Age Influences Biomechanical Changes After Participation in an Anterior Cruciate Ligament Injury Prevention Program

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Background: The prevalence of anterior cruciate ligament (ACL) injuries increases during maturation and peaks during late adolescence. Previous studies suggested an age-related association between participation in injury prevention programs and reduction of ACL injury. However, few studies have investigated differences in biomechanical changes after injury prevention programs between preadolescent and adolescent athletes.

Purpose/Hypothesis: The purpose was to investigate the influence of age on the effects of the FIFA Medical and Research Centre (F-MARC) 11+ injury prevention warm-up program on differences in biomechanical risk factors for ACL injury between preadolescent and adolescent female soccer players. It was hypothesized that the ACL injury risk factors of knee valgus angle and moment would be greater at baseline but would improve more after training for preadolescent athletes than adolescent athletes. It was further hypothesized that flexor-extensor muscle co-contraction would increase after training for both preadolescent and adolescent athletes.

Study Design: Controlled laboratory study.

Methods: Institutional Review Board–approved written consent was obtained for 51 preadolescent female athletes aged 10 to 12 years (intervention: n = 28, 11.8 ± 0.8 years; control: n = 23, 11.2 ± 0.6 years) and 43 adolescent female athletes aged 14 to 18 years (intervention: n = 22, 15.9 ± 0.9 years; control: n = 21, 15.7 ± 1.1 years). The intervention groups participated in 15 in-season sessions of the F-MARC 11+ program 2 times per week. Pre- and postseason motion capture data were collected during 4 tasks: preplanned cutting, unanticipated cutting, double-legged jump, and single-legged jump. Lower extremity joint angles and moments were estimated through biomechanical modeling. Knee flexor-extensor muscle co-contraction was estimated from surface electromyography.

Results: At baseline, preadolescent athletes displayed greater initial contact and peak knee valgus angles during all activities when compared with the adolescent athletes, but knee valgus moment was not significantly different between age groups. After intervention training, preadolescent athletes improved and decreased their initial contact knee valgus angle (–1.24° ± 0.36°; P = .036) as well as their peak knee valgus moment (–0.57 ± 0.27 percentage body weight × height; P = .033) during the double-legged jump task, as compared with adolescent athletes in the intervention. Compared with adolescent athletes, preadolescent athletes displayed higher weight acceptance flexor-extensor muscle co-contraction at baseline during all activities ($P < .05$). After intervention training, preadolescent athletes displayed an increase in precontact flexor-extensor muscle co-contraction during preplanned cutting as compared with adolescent intervention athletes (0.07 ± 0.02 vs –0.30 ± 0.27, respectively; P = .002).

Conclusion: The F-MARC 11+ program may be more effective at improving some risk factors for ACL injury among preadolescent female athletes than adolescent athletes, notably by reducing knee valgus angle and moment during a double-legged jump landing.

Clinical Relevance: ACL prevention programs may be more effective if administered early in an athlete's career, as younger athletes may be more likely to adapt new biomechanical movement patterns.

Keywords: intervention program; biomechanics; muscle co-contraction; adolescent and preadolescent athletes; age comparison

Female athletes participating in cutting and landing sports demonstrate a 4- to 6-times greater incidence of anterior cruciate ligament (ACL) injury when compared with their male counterparts.[2,19] However, sex differences in ACL injury incidence are not present for preadolescent athletes,[1,6] suggesting that boys and girls may diverge from one another during puberty in a way that increases the risk of ACL injury among females. Comparisons of jump-landing biomechanics between preadolescent and adolescent subjects revealed more movement errors among preadolescent subjects,[12] including greater knee valgus angle.[35] The increased risk of girls to sustain ACL injury could be mitigated by implementing an injury prevention program before adolescence.

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Movement patterns associated with increased injury risk emerge in female athletes after the pubertal growth spurt[13,21,22,29] and coincide with the peak prevalence of ACL injury.[22] For example, after the onset of puberty, female athletes land from a jump with greater peak knee valgus angle[13,21] and peak knee valgus moment[13] as compared with male athletes. Rapid increases in lower extremity bone length that occur during adolescence correspond with increases in muscle power and strength in male athletes but are related to a decrease in dynamic knee stability in female athletes.[22] The absence of sufficient neuromuscular adaptation to stabilize the knee in the face of larger forces and torques after growth may be an underlying cause of increased injury risk among postpubertal female athletes.[28]

A potential motor control strategy used to stabilize the knee to prevent injury is muscle co-contraction. For example, hamstring activation can act as an antagonist to quadriceps activation to decrease the load experienced by the ligaments of the knee[26] and stabilize the knee from external varus and valgus loads.[14,24] The effects of age and skill level on muscle co-contraction vary among previous studies.[7,8,15,16,33] It is not well known how muscle coordination patterns compare between pre- and postadolescent females during sport-specific movements.

A recent meta-analysis revealed that ACL injury rates were lower in early versus late adolescence for those participating in injury prevention training,[28] suggesting that preadolescence may be an optimal time to initiate injury prevention training. Our previous investigation of preadolescent female soccer players found improvement in some kinematic and kinetic risk factors for ACL injury after participation in the FIFA Medical and Research Centre (F-MARC) 11+ injury prevention warm-up program—most notably, a reduction in peak knee valgus moment during a jump-landing task.[36] Furthermore, participation in an injury prevention program can improve preparatory co-contraction of knee muscles during a subsequent cutting maneuver,[37] which may represent a more ACL-protective motor strategy. However, the effect of injury prevention training on muscle co-contraction among preadolescent athletes remains unknown.

A direct comparison of biomechanical differences between older and younger athletes would aid our understanding of age-related injury mechanisms. Despite this need, relatively few data exist comparing pre- and postadolescent athletes,[13,17,21,29,35] and few studies have investigated the influence of age on changes in biomechanical risk factors for injury after an injury prevention program.[12,28] The purpose of the current study was (1) to quantify differences in biomechanical and neuromuscular risk factors for ACL injury between preadolescent and adolescent female soccer athletes during cutting and jump-landing tasks and (2) to investigate changes in biomechanical risk factors between the age groups after participation in the F-MARC 11+ injury prevention program.[34] We hypothesized that the ACL injury risk factors of knee valgus angle and moment would be greater for preadolescent athletes than for adolescent athletes at baseline but would improve more after training. We further hypothesized that flexor-extensor muscle co-contraction would increase after training for both preadolescent and adolescent athletes, thereby demonstrating a more ACL-protective motor strategy.

METHODS

Subjects

Before testing, Institutional Review Board approval was obtained and written informed consent acquired for 94 female soccer athletes: 51 between 10 and 12 years old (preadolescent) and 43 between 14 and 18 years old (adolescent). Athletes were recruited from local area high schools and soccer club teams (Table 1). Exclusion criteria included prior ACL injury, lower extremity surgery within the past year, serious lower extremity injury within the past 6 months (defined as an injury requiring >4 weeks of absence from participation in soccer activity), and prior or current participation in an ACL injury prevention program. Twenty-eight preadolescent athletes and 22 adolescent athletes from 5 soccer teams participated in the intervention program and laboratory testing components of the research study. Twenty-three preadolescent and 21 adolescent athletes from 22 other teams served as controls and completed laboratory testing only. For preadolescent athletes, there were no differences in height (P = .094) or weight (P = .136) between the intervention and control groups before testing, despite a small but significant 0.6-year age difference (P = .017). For adolescent athletes, there were no differences in height (P = .654), weight (P = .767), or age (P = .586) between the intervention and control groups.

The laboratory testing and intervention methods have been detailed previously[36] and are briefly described here.

Laboratory Testing

All subjects (intervention and control) from both age groups participated in 2 identical laboratory testing sessions, separated by approximately 10 weeks (preadolescent, 65 ± 8 days; adolescent, 76 ± 22 days). Thirty-six retroreflective markers were affixed to each subject, according to Braun et al.[5] Marker positions were recorded at 200 Hz with an 8-camera optical motion capture system (Motion Analysis Corporation) and were synchronized with measurements from 3 floor-mounted force plates collected at 2000 Hz (Bertec Corporation). Each subject performed an initial static

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TABLE 1
Subject Demographics[a]

	Pretest		Posttest	
	Intervention	Control	Intervention	Control
Preadolescents, No.	28	23	26	20
Age, y	11.8 (0.8)	11.2 (0.6)		
Height, m	1.54 (0.08)	1.49 (0.08)	1.55 (0.08)	1.51 (0.09)
Mass, kg	41.6 (8.5)	38.1 (6.0)	42.3 (8.7)	38.2 (6.3)
Adolescents, No.	22	21	20	17
Age, y	15.9 (0.9)	15.7 (1.1)		
Height, m	1.66 (0.04)	1.66 (0.06)	1.66 (0.04)	1.67 (0.06)
Mass, kg	58.2 (5.6)	57.7 (7.7)	58.6 (4.9)	58.0 (7.2)

[a]Values are presented as mean (SD) unless noted otherwise.

standing calibration trial. Subjects then completed 2 jump-landing tasks from a 30-cm box in random order: double- and single-legged jumps on the dominant limb. The dominant limb was identified by the participant when asked which leg she would use to kick a soccer ball as far as possible. For both tasks, subjects jumped forward a distance of 50% body height (double-legged) or 40% body height (single-legged) onto the force plates and immediately performed a countermovement jump for maximal height. Upon completion of the jump-landing tasks, subjects were familiarized with and then performed 2 cutting tasks: preplanned and unanticipated. For both tasks, the subjects performed a running sidestepping cut off their dominant limb at approximately 45° from the line of approach, with an approach speed of 3.8 ± 0.5 m/s, comparable to the speed used in previous similar studies,[4,5] as monitored with timing gates (Fusion Sport). For the unanticipated cutting task, the cutting direction was randomly cued with 1 of 2 timing lights. A trial was considered good if the athlete landed with her entire dominant foot on a single force plate.

Intervention

The F-MARC 11+ injury prevention warm-up program[34] was started approximately 2 to 3 weeks after the baseline testing (preadolescent, 12 ± 6 days; adolescent, 18 ± 13 days). Regardless of participation in the research study, all athletes on the intervention teams participated in the F-MARC 11+ on-field training. The intervention was conducted during the soccer season and consisted of 15 sessions (approximately 2 per week for 7-8 weeks). Each session was approximately 25 minutes and replaced each team's standard warm-up before the start of regular practice. Full details on the exercises can be found at www.footballmedicinecentre.com/11-warm-up-program/. A minimum of 1 of 5 trained research staff members attended each training session. The research staff administered the intervention program, provided feedback on proper technique, and tracked athlete progression through increasing difficulty levels of the exercises (Table 2). Athlete attendance, defined as the percentage of total training sessions completed, was 70.2% ± 14.0% for the preadolescent athletes and 75.4% ± 16.6% for the adolescent athletes.

TABLE 2
Number of Intervention Athletes in Each Age Group Who Progressed to Levels 2 and 3 per Progressive Exercise

	Preadolescents[a]		Adolescents		
	Level 1	Level 2	Level 1	Level 2	Level 3
Front plank	28	0	22	22	6
Side plank	28	0	22	22	0
Nordic hamstring	28	13	22	22	4
Single-legged stance	28	28	22	10	4
Squats	28	12	22	22	4
Jumping	28	12	22	10	0

[a]No preadolescents advanced to level 3.

Musculoskeletal Modeling

The ground-reaction force data were low-passed filtered with a fourth-order critically damped filter with a cutoff frequency of 30 Hz. We analyzed 3 trials for each activity for each subject with OpenSim software (v 3.2).[11] Joint angles and moments were estimated as previously described.[36] Joint moments were normalized by subject body weight and height. All joint moments are reported as external moments.

Muscle Activation

Surface electromyography (EMG) data were recorded at 2000 Hz from the vastus lateralis, vastus medialis, biceps femoris, and medial gastrocnemius muscles from each subject's dominant limb with preamplified, double-differential, rectangular Ag electrodes with 10-mm interelectrode distance (Trigno Wireless; Delsys Inc). Skin preparation and electrode placement followed SENIAM recommendations.[18] Raw EMG data were high-pass filtered at 10 Hz with a fourth-order Butterworth filter, then full wave rectified and smoothed with an RMS filter with a 20-millisecond window. The RMS data were then normalized by the maximum 100-millisecond moving average for each muscle measured during a series of activities geared toward eliciting maximum

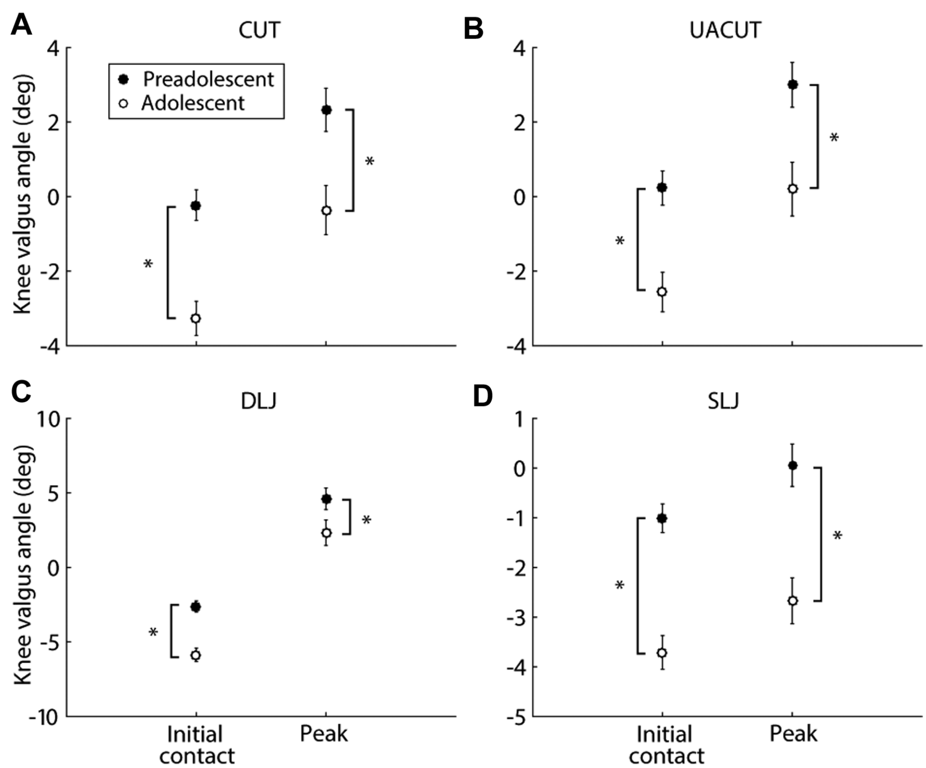

Figure 1. Baseline initial contact and peak knee valgus angles during (A) preplanned cutting (CUT), (B) unanticipated cutting (UACUT), (C) double-legged jump (DLJ), and (D) single-legged jump (SLJ). *$P < .05$, preadolescent (filled) vs adolescent (open) age groups. Error bars represent SEM.

voluntary muscle contraction, including running, squat jumping, and resisted hamstring curls. These normalization trials were performed at the beginning of each session, before the cutting and jump-landing tasks.

Muscle Co-contraction

Muscle co-contraction was estimated for the knee flexor-extensor muscles (flexors: lateral hamstrings, medial gastrocnemius; extensors: vastus lateralis, vastus medialis). A co-contraction ratio for the flexor-extensor muscles was determined with the average normalized activation for flexors and extensors according to the following equation[30]:

$$\frac{\text{lesser EMG}}{\text{greater EMG}} \times (\text{lesser EMG} + \text{greater EMG}).$$

Statistical Analysis

For all kinematic and kinetic variables for each trial and activity, we identified the values at initial contact as well as the peak values during weight acceptance, defined as the interval between initial contact and peak knee flexion. For muscle co-contraction, we identified the values during precontact, defined as the interval between 50 milliseconds before initial contact and initial contact, and the values during weight acceptance. The values from 3 trials were averaged. For comparison of baseline measures between preadolescent and adolescent athletes, the intervention and control groups were lumped together, and independent sample *t* tests were used to test for differences between the age groups. For comparison of pre- to postchange between preadolescent and adolescent athletes in each group, the pre- to postchange in each variable was calculated by subtracting each subject's mean pretest value from her mean posttest value. Univariate analyses of variance (ANOVAs) with Tukey honest significant difference post hoc tests for multiple-group comparisons were then used to test for differences in the mean change between preadolescent and adolescent intervention athletes who participated in the training program, as well as differences between control and intervention athletes within each age group. All statistical tests were performed in SPSS Software (v 21.0; IBM), and the level of significance was set at $\alpha = 0.05$. Results are presented as the mean ± SEM.

RESULTS

Baseline Knee Valgus Angle and Moment

For all activities, initial contact and peak knee valgus angles were greater at baseline among preadolescent athletes as compared with adolescent athletes (Figure 1). Baseline knee valgus moment was not significantly different between age groups for any of the activities (Figure 2).

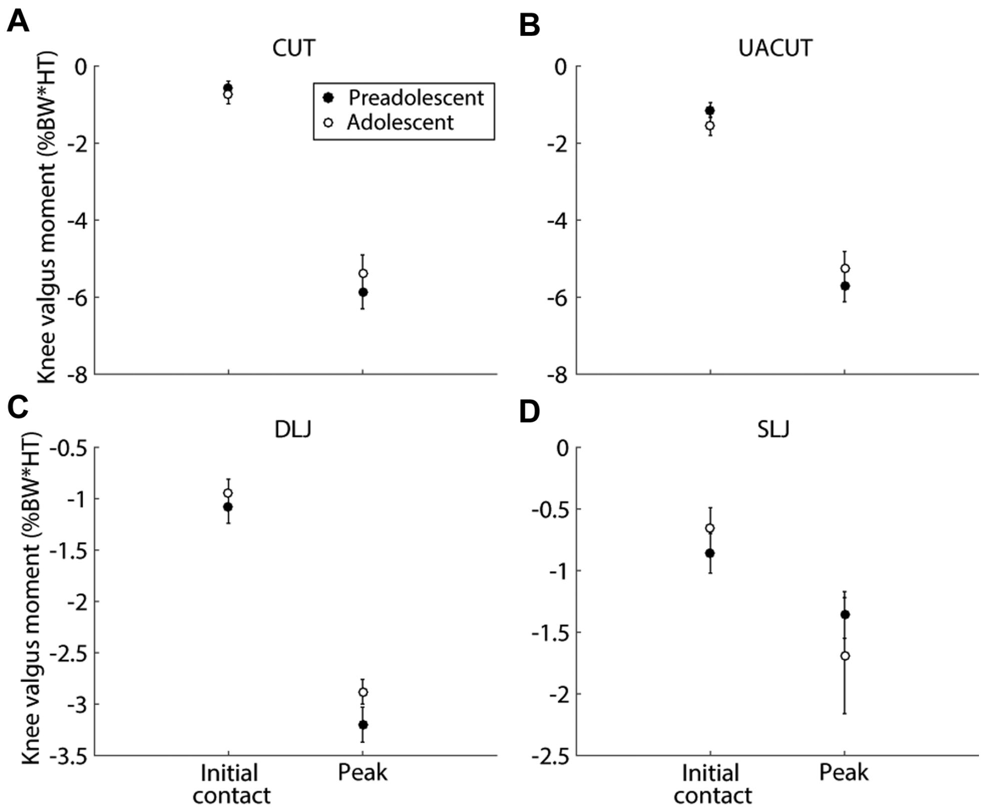

Figure 2. Baseline knee valgus moments, normalized by body weight (BW) and height (HT), at initial contact and peak during (A) preplanned cutting (CUT), (B) unanticipated cutting (UACUT), (C) double-legged jump (DLJ), and (D) single-legged jump (SLJ). There were no significant differences between preadolescent (filled) and adolescent (open) age groups ($P > .05$). Error bars represent SEM.

Baseline Muscle Co-contraction

At baseline, the only difference in precontact flexor-extensor muscle co-contraction was a higher co-contraction ratio for preadolescent athletes during the single-legged jump when compared with adolescent athletes ($P = .021$). During weight acceptance, the preadolescent athletes displayed higher co-contraction during cutting ($P = .016$), unanticipated cutting ($P = .002$), double-legged jump ($P < .001$), and single-legged jump ($P < .001$) as compared with the adolescent athletes (Figure 3).

Knee Valgus Differences After the Intervention Program

The ANOVA revealed a significant group effect in the pre- to postchange for initial contact knee valgus angle ($P = .004$) and peak knee valgus moment ($P = .011$) during the double-legged jump task. This group effect was driven by differences between the preadolescent and adolescent athletes in the intervention. Specifically, after participation in the F-MARC 11+ program, the preadolescent athletes improved (ie, decreased) their initial contact knee valgus angle (Figure 4A) ($P = .036$) for the double-legged jump-landing task versus the change for adolescent athletes. After the intervention, the preadolescent athletes also improved their peak knee valgus moment (Figure 4D) ($P = .033$) during the double-legged jump-landing task as compared with adolescent athletes. No other significant differences were detected between intervention groups for knee valgus angle or knee valgus moment (Figure 4).

For all activities in both age groups, the changes in initial contact and peak knee valgus angles were not significantly different between the intervention athletes (ie, who participated in the F-MARC 11+ program) and the control athletes (ie, who did not participate in the F-MARC 11+ program). Preadolescent athletes in the intervention improved their peak knee valgus moment ($P = .046$) during the double-legged jump-landing task when compared with the preadolescent controls.

Muscle Co-contraction Differences After the Intervention Program

The ANOVA revealed a significant group effect in the pre- to postchange for precontact flexor-extensor muscle co-contraction during preplanned cutting ($P = .004$). This group effect was driven by differences between the preadolescent and adolescent athletes in the intervention. After participation in the F-MARC 11+ program, preadolescent

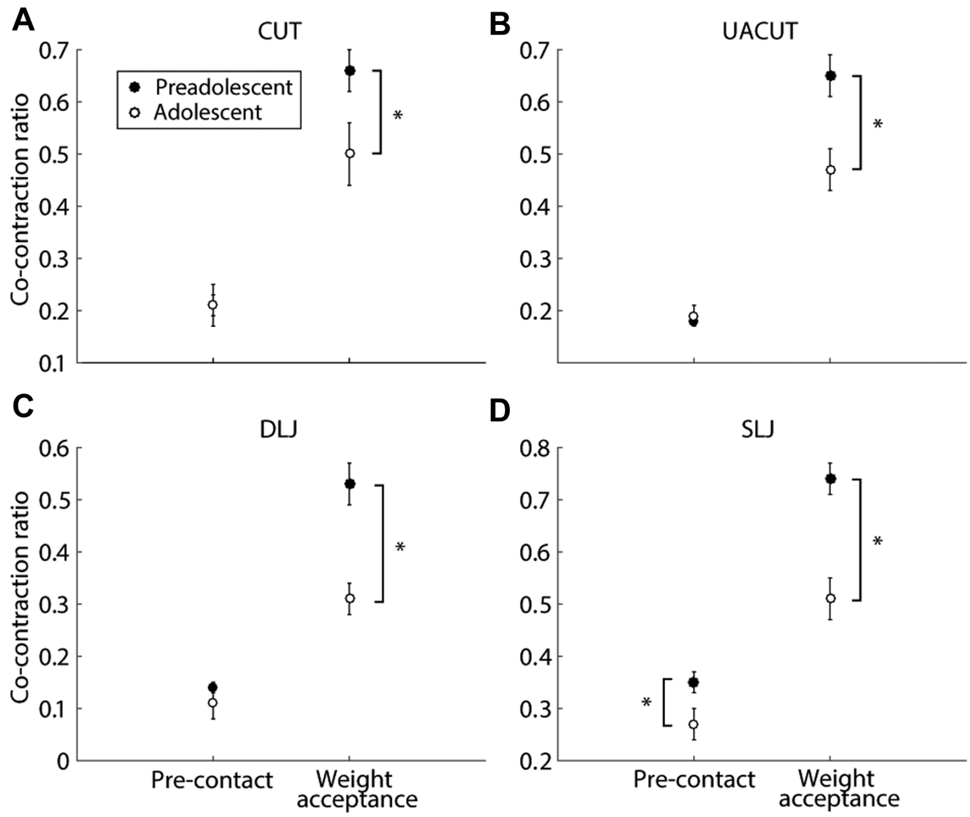

Figure 3. Baseline flexor-extensor muscle co-contraction ratio at initial contact and peak during (A) preplanned cutting (CUT), (B) unanticipated cutting (UACUT), (C) double-legged jump (DLJ), and (D) single-legged jump (SLJ). *$P < .05$, preadolescent (filled) vs adolescent (open) age groups. Error bars represent SEM.

athletes displayed increased precontact flexor-extensor muscle co-contraction as compared with the change for adolescent athletes during preplanned cutting (Table 3) (P = .002). There were no differences in muscle co-contraction between the preadolescent controls and the intervention athletes during precontact or weight acceptance for any activity. Compared with controls, adolescent athletes in the intervention displayed decreased precontact flexor-extensor co-contraction during preplanned cutting (P = .020). There were no additional differences between adolescent controls and the intervention athletes.

DISCUSSION

The aims of this study were to quantify differences in biomechanical risk factors between preadolescent and adolescent female soccer players and to investigate if the F-MARC 11+ injury prevention program was more effective in younger versus older athletes. In partial support of our hypothesis, we found that the knee valgus moment improved more for preadolescent athletes than adolescent athletes but only for the double-legged jump task. Our hypothesis that flexor-extensor muscle co-contraction would increase after training was unsupported, with the exception of an increase in precontact co-contraction among preadolescent athletes versus adolescent athletes during preplanned cutting.

Before participation in the injury prevention program, preadolescent athletes displayed "worse" initial contact and peak knee valgus angles when compared with adolescent athletes during all activities. Previous work suggests that intervention training programs may have a greater effect on athletes classified as "high risk" for ACL injury (ie, displaying poor movement techniques) as compared with those classified as "low risk."[12,27] Our findings expand this work by showing that preadolescent athletes not only display riskier movement patterns than adolescent females but benefit more from participation in the F-MARC 11+ program. Specifically, previous studies used a double-legged jump task similar to ours, involving a takeoff from an approximately 30-cm-high box and a vertical jump for maximal height.[12,27] In agreement with these studies, we found that preadolescent athletes, who displayed more at-risk biomechanics at baseline, benefited more from participation in the F-MARC 11+ program than the adolescent athletes. However, unlike previous studies that grouped athletes into high- and low-risk categories, ours compared the changes within each age group as a whole. The lower-risk biomechanics of the adolescent athletes in general may explain their relative lack of improvement after the intervention program when compared with the improvements observed by others.

Our observation that flexor-extensor muscle co-contraction did not increase after training for most tasks may be

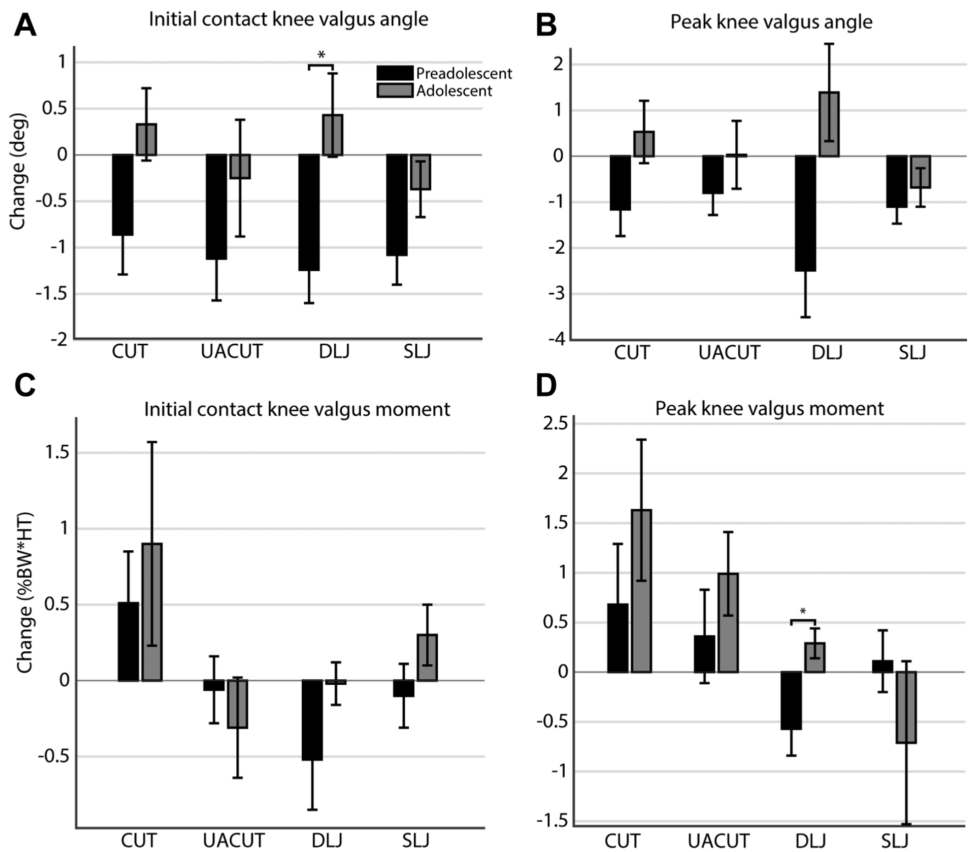

Figure 4. Change among athletes in the intervention for (A) initial contact and (B) peak knee valgus angles and (C) initial contact and (D) peak knee valgus moments for preplanned cutting (CUT), unanticipated cutting (UACUT), double-legged jump (DLJ), and single-legged jump (SLJ). Moments are normalized by body weight (BW) and height (HT). A negative change indicates improvement pre- to posttest. *$P < .05$, preadolescent (black) vs adolescent (gray) intervention groups. Error bars represent SEM.

explained by a motor control theory, which suggests that during maturation and skill development, diminished muscle co-contraction may develop as more efficient movement patterns are obtained.[3] Co-contraction has been suggested as a motor control strategy for stabilizing and protecting a joint, which may be accomplished without a change in kinematics.[37] However, previous studies lack consensus on how co-contraction is affected by age. Croce et al[7] and Russell et al[31] found higher co-contraction among adults than children before landing from a vertical jump (precontact); however, Croce and colleagues observed a higher co-contraction ratio among preadolescent subjects after landing, while Russell and colleagues found no difference between age groups. The increase in co-contraction that we observed for preadolescent athletes during preplanned cutting may be due to new skill acquisition,[9,32] since they had less experience performing plant-and-cut maneuvers than the adolescent athletes. Although limited to a single exercise, the plant-and-cut component of the F-MARC 11+ program may have provided sufficient training for the preadolescent athletes to increase their preparatory muscle activation during the preplanned cutting task.

Despite biomechanical differences at baseline between preadolescent and adolescent athletes, there were few differences between age groups after training. The distribution of exercises included in the F-MARC 11+ program emphasizes squatting and landing movements more than cutting movements.[36] The greater improvement in knee valgus angle and moment during the double-legged jump for preadolescent athletes suggests that they may benefit more from participation in the F-MARC 11+ program than adolescent athletes. However, the lack of differences in muscle co-contraction during this task suggests that the improved biomechanics of the preadolescent athletes may not be a result of improved muscle activation strategies. Zebis et al[37] measured differences in muscle activity after an injury prevention program but no detectable change in kinematics or kinetics, leading the authors to conclude that the effect of the training program was likely purely neuromuscular. In our current study, the opposite may be true: the preadolescent athletes may have modified their kinematics and kinetics in response to the F-MARC 11+ program without changing their muscle activation. Further work is needed to elucidate the relationship between muscle co-contraction and movement patterns after an injury prevention program, particularly for preadolescent athletes. The higher incidence of injury among adolescent athletes may also be attributable to additional

TABLE 3
Changes and *P* Values From Analysis of Variance for Knee Flexor-Extensor Muscle Co-contraction Ratios[a]

	Change in Knee Flexor-Extensor Co-contraction Ratio, Mean (SE)				*P* Value			
	CON		INT		AD CON vs		PREAD INT vs	
Activity: Variable	AD	PREAD	AD	PREAD	PREAD CON	AD INT	AD INT	PREAD CON
CUT								
Precontact	0.03 (0.03)	0.05 (0.04)	–0.30 (0.27)	0.07 (0.02)	.993	.020[b]	.002[b]	.950
Weight acceptance	0.05 (0.07)	0.07 (0.08)	–0.07 (0.11)	–0.02 (0.06)	.999	.836	.973	.787
UACUT								
Precontact	0.01 (0.08)	0.07 (0.03)	0.01 (0.05)	0.07 (0.02)	.723	>.999	.699	.998
Weight acceptance	0.03 (0.06)	0.00 (0.06)	0.13 (0.05)	–0.03 (0.07)	.995	.832	.410	.986
DLJ								
Precontact	–0.04 (0.02)	–0.05 (0.02)	–0.04 (0.01)	0.01 (0.02)	.996	>.999	.495	.176
Weight acceptance	0.05 (0.06)	–0.01 (0.08)	0.12 (0.04)	–0.06 (0.05)	.917	.840	.087	.908
SLJ								
Precontact	0.01 (0.04)	0.04 (0.05)	–0.10 (0.08)	–0.02 (0.03)	.949	.494	.596	.673
Weight acceptance	0.03 (0.07)	–0.07 (0.06)	0.15 (0.05)	–0.06 (0.06)	.705	.553	.062	>.999

[a]AD, adolescent; CON, control; CUT, preplanned cutting; INT, intervention; DLJ, double-legged jump; PREAD, preadolescent; SLJ, single-legged jump; UACUT, unanticipated cutting.
[b]$P < .05$.

factors, such as differences in hormonal or anatomic variables between preadolescent and adolescent females,[20] or external factors, such as increased intensity of sport activities with increasing age.[10]

The limitations of the F-MARC 11+ program and specific limitations of the preadolescent athletes' participation have been discussed.[36] The current study should be considered in light of several additional limitations. Note that the intervention teams voluntarily enrolled in the program. This nonrandomized study design may have led to a selection or motivational bias, which could have influenced the results. Despite standardized EMG electrode placement and preparation, numerous factors can introduce slight variations in the EMG signal.[23,25] An additional limitation is the inherent differences in ability and skill level between the preadolescent and adolescent athletes. Many of the exercises in the F-MARC 11+ program include progressions to higher levels of difficulty. The greater strength and skill level of the adolescent athletes enabled them to advance more quickly and to higher-level exercises as compared with the preadolescent athletes. Therefore, the 2 age groups participated in slightly different sets of exercises, despite using the same overall program.

This study found that the F-MARC 11+ program was effective in reducing knee valgus, a key risk factor for ACL injury, in preadolescent athletes during a double-legged jump task when compared with adolescent athletes. Improvements in kinematics and kinetics, however, did not coincide with changes in flexor-extensor muscle co-contraction. Future work should continue to investigate the influence of age on the complex relationship between muscle co-contraction and movement patterns, with the aim of developing more effective injury prevention programs targeting neuromuscular and biomechanical risk factors for injury.

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REFERENCES

1. Andrish JT. Anterior cruciate ligament injuries in the skeletally immature patient. *Am J Orthop (Belle Mead NJ)*. 2001;30(2):103-110.
2. Arendt E, Dick R. Knee injury patterns among men and women in collegiate basketball and soccer: NCAA data and review of literature. *Am J Sports Med*. 1995;23(6):694-701.
3. Basmajian JV. Motor learning and control: a working hypothesis. *Arch Phys Med Rehabil*. 1977;58(1):38-41.
4. Besier TF, Lloyd DG, Ackland TR. Muscle activation strategies at the knee during running and cutting maneuvers. *Med Sci Sports Exerc*. 2003;35(1):119-127.
5. Braun HJ, Shultz R, Malone M, Leatherwood WE, Silder A, Dragoo JL. Differences in ACL biomechanical risk factors between field hockey and lacrosse female athletes. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(4):1065-1070.
6. Clanton TO, DeLee JC, Sanders B, Neidre A. Knee ligament injuries in children. *J Bone Joint Surg Am*. 1979;61(8):1195-1201.
7. Croce RV, Russell PJ, Swartz EE, Decoster LC. Knee muscular response strategies differ by developmental level but not gender during jump landing. *Electromyogr Clin Neurophysiol*. 2004;44(6):339-348.
8. da Fonseca ST, Vaz DV, de Aquino CF, Bricio RS. Muscular co-contraction during walking and landing from a jump: comparison between genders and influence of activity level. *J Electromyogr Kinesiol*. 2006;16(3):273-280.

9. Davids K, Lees A, Burwitz L. Understanding and measuring coordination and control in kicking skills in soccer: implications for talent identification and skill acquisition. *J Sports Sci*. 2000;18(9):703-714.
10. DeHaven KE, Lintner DM. Athletic injuries: comparison by age, sport, and gender. *Am J Sports Med*. 1986;14(3):218-224.
11. Delp SL, Anderson FC, Arnold AS, et al. OpenSim: open-source software to create and analyze dynamic simulations of movement. *IEEE Trans Biomed Eng*. 2007;54(11):1940-1950.
12. DiStefano LJ, Padua DA, DiStefano MJ, Marshall SW. Influence of age, sex, technique, and exercise program on movement patterns after an anterior cruciate ligament injury prevention program in youth soccer players. *Am J Sports Med*. 2009;37(3):495-505.
13. 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):1923-1931.
14. Ford KR, van den Bogert J, Myer GD, Shapiro R, Hewett TE. The effects of age and skill level on knee musculature co-contraction during functional activities: a systematic review. *Br J Sports Med*. 2008;42(7):561-566.
15. Frost G, Bar-Or O, Dowling J, Dyson K. Explaining differences in the metabolic cost and efficiency of treadmill locomotion in children. *J Sports Sci*. 2002;20(6):451-461.
16. Hamstra-Wright KL, Swanik CB, Sitler MR, et al. Gender comparisons of dynamic restraint and motor skill in children. *Clin J Sport Med*. 2006;16(1):56-62.
17. 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):100-107.
18. Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol*. 2000;10(5):361-374.
19. Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes: a prospective study. *Am J Sports Med*. 1999;27(6):699-706.
20. Hewett TE, Myer GD, Ford KR. Anterior cruciate ligament injuries in female athletes: part 1, mechanisms and risk factors. *Am J Sports Med*. 2006;34(2):299-311.
21. 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(8):1601-1608.
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):2579-2585.
23. Lagasse P. *Neuromuscular Considerations*. Champaign, IL: Human Kinetics Publishers Inc; 1987.
24. Lloyd DG, Buchanan TS. Strategies of muscular support of varus and valgus isometric loads at the human knee. *J Biomech*. 2001;34(10):1257-1267.
25. Loeb GE, Gans C. *Electromyography for Experimentalists*. Chicago, IL: The University of Chicago Press; 1986.
26. MacWilliams BA, Wilson DR, DesJardins JD, Romero J, Chao EY. Hamstrings cocontraction reduces internal rotation, anterior translation, and anterior cruciate ligament load in weight-bearing flexion. *J Orthop Res*. 1999;17(6):817-822.
27. Myer GD, Ford KR, Brent JL, Hewett TE. Differential neuromuscular training effects on ACL injury risk factors in''high-risk'' versus ''low-risk'' athletes. *BMC Musculoskelet Disord*. 2007;8:39.
28. Myer GD, Sugimoto D, Thomas S, Hewett TE. The influence of age on the effectiveness of neuromuscular training to reduce anterior cruciate ligament injury in female athletes: a meta-analysis. *Am J Sports Med*. 2013;41(1):203-215.
29. Quatman CE, Ford KR, Myer GD, Hewett TE. Maturation leads to gender differences in landing force and vertical jump performance: a longitudinal study. *Am J Sports Med*. 2006;34(5):806-813.
30. Rudolph KS, Axe MJ, Buchanan TS, Scholz JP, Snyder-Mackler L. Dynamic stability in the anterior cruciate ligament deficient knee. *Knee Surg Sports Traumatol Arthrosc*. 2001;9(2):62-71.
31. Russell PJ, Croce RV, Swartz EE, Decoster LC. Knee-muscle activation during landings: developmental and gender comparisons. *Med Sci Sports Exerc*. 2007;39(1):159-170.
32. Schmidt RA, Lee TD. *Motor Control and Learning: A Behavioral Emphasis*. 3rd ed. Champaign, IL: Human Kinetics Publishers Inc; 1999.
33. Sigward S, Powers CM. The influence of experience on knee mechanics during side-step cutting in females. *Clin Biomech (Bristol, Avon)*. 2006;21(7):740-747.
34. Soligard T, Myklebust G, Steffen K, et al. Comprehensive warm-up programme to prevent injuries in young female footballers: cluster randomised controlled trial. *BMJ*. 2008;337:a2469.
35. Swartz EE, Decoster LC, Russell PJ, Croce RV. Effects of developmental stage and sex on lower extremity kinematics and vertical ground reaction forces during landing. *J Athl Train*. 2005;40(1):9-14.
36. Thompson JA, Tran AA, Gatewood CT, et al. Biomechanical effects of an injury prevention program in preadolescent female soccer athletes. *Am J Sports Med*. 2017;45(2):294-301.
37. Zebis MK, Andersen LL, Brandt M, et al. Effects of evidence-based prevention training on neuromuscular and biomechanical risk factors for ACL injury in adolescent female athletes: a randomised controlled trial. *Br J Sports Med*. 2016;50(9):552-557.