliance on muscle activity in these phases to stabilize the knee and possible use of a feedback as opposed to a feed-forward mechanism (11). Current data did not support this hypothesis. Children did exhibit slightly greater CCR in both the REF and VOL phases (Table 2), but with the introduction of the offset-target condition in this study, the REF and VOL-CCR were not significantly different from those of adults.

This finding clearly needs further investigation. How is it that children are controlling the impact forces of landing without injury? Given the cited importance of preparatory muscle activity at entry into landing, the smaller amounts of preparatory activity exhibited by children may decrease knee-joint rigidity and stiffness, suggesting decreased capacity to adapt to sudden and unexpected loads. However, children progressed through a significantly greater percentage of knee flexion (84.5%) than adults (74.5%) during the REF phase under both target conditions, and knee flexion during this phase of landing may "unload" the ACL and decrease injury risk (6). Perhaps adults overuse preparatory muscle activity to increase joint stiffness, creating a system that is so rigid it is less capable of adaptation.

A similar notion, that a system could be too rigid and may benefit from pliability, has been put forth by Hamill et al. (17) and Pollard et al. (31) in investigations of coordination and movement variability as related to injury risk in walking, running, and cutting maneuvers. A rigid system (e.g., the knee joint of adults versus children at entry into landing) is less malleable, less capable of variation in movement when loaded, and potentially at greater risk of injury. In functional landing tasks, Pollard et al. (31) recently found that women displayed decreased variability in intralimb couplings (i.e., a simultaneous assessment of segment motions such as hip abduction and adduction coupled with knee rotation) and used constrained, less variable movements. They concluded that use of constrained or more fixed movements may decrease the ability to adapt to unexpected perturbations, such as those encountered in sport participation, and increase the risk of acute injury or repetitive microtrauma (31). Although the current findings did not assess movement variability or examine more than one degree of freedom at a single joint, differences in knee-joint CCR between adults and children in the PRE phase affect muscle activity in the REF phase, movement kinematics, and, perhaps, adaptability to the impact of landing. The higher levels of cocontraction exhibited by adults in the PRE phase could constrain their landing mechanics, increasing their risk of injury. Children, using smaller amounts of cocontraction in preparation for landing, may have more pliable landing mechanics than adults. This pliability could contribute to the decreased rate of injury in children compared with adults.

Children's preparation for landing may also be different from adult preparation, simply because they are children. These children (ages 8–11) have different levels of physical maturation, skill, and experience compared with the adults (ages 17–29). These differences may necessitate varied landing-control strategies. Larkin and Parker (23) suggested that children (ages 7–9) used a hip strategy to control dynamic balance during two-footed drop-stop landings. Pelland et al. (30) also noted proximal control strategies in 7- to 8-yr-olds landing from jumps. Presetting tension in proximal hip and knee muscles before landing is important to posture at the time of IC (12). With smaller amounts of preparatory cocontraction about the knee exhibited by the children of this study, postural control at landing may have faced a greater challenge, demanding the use of a strategy different from that of adults.

Postural-control mechanisms are varied and complex, particularly when applied to stability and balance during landings. Both ankle- and hip-control strategies have been suggested for the stance phase of gait. The hip strategy is used in scenarios with large perturbations or when the performer is unable to generate enough force with the ankle (42). Perhaps the interplay of developing muscular strength and maturation of proximal to distal neuromuscular control dictate the use of a more proximal control strategy by children. That is, children generate greater peak impact forces at landing relative to body weight and jump height (20,40) and have yet to acquire mature force-production and modulation capabilities (23). Consequently, the relative loads at the IC of landing may be much larger for a child than for an adult. Children may be unable to handle these larger loads with an ankle-control strategy, dictating the use of a more proximal control strategy that draws on the larger and stronger muscles of the torso and hip as opposed to the knee and ankle.

Adults tend to modulate ankle-muscle activity as the parameters of two-footed drop-and-stop landings become more demanding (35), or adults may control ankle and knee motions first, at IC, followed by hip and torso actions (12). These observations may indicate use of a more distal control strategy by adults. More PRE-phase knee-joint cocontraction, greater muscular strength, and mature neuromuscular control may allow adults to use a more distal landing-control strategy, whereas children use a more proximal strategy. The influence of these maturation-related landing-control differences on the risk of ACL injury is unknown and clearly merits further investigation, but recent inquiry shows that neuromuscular changes during puberty, coupled with the ability to attenuate force, may be critical to the control of landing and, perhaps, ACL injury risk (21).

Other potential influences on preparatory muscle activity for landing include proprioceptive, visual, and vestibular inputs, learned responses (3), time to prepare and anticipate, and segment kinematics. All of these factors may shape knee-joint cocontraction at entry into landing, influencing developmental differences. In addition, landing skills may improve with jumping ability. If maximal VJ height reflects jumping ability, adults were the most skilled jumpers. A higher absolute jump height certainly allowed adults more time to prepare for landing. Discussion of all of the aforementioned factors is beyond the scope of this paper, but preparatory anteroposterior knee-joint muscle activation differences clearly exist, coupled with data showing a higher rate of injury in older age groups. Whatever prepubescent children are doing to prepare for landing, it does not seem to exacerbate ACL injury risk. Perhaps adults need to adopt a "safer" landing strategy (20), one that includes preparatory muscle activity similar to that of children.

Gender comparisons. There were no significant gender differences in CCR in the PRE, REF, or VOL phases of landing. Males (PRE-CCR = 448.92; REF-CCR = 95.28; VOL-CCR = 126.33) and females (PRE-CCR = 464.03; REF-CCR = 93.23; VOL-CCR = 111.93) used similar amounts of cocontraction about the knee in preparation for landing and in response to landing under both target conditions. These findings did not support our hypothesis that the offset-target condition would challenge the neuromuscular system enough to provoke existing gender differences.

Gender comparisons in the quantity of muscle activity in preparation for and in response to various landings have shown differences under some conditions (10,36) but have failed to distinguish males from females in other scenarios (8,14). In an examination of average normalized SEMG values for single quadriceps and hamstring muscles when landing on one leg from a drop jump and maximum VJ, the muscle activity of adult males was similar to that of adult females during a 100-ms PRE phase and during the first and second 100-ms phases after landing (14). These conclusions were true even under conditions of fatigue. Boros and Challis (8) also found no differences in mean normalized peak SEMG amplitudes in knee-flexor and knee-extensor muscles of adult males and females during the preparation and landing phases of two-footed drop-stop landings onto the heels. The current findings for adults support the findings of these studies, but other cutting- and landing-task investigations show dissimilarities in muscle activation between adult males and females (10,36). Given the variety of landing activities (e.g., functional task, isolated test, number of legs) subject characteristics (e.g., gender, age, skill, conditioning, ACL status), and conditions of examination (e.g., fatigue, perturbation), research findings have yet to consistently support gender differences in muscle activation between adult males and females in preparation for and in response to landing. Very little is known about gender differences in the neuromuscular traits of children as they prepare for and respond to landing, but because children generally display more movement and muscular activation variability than adults, these conclusions may be even harder to draw.

The offset-target condition did not expose gender differences in cocontraction about the knee. This target condition may not have challenged the neuromuscular system enough, because the relative height was 50% of the maximum VJ height and the offset was standardized, one distance for adults and another for children. Height and offset distances were selected to enable successful target capture and landing for both children and adults. Perhaps the use of a greater jump height, coupled with an offset relative to the functional reach of each subject, would have created enough challenge to provoke any underlying gender differences. In addition, the offset target did not present an unexpected perturbation. Subjects knew where the target was located before jumping and practiced landings from the offset-target condition. These procedures enabled successful landings but familiarized the neuromuscular system with the offset-target condition and allowed it to preprogram a response. Had the offset-target landings been a surprise, muscle activity may have been very different from the normal target conditions, and gender differences may have been evident. Thus, the nature of the offset-target condition may not have triggered existing gender differences in this sample, or gender differences may simply not exist for these recreational athletes during two-footed landings from a self-initiated VJ.

Target considerations. Introduction of the offset-target condition did not significantly alter cocontraction about the knee as indicated by the calculated CCR, but it did create subtle yet significant changes in HAMS muscle activity. Adults kept VM activity relatively constant but used significantly more HAMS activity than children in the offset-target condition as opposed to the straight-target condition (Table 4). Children kept both VM and HAMS activity constant under both target conditions. Because hamstring activity is protective of the ACL with the loads imposed by landing, the adult response may indicate a tendency to create a more rigid link between segments in response to a potentially destabilizing task. Children may not increase HAMS activity for numerous reasons, such as a tendency to remain more pliable under destabilizing conditions, use of a more proximal landing strategy, or factors related to physical maturation, skill development, and experience. Although statistically significant and interesting, these developmental differences in HAMS activity when landing from the offset target did not alter the CCR at the knee. Presentation of a more challenging offset-target condition or other destabilizing task may clarify the impact of altered HAMS activity on knee cocontraction and refine the nature of any developmental differences.

Knee-joint kinematics varied slightly with target condition. Adults and children completed significantly less knee flexion in the REF phase in the offset-target condition (79.3%) as opposed to the straight-target (80.9%) condition. This difference reflects statistically significant alterations in knee angle at entry into each target (offset = 10.4°; straight = 11.9°) combined with the completion of dissimilar ranges of motion during the REF phase (offset = 49.7°; straight = 51.2°). These knee-kinematic differences could reflect a tendency towards more segment rigidity in preparation for and in response to landing under the novel offset-target condition. However, the magnitudes of these differences are very small: 1.5° at entry into landing and during the REF phase, yielding approximately a 3° difference in the mean absolute amount of knee flexion at the end of the REF phase (offset = 60.1°; straight = 63.0°). It is hard to conclude that a 3° statistical difference has functional and meaningful significance to ACL injury potential, particularly because at the end of the REF phase, subjects responded to both target conditions with at least 60°of knee flexion. This amount of knee flexion should safeguard the ACL (25). Further investigation into preparatory cocontraction about the knee and its relationship to the amount of knee flexion immediately after the IC of landing may help explain the functional significance of these findings.

Limitations. Controlled laboratory ACL injury–risk studies are limited in their generalizability to true ACL injury potential, because it is next to impossible for laboratory studies to mimic ACL injury risk in competitive and practice games. Yet, controlled settings can yield valuable information and isolate the influence of certain factors within the real game. This study attempted to replicate real injury situations by using a functional jump-landing task as opposed to a drop jump. The functional task allowed the neuromuscular system to produce and respond to familiar force generation and loading. Beyond this attempt at a realistic task, all of the subject-preparation and data-collection procedures could have shaped the findings. Lack of the influences of a game setting, and even of a real ACL injury, must be considered in interpreting these results and results from similar ACL injury–risk studies conducted in laboratory settings.

Both EMG and three-dimensional motion-analysis data-collection processes have limitations. The EMG signal is very complex, random (27), and susceptible to multiple influences inherent within an individual. These influences include, but are not limited to, the type, size, and distribution of muscle fibers; motor point location within a muscle (27); and an individual's skill level and ability to generate muscle power (22). Differences in these factors create increased variability in the EMG signal, despite, as was done in this study, standardized electrode placement, preparation, and use of subjects with a mature VJ. To further minimize EMG variability, individual muscle signals were verified with manual muscle testing and performance of the jump-landing task after electrode placement. However, for some groups in this study, EMG signal variation was still large. Among other factors, this variability could be related to the introduction of a novel task (offset target) and the use of groups with different strength and skill characteristics (e.g., both the male and female groups include both children and adults). The study design and protocol could have further increased EMG variability and affected the significance of results.

Use of a segment-linked model coupled with an inverse dynamics approach necessitates acceptance of link-segment modeling assumptions (43). The reliability of knee-angle data was influenced by collected position–time data (e.g., varies with marker placement, marker movement) and data-reduction procedures (e.g., varies with computer program treatments of digitizing, smoothing, etc.). The motion-analysis calibration protocol allowed marker accuracy within 0.5 mm (32), and the same investigator consistently attached and secured the markers. Marker movement was monitored during data collection. These procedures improve the accuracy of the reported knee-angle data.

CONCLUSIONS

Even with the aforementioned limitations, important findings resulted from this study. Anteroposterior cocontraction about the knee differed between adults and children in preparation for landing from a self-initiated vertical jump. CCR indicated that adults, compared with children, used more muscle activity from the HAMS relative to the VM. This developmental difference may exist because children rely on a proximal strategy (e.g., one that uses the larger and stronger muscles in the hip and torso) as opposed to a knee or ankle strategy to control the forces of landing. Children might prepare for landing differently than adults, simply because they remain more pliable and less constrained when presented with destabilizing tasks. Whatever it is that these prepubescent children are doing to prepare for and control landing, their strategy does not seem to be linked to increased ACL injury risk, because adults have exhibited a greater incidence of ACL injury (16).

Gender differences were absent from this sample and were not elicited by the inclusion of an offset-target condition. Multiple research findings indicate both gender similarities and dissimilarities in the neuromuscular preparation and response to various landings. Lack of consensus suggests a need for further investigation. The offset-target condition provoked greater hamstring muscle activity throughout landing for adults, but this increased activity did not alter the CCR. Introduction of a more challenging target may change the CCR, clarifying the adult response to a potentially destabilizing task.

The developmental difference in preparatory muscle activity, coupled with the smaller rate of injury in prepubescent subjects, may indicate a need for adults to develop the pliability exhibited by children. Because the neuromuscular response is the only aspect of stiffness and dynamic knee stability influenced by training, interventions should continue to expose participants to numerous and varied tasks at multiple levels of difficulty. The influence of these interventions on the neuromuscular characteristics of landing warrants more coverage as related to ACL injury risk.

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