Biomechanical Effects of an Injury Prevention Program in Preadolescent Female Soccer Athletes

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Background: Anterior cruciate ligament (ACL) injuries are common, and children as young as 10 years of age exhibit movement patterns associated with an ACL injury risk. Prevention programs have been shown to reduce injury rates, but the mechanisms behind these programs are largely unknown. Few studies have investigated biomechanical changes after injury prevention programs in children.

Purpose/Hypothesis: To investigate the effects of the F-MARC 11+ injury prevention warm-up program on changes to biomechanical risk factors for an ACL injury in preadolescent female soccer players. We hypothesized that the primary ACL injury risk factor of peak knee valgus moment would improve after training. In addition, we explored other kinematic and kinetic variables associated with ACL injuries.

Study Design: Controlled laboratory study.

Methods: A total of 51 female athletes aged 10 to 12 years were recruited from soccer clubs and were placed into an intervention group (n = 28; mean [±SD] age, 11.8 ± 0.8 years) and a control group (n = 23; mean age, 11.2 ± 0.6 years). The intervention group participated in 15 in-season sessions of the F-MARC 11+ program (2 times/wk). Pre- and postseason motion capture data were collected during preplanned cutting, unanticipated cutting, double-leg jump, and single-leg jump tasks. Lower extremity joint angles and moments were estimated using OpenSim, a biomechanical modeling system.

Results: Athletes in the intervention group reduced their peak knee valgus moment compared with the control group during the double-leg jump (mean [±standard error of the mean] pre- to posttest change, –0.57 ± 0.27 %BW×HT vs 0.25 ± 0.25 %BW×HT, respectively; *P* = .034). No significant differences in the change in peak knee valgus moment were found between the groups for any other activity; however, the intervention group displayed a significant pre- to posttest increase in peak knee valgus moment during unanticipated cutting (*P* = .044). Additional analyses revealed an improvement in peak ankle eversion moment after training during preplanned cutting (*P* = .015), unanticipated cutting (*P* = .004), and the double-leg jump (*P* = .016) compared with the control group. Other secondary risk factors did not significantly improve after training, although the peak knee valgus angle improved in the control group compared with the intervention group during unanticipated cutting (*P* = .018).

Conclusion: The F-MARC 11+ program may be effective in improving some risk factors for an ACL injury during a double-leg jump in preadolescent athletes, most notably by reducing peak knee valgus moment.

Clinical Relevance: This study provides motivation for enhancing injury prevention programs to produce improvement in other ACL risk factors, particularly during cutting and single-leg tasks.

Keywords: ACL injury; intervention program; biomechanics; youth athletes

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Anterior cruciate ligament (ACL) injuries are common in athletes and often require surgery, followed by extensive rehabilitation. Estimates of the incidence of ACL injuries in soccer range from 0.06 to 3.7 per 1000 hours of active play (training and games).[3,12] More than 25% of soccer athletes who sustain an ACL injury do not return to their previous activity levels, and at 7 years after an ACL injury, 65% of players no longer play soccer.[6] In recognition of these facts, several injury prevention programs have been developed and shown to reduce ACL injury rates in athletes.[23,32,36] However, the mechanisms by which these programs reduce injury rates are unclear.

The ACL injury risk is multifactorial[24] and includes anatomic, hormonal, neuromuscular, and biomechanical factors.[1,24] Biomechanical and neuromuscular factors may be modifiable and provide the greatest potential for injury prevention. Peak knee valgus moment during landing has been

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shown to be the primary risk factor associated with noncontact ACL injuries.[26] Video analysis of noncontact injuries also suggests a combination of hip adduction and internal rotation, knee valgus, tibial external rotation, and ankle eversion; together, these create "dynamic knee valgus" and increase the risk of ACL injuries.[5,24,27] Of these measurements, increased frontal-plane ankle range of motion and joint moment have been shown to be related to an increased ACL injury risk during drop jumps and cutting in female athletes.[15,16,29] Injury prevention programs attempt to modify biomechanical risk factors, with the assumption that they will improve after training, but most programs have not been systematically evaluated.

Female athletes are 2 to 9 times more likely to experience an ACL injury than male athletes,[39,44] most of which (~70%) occur by noncontact mechanisms.[19,33,45] Compared with male athletes, adolescent female athletes exhibit greater normalized landing forces and loading rates and greater frontal-plane motion during cutting and jump-landing tasks.[14,16,25,40] It is possible that the disparity between male and female athletes arises during puberty. While female athletes in late adolescence are at the greatest risk of injuries, the incidence of ACL injuries starts to increase between 10 and 12 years of age.[17] Children as young as 10 years old demonstrate "risky" movement patterns during landing tasks,[22,43] which include decreased knee flexion and increased knee valgus.[4,28] Training implemented in preadolescence may reduce the risk of injuries,[35] but only a handful of studies have investigated changes in biomechanics after an injury prevention program in children younger than 13 years of age.[9,10,18] A recent review of injury prevention programs in youth athletes concluded that the benefit of preventive exercises in children remains unknown.[30]

The F-MARC 11+ injury prevention warm-up program was developed with the aim of reducing the risk of injuries in soccer athletes.[41] This program can be completed in less than 30 minutes, requires minimal training to implement, and does not require any special equipment. Previous studies examining the effectiveness of the F-MARC 11+ program in adolescent male and female athletes have reported overall injury reductions as high as 81%,[20,31,41] although none specifically reported a reduction in ACL injuries. Furthermore, these studies did not investigate the biomechanical mechanisms underlying the program's success in reducing injuries. A better understanding of the mechanisms by which the F-MARC 11+ program reduces injury rates may aid in the development of more efficient and focused intervention programs that address specific injury risk factors.

The purpose of this study was to investigate the effects of the F-MARC 11+ injury prevention warm-up program on changes to biomechanical risk factors for an ACL injury in preadolescent female soccer players. We examined cutting and jump-landing tasks, which are associated with the majority of noncontact ACL injuries.[4,12,13] For each of these activities, we hypothesized that the primary ACL injury risk factor of peak knee valgus moment would improve after the F-MARC 11+ program. Additionally, we explored and reported changes in other kinematic and kinetic variables associated with ACL injuries, particularly hip adduction, knee valgus, and ankle eversion angles and moments, all of which contribute to a "dynamic knee valgus" position.

TABLE 1
Participant Demographics[a]

	Pretest		Posttest	
	Intervention (n = 28)	Control (n = 23)	Intervention (n = 26)	Control (n = 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

[a] Values are reported as mean ± SD.

METHODS

Participants

Before testing, institutional review board approval was obtained, and written informed consent was acquired for 51 female soccer athletes between 10 to 12 years of age recruited from local area soccer club teams (Table 1). Exclusion criteria included a prior ACL injury, lower extremity surgery within the past year, a serious lower extremity injury within the past 6 months (defined as an injury requiring more than 4 weeks of absence from participation in soccer activity), and prior or current participation in an ACL injury prevention program. A total of 28 players, from 2 separate soccer teams, participated in the laboratory testing component of the research study. On-field injury prevention training was completed by all athletes from both teams regardless of participation in the study. Athletes from 11 other teams served as a control and completed baseline laboratory testing (n = 23). There were no differences in height (P = .094) or mass (P = .136) between the intervention and control groups before testing, despite a small but significant 0.6-year age difference (P = .017).

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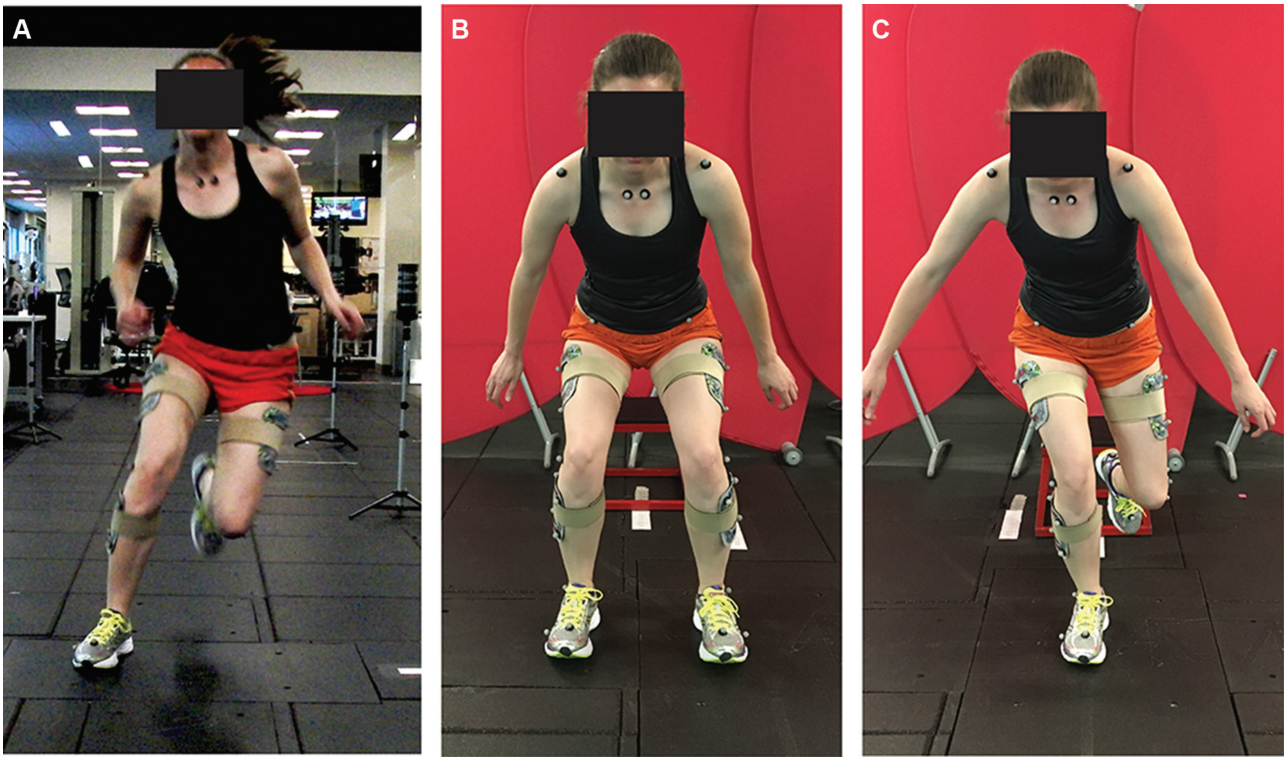

Figure 1. Marker placement and example of athlete positioning after initial contact during (A) preplanned and unanticipated cutting, (B) the double-leg jump, and (C) the single-leg jump.

Preintervention Testing

The positions of 36 retroreflective markers were recorded at 200 Hz using an 8-camera optical motion capture system (Motion Analysis Corp) and were synchronized with measurements from 3 floor-mounted force plates collected at 2000 Hz (Bertec Corp). Each participant performed an initial static, standing calibration trial. Participants then completed 2 jump-landing tasks from a 30-cm box in random order: double-leg jump and single-leg jump on the dominant limb (Figure 1, B and C). 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 the double-leg jump, participants jumped forward from the box onto 2 force plates at a distance of 50% body height. The participant landed with each foot on a separate force plate and immediately performed a countermovement jump to achieve maximal height. For the single-leg jump, participants jumped forward from the box with their dominant leg onto a force plate at a distance of 40% body height. The participant landed on her dominant leg and immediately performed a countermovement jump to achieve maximal height. Upon completion of the jump-landing tasks, participants performed 2 cutting tasks: preplanned and unanticipated. For both tasks, the participants performed a running, sidestepping cut-off of their dominant limb at approximately 45° from the line of approach (Figure 1A), with an approach speed of 3.8 ± 0.5 m/s 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 the entire dominant foot on a single force plate.

Intervention

The F-MARC 11+ injury prevention warm-up program[41] was started approximately 2 weeks after preintervention testing (mean [±SD], 12 ± 6 days). The intervention was conducted during the soccer season and consisted of 15 sessions (approximately 2 per week for 7-8 weeks). Each session was allotted approximately 25 minutes and replaced each intervention team's standard warm-up before the start of regular practice. Full details on the exercises can be found at www.f-marc.com/11plus. The program consists of 3 components: (1) 6 running exercises at moderate speed combined with dynamic stretching and controlled contact with a partner; (2) 6 exercises targeting strength, balance, and jump-landing techniques with 3 levels of increasing difficulty; and (3) 3 high-speed running and cutting drills. For the second component only, athletes progressed to the next difficulty level of an exercise once they demonstrated the correct form for the entire duration of the exercise. A minimum of 1 of 4 trained research staff members attended each training session. The research staff administered the intervention program and provided feedback on the proper technique (Figure 2). Athlete attendance,

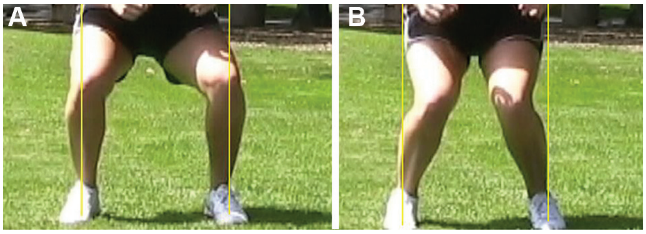

Figure 2. Example of (A) correct lower extremity alignment and (B) incorrect lower extremity alignment (knee valgus) during a double-leg jump.

defined as the percentage of total training sessions completed, was a mean 70.2% ± 14.0%. This statistic also took into account partial attendance during a training session (eg, if an athlete showed up late and only completed half of the program, she received an attendance score of 50% for that session).

Postintervention Testing

The athletes returned to participate in postintervention laboratory testing within 2 weeks of completing the intervention phase (mean [±SD], 8 ± 6 days). During this time, athletes continued to practice and compete with their teams. Postintervention data collection followed the same procedure used for preintervention data collection. Twenty-six participants in the intervention group returned for postintervention testing (mean, 67 ± 8 days after preintervention testing). One participant did not return because of an injury, and 1 did not return because of scheduling conflicts. Twenty control participants returned for follow-up laboratory testing (mean, 63 ± 7 days after baseline testing). Two participants did not return because of an injury, and 1 participant withdrew from the study.

Musculoskeletal Modeling

The ground-reaction force data were low-pass filtered using a fourth-order critically damped filter with a cutoff frequency of 30 Hz. We analyzed 3 trials for each activity and participant using OpenSim software version 3.2.[8] A generic 34 degrees of freedom musculoskeletal model[7] was scaled to match the anthropometric data of the individual participants using markers located on anatomic landmarks. Joint angles were estimated using the inverse kinematics tool, which reproduced the experimental movement patterns in the scaled model using a weighted least-squares approach to minimize the differences between the experimental marker locations and the model's virtual marker locations. Kinematic data were then filtered at 30 Hz using the filter included in the OpenSim software (low-pass IIR Butterworth, third order) and input to the inverse dynamics tool to estimate joint moments. The same 30-Hz filter used for the ground-reaction force data was then reapplied to the joint moments to reduce kinetic artifacts.[2] Joint moments were normalized by the participants' body weight and height (%BW×HT). All joint moments are reported as external moments.

Statistical Analysis

Three trials from each activity were analyzed. For each trial, activity, and variable of interest, we identified the peak values during weight acceptance, which was defined as the interval between initial contact and peak knee flexion. The values from the 3 trials were averaged, and a repeated-measures analysis of variance was performed to test the effect of time (pre- vs posttest) and the interaction of time and group (intervention vs control) for each variable of interest. Post hoc analyses were subsequently performed using the Tukey honest significant difference test to evaluate significant group × time interactions. In addition, paired-samples t tests were used to test for differences between pre- and posttest peak knee valgus moments for both groups. All statistical analyses were performed with SPSS software (version 21.0; IBM Corp), and the level of significance was set at $\alpha = .05$. Results are presented as the mean ± standard error of the mean.

RESULTS

Peak Knee Valgus Moment

Athletes who participated in the F-MARC 11+ injury prevention warm-up program improved their peak knee valgus moment compared with control athletes during the double-leg jump task (mean change, –0.57 ± 0.27 %BW×HT vs 0.25 ± 0.25 %BW×HT, respectively; $P = .034$). The mean change in peak knee valgus moment was not significantly different between the intervention and control groups for any of the other activities (Figure 3). Athletes in the intervention group reduced their peak knee valgus moment from 3.62 to 3.05 %BW×HT during the double-leg jump ($P = .045$) (Table 2). In comparison, the control athletes did not change ($P = .331$). The only other effect of time was observed with a significant increase in peak knee valgus moment during unanticipated cutting ($P = .042$), indicating that the athletes, regardless of their group, increased their peak knee valgus moment from pre- to posttest during unanticipated cutting (Table 3).

Secondary Kinematic and Kinetic Variables

Of the secondary variables investigated, the intervention group improved peak ankle eversion during most activities compared with the control group (Table 3). Compared with the control group, the intervention group decreased peak ankle eversion angles during unanticipated cutting ($P = .034$) and decreased peak ankle eversion moments during preplanned cutting ($P = .015$), unanticipated cutting ($P = .004$), and the double-leg jump ($P = .016$). The only other significant pre- to posttest difference between the groups in the secondary variables was an improvement and decrease in peak knee valgus angles in the control group compared with the intervention group during unanticipated cutting

TABLE 2
Pre- and Posttest Peak Knee Valgus Moments[a]

	Intervention			Control		
Activity	Pretest	Posttest	*P* Value	Pretest	Posttest	*P* Value
CUT	6.15 ± 0.63	6.82 ± 0.48	.280	5.51 ± 0.61	6.05 ± 0.69	.343
UACUT	5.51 ± 0.51	6.51 ± 0.50	.044[b]	5.93 ± 0.71	6.37 ± 0.68	.384
DLJ	3.62 ± 0.27	3.05 ± 0.26	.045[b]	2.68 ± 0.14	2.93 ± 0.26	.331
SLJ	1.45 ± 0.29	1.56 ± 0.26	.735	1.24 ± 0.24	1.40 ± 0.25	.518

[a] Values are reported as mean ± standard error of the mean and were normalized by body weight and height (%BW×HT). CUT, preplanned cutting; DLJ, double-leg jump; SLJ, single-leg jump; UACUT, unanticipated cutting.

[b] Statistically significant difference between pre- and posttest values ($P < .05$).

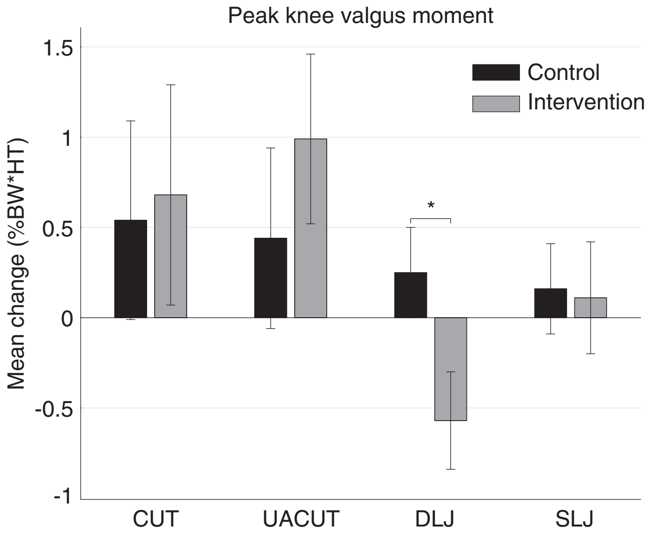

Figure 3. Mean change in peak knee valgus moment, normalized by body weight (BW) and height (HT), for preplanned cutting (CUT), unanticipated cutting (UACUT), the double-leg jump (DLJ), and the single-leg jump (SLJ). A negative change indicates an improvement from pre- to posttest. *Significant group × time interaction ($P < .05$). Error bars represent the standard error of the mean.

(P = .018). The only significant main effect of time in the secondary kinetic variables was peak hip adduction moment during the single-leg jump (P = .006), indicating that athletes, regardless of their group, reduced their peak hip adduction moment from pre- to posttest.

DISCUSSION

The purpose of this study was to evaluate changes in biomechanical risk factors for an ACL injury after participation in the F-MARC 11+ injury prevention warm-up program in female preadolescent soccer players. In partial support of our hypothesis, we measured a reduction in peak knee valgus moment during the double-leg jump task after training. However, we found no difference in the change in peak knee valgus moment between the intervention and control groups for the single-leg jump or cutting tasks.

The effectiveness of injury prevention programs in improving risk factors for an ACL injury in children has not been comprehensively investigated.[9,10,18] For example, Grandstrand et al[18] and DiStefano et al[10] examined changes during a jump-landing task, but neither study reported joint angles or moments and instead reported knee separation distance and Landing Error Scoring System (LESS) scores[38] as outcome measures, respectively. We sought to expand on these studies by reporting kinematic and kinetic variables associated with ACL injuries, including what is thought to be the primary risk factor: peak knee valgus moment. The results of our study suggest that it is possible to improve peak knee valgus moment in a preadolescent population during a double-leg jump.

We further built upon previous studies by investigating unanticipated cutting and single-leg jump tasks, movements that have not previously been investigated in preadolescent athletes after participation in an injury prevention program. DiStefano and colleagues[9] reported findings for a large number of angle and moment variables during a preplanned cutting task but only found improvement in knee external rotation at initial contact. Similarly, our results revealed only minimal changes during both unanticipated cutting and single-leg jump tasks. A potentially concerning finding of our study was the increase in peak knee valgus moment during the unanticipated cutting task for both the control and intervention groups. Although the pre- to posttest increase in peak knee valgus moment was greater for the intervention group (Figure 3), the increase was not statistically different from that of the control group. Because the program does not include an unanticipated cutting task, the athletes did not receive training in this type of movement. This likely suggests that the F-MARC 11+ program was not responsible for making the athletes “worse” in the unanticipated cutting task. Rather, the F-MARC 11+ program does not appear to adequately address deficits in cutting biomechanics in preadolescent athletes.

The distribution of exercises included in the F-MARC 11+ program may have contributed to our finding of an improvement in peak knee valgus moment during the double-leg jump task but not during the single-leg jump, preplanned cutting, or unanticipated cutting. The second component of

TABLE 3
Pre- to Posttest Joint Angle and Moment Changes[a]

	Joint Angle Changes, deg				Joint Moment Changes, %BW×HT			
	Mean ± SEM		*P* Value		Mean ± SEM		*P* Value	
	Intervention	Control	Group × Time	Time	Intervention	Control	Group × Time	Time
CUT								
Peak hip adduction	0.3 ± 0.9	0.1 ± 1.1	.917	.771	–0.46 ± 0.58	–0.42 ± 0.59	.966	.302
Peak knee flexion	–1.6 ± 1.2	–0.5 ± 1.3	.527	.258	–0.63 ± 0.47	–0.03 ± 0.57	.417	.369
Peak ankle eversion	0.2 ± 1.2	1.1 ± 1.1	.588	.418	–0.48 ± 0.32	0.57 ± 0.24	.015[b]	.827
Peak knee valgus	–1.2 ± 0.6	–2.1 ± 0.8	.339	.002[b]	0.68 ± 0.61	0.54 ± 0.55	.868	.158
UACUT								
Peak hip adduction	–2.0 ± 1.3	–2.7 ± 1.4	.708	.017[b]	–0.01 ± 0.56	–0.16 ± 0.50	.846	.821
Peak knee flexion	–1.1 ± 1.3	0.1 ± 1.5	.537	.629	–0.63 ± 0.62	0.78 ± 0.56	.104	.860
Peak ankle eversion	–0.2 ± 1.1	3.2 ± 1.0	.034[b]	.056	–0.69 ± 0.29	0.59 ± 0.30	.004[b]	.808
Peak knee valgus	–0.8 ± 0.5	–3.1 ± 0.8	.018[b]	<.001[b]	0.99 ± 0.47	0.44 ± 0.50	.428	.042[b]
DLJ								
Peak hip adduction	–1.4 ± 0.8	–1.5 ± 0.8	.938	.018[b]	0.09 ± 0.30	0.14 ± 0.27	.903	.583
Peak knee flexion	–3.1 ± 1.9	–4.5 ± 2.1	.609	.008[b]	0.03 ± 0.47	0.66 ± 0.50	.362	.316
Peak ankle eversion	–0.3 ± 1.0	1.1 ± 1.0	.325	.552	–0.34 ± 0.22	0.45 ± 0.22	.016[b]	.722
Peak knee valgus	–2.5 ± 1.0	–5.3 ± 1.0	.060	<.001[b]	–0.57 ± 0.27	0.25 ± 0.25	.034[b]	.394
SLJ								
Peak hip adduction	–0.6 ± 0.6	–1.0 ± 0.9	.739	.162	–0.53 ± 0.38	–1.04 ± 0.36	.342	.006[b]
Peak knee flexion	–1.5 ± 1.1	0.1 ± 2.0	.468	.498	0.37 ± 0.64	0.25 ± 0.63	.900	.499
Peak ankle eversion	0.8 ± 0.6	1.7 ± 0.6	.322	.008[b]	–0.23 ± 0.37	0.22 ± 0.30	.363	.976
Peak knee valgus	–1.1 ± 0.4	–1.5 ± 0.6	.532	<.001[b]	0.11 ± 0.31	0.16 ± 0.25	.888	.512

[a] A negative value indicates a decrease in pre- to posttest changes. BW, body weight; CUT, preplanned cutting; DLJ, double-leg jump; HT, height; SEM, standard error of the mean; SLJ, single-leg jump; UACUT, unanticipated cutting.

[b] Statistically significant effect ($P < .05$, repeated-measures analysis of variance).

the program includes multiple squatting and jumping exercises, for which the athletes can, and did, progress to increasing levels of difficulty. Level 1 of the squat and jump exercises emphasize proper double-leg form. Twelve athletes of the intervention group progressed to level 2 for the squat (walking lunges) and jump (lateral side-to-side) exercises. All athletes of the intervention group progressed to level 2 on the single-leg stance exercise (single-leg balance while throwing a ball to a partner), but the exercise emphasizes balance rather than jump-landing mechanics, which may explain why we measured no change in the single-leg jump task. The third component of the program includes a single plant-and-cut maneuver, for which the athletes cannot progress in difficulty. The cutting movement proved to be a greater challenge compared with the other exercises because many of the preadolescent girls had not yet learned to execute true plant-and-cut maneuvers. The lack of improvement in the single-leg jump and cutting tasks may suggest that the F-MARC 11+ program does not address some key mechanisms of injuries, which often involve single-leg landings or quick changes in direction.[4,33,37]

Our investigation of other kinematic and kinetic variables associated with ACL injuries revealed few changes after the intervention, with the exception of peak ankle eversion moment. Athletes improved their peak ankle eversion moment significantly after training during preplanned cutting, unanticipated cutting, and the double-leg jump compared with control athletes. Excessive ankle eversion is part of the dynamic knee valgus position observed in many noncontact ACL injuries.[5,24,27] Previous work suggests that improper foot and ankle kinematics may play a role in an increased ACL injury risk.[11,21] Nevertheless, this is not universally accepted; Mitchell et al[34] found no relationship between foot loading patterns and knee biomechanics during a drop jump in collegiate female soccer players. In our study, an improvement in peak ankle eversion moment coincided with an improvement in peak knee valgus moment in only the double-leg jump task, suggesting a possible association between foot eversion and knee valgus in double-leg landings. However, the exact effect of foot biomechanics on the ACL injury risk, particularly in the preadolescent athlete, remains unknown and warrants further investigation.

The results of the current study should be considered in light of several limitations. The duration of the intervention program was limited to the duration of the athletes' soccer season, which included 15 sessions of in-season training over the course of 8 weeks. While some previous studies have shown a reduction in ACL injuries using lengthy training sessions[23] or high-frequency programs,[32] other research suggests that brief training sessions may be sufficient to show benefits.[36,42] An additional limitation was the lack of progression of the athletes to higher level exercises. Significant improvements may have been observed had the athletes progressed to the more challenging balance and plyometric exercises, particularly single-leg exercises. The F-MARC 11+ program may therefore require a longer intervention period for preadolescent athletes to acclimate and progress to higher levels compared with older athletes.

Whether the biomechanical changes that we observed will translate to a reduction in ACL injuries in this population remains unknown and is beyond the scope of this study. Previous studies that implemented the F-MARC 11+ program found a significant reduction in overall injuries and various other injury categories, but none of them reported a significant reduction in ACL injuries.[20,31,41] While the F-MARC 11+ program appears to reduce overall injury rates, it remains unknown if the F-MARC 11+ program reduces ACL injuries in particular. Additional work is needed to determine what components hold the greatest potential for ACL injury prevention.

To our knowledge, our study is the first to measure changes in biomechanical risk factors for an ACL injury after implementation of the F-MARC 11+ program and the first to evaluate biomechanical changes during an unanticipated cutting task and single-leg jump task after any prevention program in preadolescent athletes. Our findings suggest that the F-MARC 11+ injury prevention warm-up program may be effective in improving peak knee valgus moment, a risk factor for ACL injuries, during a double-leg jump in preadolescent athletes. However, the finding of increased peak knee valgus moment during the unanticipated cutting task also provides motivation for modifying intervention programs to produce more comprehensive improvement in other movement patterns associated with the ACL injury risk, particularly cutting and single-leg tasks. The potential to improve or prevent risky movement patterns in young athletes, before they reach adolescence and the peak age for injuries, is a largely untapped avenue of research that merits future study.

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