Different Exercise Training Interventions and Drop-Landing Biomechanics in High School Female Athletes

Kate R. Pfile, PhD, ATC*; Joseph M. Hart, PhD, ATC†; Daniel C. Herman, MD, PhD‡; Jay Hertel, PhD, ATC, FNATA, FACSM§; D. Casey Kerrigan, MD, MS||; Christopher D. Ingersoll, PhD, ATC, FNATA, FACSM¶

*College of Charleston, SC; †Department of Orthopaedics, University of Virginia, Charlottesville; ‡University of Florida, Gainesville; §Department of Kinesiology, University of Virginia, Charlottesville; ||JKM Technologies, Charlottesville, VA; ¶The Herbert H. and Grace A. Dow College of Health Professions, Central Michigan University, Mt Pleasant

Context: Anterior cruciate ligament (ACL) injuries are common in female athletes and are related to poor neuromuscular control. Comprehensive neuromuscular training has been shown to improve biomechanics; however, we do not know which component of neuromuscular training is most responsible for the changes.

Objective: To assess the efficacy of either a 4-week core stability program or plyometric program in altering lower extremity and trunk biomechanics during a drop vertical jump (DVJ).

Design: Cohort study.

Setting: High school athletic fields and motion analysis laboratory.

Patients or Other Participants: Twenty-three high school female athletes (age = 14.8 ± 0.8 years, height = 1.7 ± 0.07 m, mass = 57.7 ± 8.5 kg).

Intervention(s): Independent variables were group (core stability, plyometric, control) and time (pretest, posttest). Participants performed 5 DVJs at pretest and posttest. Intervention participants engaged in a 4-week core stability or plyometric program.

Main Outcome Measure(s): Dependent variables were 3-dimensional hip, knee, and trunk kinetics and kinematics during the landing phase of a DVJ. We calculated the group means and associated 95% confidence intervals for the first 25% of landing. Cohen *d* effect sizes with 95% confidence intervals were calculated for all differences.

Results: We found within-group differences for lower extremity biomechanics for both intervention groups ($P \leq .05$). The plyometric group decreased the knee-flexion and knee internal-rotation angles and the knee-flexion and knee-abduction moments. The core stability group decreased the knee-flexion and knee internal-rotation angles and the hip-flexion and hip internal-rotation moments. The control group decreased the knee external-rotation moment. All kinetic changes had a strong effect size (Cohen *d* > 0.80).

Conclusions: Both programs resulted in biomechanical changes, suggesting that both types of exercises are warranted for ACL injury prevention and should be implemented by trained professionals.

Key Words: anterior cruciate ligament, plyometrics, core stability

Key Points

- Kinematic and kinetic changes occurred in high school female athletes after an in-season, 4-week training program of core stability and plyometric exercises.
- The plyometric group demonstrated changes only at the knee joint, but the core stability group demonstrated changes in kinetics at the hip joint and kinematics at the knee joint.
- Core stability and plyometric exercises are warranted in programs designed to prevent anterior cruciate ligament injury because they contribute different biomechanical adaptations.

The rate of noncontact anterior cruciate ligament (ACL) injury is more than 3 times higher in adult and adolescent females than in their male counterparts.¹ Noncontact ACL injuries commonly occur during dynamic activities when the individual is decelerating, such as landing from a jump or changing direction.² Kinematic patterns thought to be associated with greater risk for injury include landing in an extended posture through the knee, hip, and trunk, resulting in increased shear force on the ACL.^{3,4} Frontal- and transverse-plane movements, including increased knee abduction and internal rotation and decreased hip abduction, also are thought to place rotational force on the static stabilizer.^{5–9}

A link between ACL injury and proximal lower extremity and trunk neuromuscular control has been established. Hewett et al⁶ found that individuals who sustained an ACL injury had larger external knee-abduction moments that were correlated with the hip-adduction moment. In addition, females who had greater lateral trunk displacement in response to a sudden force were more likely to incur an ACL injury.⁹ These results suggest that the risk for noncontact ACL injury may be related to forces at the knee affected by decreased neuromuscular control at the hip and trunk.

Biomechanical and neuromuscular control patterns have been shown to be modifiable in response to training.^{5,10,11}

Training programs that have resulted in favorable changes to biomechanical patterns have involved a broad approach, incorporating balance, lower extremity strength, plyometric, and agility components to address all aspects of neuromuscular control.^{7,8,10,11} These comprehensive programs often involve lengthy training sessions and may require equipment that is not always easily accessible for group training purposes. Furthermore, we do not know whether all components of comprehensive training programs are effective or necessary in altering biomechanical patterns. The variety and volume of the components included in an intervention program possibly can be reduced to make it more manageable to incorporate in various athletic settings. Researchers^{12,13} have investigated the contributions of specific muscles during commonly prescribed lower extremity and trunk exercises; however, little information exists about how a group of exercises affects lower extremity and trunk biomechanics during a dynamic landing task. In 1 study,¹⁴ 9 weeks of lower extremity strength training did not result in any lower extremity biomechanical changes despite an increase in strength. In contrast, researchers¹⁰ who compared traditional strength training and plyometric training found similar changes in kinematic and kinetic variables for both groups. By gaining a better understanding of how individual components effectively alter neuromuscular patterns, clinicians may be able to develop more effective and efficient injury-prevention programs.

Therefore, the purpose of our study was to assess the efficacy of either a 4-week core stability program or plyometric program in altering lower extremity and trunk biomechanics during a drop vertical jump (DVJ). We hypothesized that (1) the plyometric group would decrease lateral trunk-flexion, hip-adduction, hip internal-rotation, knee-abduction, and knee internal-rotation angles; (2) the plyometric group would increase hip- and knee-flexion angles; (3) the plyometric group would decrease their external flexion, abduction, and external-rotation moments at the hip; (4) the plyometric group would decrease their external flexion, abduction, and internal-rotation moments at the knee; (5) the core stability group would decrease lateral trunk-flexion, hip internal-rotation and adduction angles and external joint moments; and (6) the control group would not show changes in kinematic or kinetic variables.

METHODS

We used a cohort design in which the independent variables tested were group (core stability, plyometric, control) and time (pretest, posttest). The dependent variables were lower extremity kinematic and kinetic group mean values during the first 25% of stance phase at pretest and posttest. The kinematic variables assessed were lateral trunk-flexion angle; hip-flexion, adduction, and internal-rotation angles; and knee-flexion, abduction, and internal-rotation angles. External joint moments for hip flexion, adduction, and internal rotation and for knee flexion, abduction, and internal rotation also were collected.

Participants

Twenty-three girls from 3 area high schools participated in this study (Figure 1). Participants (age = 14.8 ± 0.8

years, height = 1.7 ± 0.07 m, mass = 57.7 ± 8.5 kg) were active on a junior varsity lacrosse or soccer team, had no history of trunk or lower extremity surgery, and had no injury within the 6 weeks before the study that limited their athletic or physical activity. The control and core stability groups comprised athletes from both sports, whereas the plyometric group consisted solely of lacrosse players. Furthermore, participants had no neurologic disorders that affected balance and had not been involved in a formal core stability or plyometric training program. The study was approved by the Institutional Review Board for Health Sciences Research of the University of Virginia. Parents or guardians of the participants provided written informed consent, and the participants provided written informed assent.

Instrumentation

A force platform (OR6-7; AMTI, Watertown, MA) was used to collect raw ground reaction forces at 1000 Hz and interfaced with a 10-camera motion analysis system (model 624; Vicon Peak, Lake Forest, CA) to capture the 3-dimensional position of markers at 250 Hz.

Testing Procedures

Participants reported to the Motion Analysis Laboratory for pretesting within the first third of the high school spring athletic season. Anthropometric measurements, including height, mass, leg length, knee width, and ankle width, were taken and recorded. Participants were fitted with running shoes (model Radius 06; Brooks Sports, Inc, Bothell, WA). Retroreflective markers were placed bilaterally on the following anatomic landmarks to represent the lower extremity segments in accordance with the Vicon Clinical Manager (Vicon, Centennial, CO) protocol: second metatarsal head, calcaneus, lateral malleolus, lateral midshank, lateral femoral condyle, and lateral midthigh. A 4-marker cluster was secured around the hips over the sacrum with elastic tape. To capture trunk motion, markers also were placed on the sternum, xiphoid process, C7 and T10 spinous processes, and bilateral acromion processes. A static marker trial was collected before the dynamic testing.

Participants were instructed in how to perform the DVJ task, and a demonstration was given to ensure comprehension. No instructions or feedback on landing performance was provided. For the DVJ, participants were directed to stand on a 25-cm box and lead with their right lower extremities to step off the box, landing on both feet. The right and left foot contacted separate embedded force plates, and the participant performed a maximal vertical jump immediately upon contacting the ground. Each participant practiced the task until she felt comfortable, then 5 test trials were collected for analysis. The height of the box is the average maximal vertical jump height achieved by adolescent girls when performing a DVJ.¹⁵ Kinetic and kinematic data were collected for all participants, and the mean values were used for analyses.

Each participant repeated the testing after the 4-week intervention. All participants completed testing within 10 days after the final session of intervention exercises. They were retaught how to perform the DVJ and allowed to reacquaint themselves with the task. After the posttesting

Figure 1. Flowchart outlining the progression of testing order and participant dropout.

session, participants were dismissed from the study (Figure 1).

Intervention Programs

Teams were allocated to 1 of 3 groups, and the athletes participated as an entire team in either the plyometric or core stability program 3 times each week for 4 weeks. The tester (K.R.P.) was not blinded to which school was allocated to the control group but was unaware of the specific intervention group assignment for the remaining 2 groups. The control group continued its normal team activities for 4 weeks: 1 to 2 games per week and 3 to 4 practices per week, depending on the game schedule. The coaches were given an attendance log to monitor compliance of the athletes enrolled in the study. They also were provided with a standardized exercise protocol that included directions for the athletes and pictures of how to correctly perform the exercises, common mistakes made during each exercise, and potential corrections to make based on common errors (see Supplemental Appendixes S1 and S2, available online at <http://dx.doi.org/10.4085/1062-6050-48.4.06.S1>). The coaches were not given a

tutorial on the exercises other than the material presented to them via the standardized manual, and no script was provided to read for each intervention session. As an outside assessment, a certified athletic trainer (AT) from each school observed 1 session each week and completed a form for 6 criteria (Table 1). The plyometric and core stability programs were designed to be conducted within 20 minutes and require no additional exercise or rehabilitation equipment.

The plyometric program (Table 2) consisted of a series of double-limb and single-limb jumps and of skipping exercises focused on quality takeoff and landing form. The included exercises were adapted from various ACL injury-prevention and neuromuscular training programs in which the emphasis was placed on soft, balanced, and controlled landings.^{5,10,16–18} The plyometric program was divided into 2 phases, with a progression occurring after the sixth session that increased the level of difficulty by incorporating more single-legged landings and multiplanar movements. The participants performed the exercises with partners to help reinforce the use of correct form; however, no specific partner instructions were given. Exercises for the core stability group were targeted at improving

Table 1. Assessment Tool Used by the High School Certified Athletic Trainer, Criteria and Means $\pm$ SDs

Grading Criteria	Result ^a
1. The coach is instructing the athletes how to correctly perform the exercises.	3.00 $\pm$ 0.76
2. The coach is emphasizing key mistakes to look for.	2.75 $\pm$ 0.71
3. The coach is giving constructive feedback during the exercises.	3.13 $\pm$ 1.25
4. The athletes are listening and following the directions given.	3.5 $\pm$ 0.53
5. The athletes are working hard to perform the exercises correctly.	2.88 $\pm$ 0.64
5. The athletes seem challenged by the exercises they are asked to perform.	2.75 $\pm$ 0.46

^a The scores were based on a 5-point Likert scale: 0 = *never*, 1 = *rarely*, 2 = *some of the time*, 3 = *most of the time*, 4 = *always*.

coordination of the abdominal and lumbar stabilizers and hip extensors, external rotators, and abductors (Table 3).^{14,19,20} After completing 6 sessions, participants progressed to a second phase of exercises that incorporated more challenging positions and combined maneuvers from phase 1 that focused on increasing trunk stability with more traditional strength-gain exercises. All exercises in the plyometric and core stability programs were performed bilaterally. Data were included in the analysis for all who participated in at least 9 of the 12 sessions.

Data Analysis

A Woltring filtering technique was applied to the marker data with a predicted mean square error value of 20 according to recommended Vicon processing protocols. Ground reaction force data were synchronized with the Vicon system for simultaneous collection. The ground reaction forces were filtered using a low-pass, antialiasing filter with a cutoff frequency of 30 Hz. Initial contact was identified by marking the point at which the ground reaction force vector first appeared, and toe-off was identified in a similar manner by indicating the point at which the vector was no longer present; the ground reaction force vector was associated with a 20-N threshold. The data between initial contact and toe-off were normalized to 101 data points for the stance phase. The ground reaction force data were time synchronized with the kinematic data and processed using Plug-in Gait (Vicon) to determine hip- and knee-joint moments. Joint moment calculations were based on the following variables: mass and inertial characteristics of each lower extremity segment, the derived linear and

angular velocities and accelerations of each lower extremity segment, and estimates of ground reaction force and joint-center position. Moments were normalized to a product of mass and height and reported in newton meters per kilogram (Nm/kg-m).

Statistical Analysis

We made within-group comparisons for all dependent variables. We implemented an intention-to-treat analysis, carrying the last data point forward (baseline) for the 1 participant in the plyometric group who did not report for posttest. Group means and associated 95% confidence intervals (CIs) were calculated for each percentage of the landing phase. Data during the first 25% of landing were compared to assess intervals for which the CI bands did not overlap. We chose this period because most noncontact ACL injuries are reported in the early phase of landing.²¹ We set the α level at .05 to determine differences throughout the landing phase by identifying periods in which the 95% CI bands for the 2 data sets did not cross.²² Confidence interval bootstrapping allows for comparisons during a period of the landing phase rather than peak points; the latter tend to represent only a discrete minimum or maximum value of the landing phase (Figure 2). Effect size (Cohen *d*) was calculated for each joint moment at the point where the mean difference between pretest and posttest scores was the largest and where the CI bands did not cross. Cohen *d* was calculated by taking the mean difference between pretests and posttests and dividing by the pooled standard deviation. An effect size of 0.8 or larger with a CI that did not cross zero was considered a

Table 2. Plyometric Group Exercise Progression

Phase	Sets $\times$ Repetitions
1 (weeks 1 and 2)	
Forward/backward single-legged line jumps	1 $\times$ 30
Side-to-side single-legged line jumps	1 $\times$ 30
High skips	1 $\times$ field length
Distance skips	1 $\times$ field length
Broad jumps ^a	2 $\times$ 10
Tuck jumps ^a	2 $\times$ 10
Alternating single-legged lateral jumps	2 $\times$ 10
2 (weeks 3 and 4)	
Forward single-legged hop, hop, hop, and stick ^a	1 $\times$ 10
Squat jumps ^a	2 $\times$ 10
Single-legged maximal vertical jump ^a	1 $\times$ 10
Single-legged jump for distance ^a	1 $\times$ 10
Broad jump, jump, jump, vertical jump ^a	1 $\times$ 5
180° jumps ^a	1 $\times$ 10
Single-legged lateral jumps ^a	1 $\times$ 10

^a Indicates the exercise was performed with a partner watching.

Table 3. Core Stability Group Exercise Progression

Phase	Sets $\times$ Repetitions
1 (weeks 1 and 2)	
Abdominal draw in	10 $\times$ 5 s
Side plank knee bent	2 $\times$ 20 s
Side-lying hip abduction	3 $\times$ 10
Side-lying hip external rotation (clam shells)	3 $\times$ 10
Crunches	3 $\times$ 15
Lumbar extension, hands on head	3 $\times$ 10
Walking lunges, hands on hips	Field length
2 (weeks 3 and 4)	
Hamstrings bridge with abdominal draw-in	3 $\times$ 20 s
Side plank legs extended with abdominal draw-in	2 $\times$ 10 s
Quadruped hip extension/external rotation/abduction	2 $\times$ 10
Crunches, opposite elbow to knee	3 $\times$ 15
Lumbar extension, upper extremities straight	3 $\times$ 10
Squats with upper extremities overhead ^a	3 $\times$ 10
Lunges with ball toss ^a	3 $\times$ 10

^a Indicates the exercise was performed with a partner watching.

Figure 2. Confidence interval analysis graphs. Each graph depicts a group change from pretest to posttest for a specific dependent variable that was different. The lines surrounding the mean scores represent the upper and lower 95% confidence intervals. The dependent variable was graphed for the entire stance phase but only differences that occurred within the first 25% of stance were analyzed. A, Control group knee internal-rotation (IR) moment. B, Plyometric group knee-flexion angle. C, Plyometric group knee IR angle. Abbreviation: ER, external rotation.

Figure 2. Continued. D, Plyometric group knee-flexion moment. E, Plyometric group knee-abduction (ABD) moment. F, Core stability group knee-flexion angle.

Figure 2. Continued. G, Core stability group knee IR angle. H, Core stability group hip-flexion moment. I, Core stability group hip IR moment.

Table 4. Group Demographics at Pretest and Posttest

Group	Characteristic, Mean $\pm$ SD		
	Age, y	Height, cm	Mass, kg
Control			
Pretest	14.8 $\pm$ 0.4	168.6 $\pm$ 4.5	52.1 $\pm$ 6.1
Posttest	14.8 $\pm$ 0.4	168.9 $\pm$ 4.4	52.0 $\pm$ 5.7
t_5 value	Not applicable	−1.68	0.24
P value	Not applicable	.15	.82
Plyometric			
Pretest	15.1 $\pm$ 1.1	172.1 $\pm$ 8.0	62.6 $\pm$ 8.8
Posttest	15.3 $\pm$ 1.04	172.5 $\pm$ 8.4	64.0 $\pm$ 9.1
t_8 value	Not applicable	−1.41	−0.60
P value	Not applicable	.18	.56
Core stability			
Pretest	14.5 $\pm$ 0.8	169.2 $\pm$ 7.3	56.8 $\pm$ 7.9
Posttest	14.5 $\pm$ 0.8	169.3 $\pm$ 7.4	57.4 $\pm$ 7.8
t_7 value	Not applicable	−1.09	−2.24
P value	Not applicable	.31	.06

strong effect that could be interpreted as a clinically meaningful magnitude of difference.²³

All graphs were created and effect sizes calculated using Excel (version 2003; Microsoft Corporation, Redmond, WA). We used SPSS (version 15.0; SPSS Inc, Chicago, IL) to calculate descriptive statistics for age, height, and mass. Furthermore, we used separate dependent t tests to compare within-group changes over time for height and mass ($P < .05$).

RESULTS

We found no within-group differences for height or mass ($P > .05$; Table 4). All participants enrolled in the plyometric group completed 100% of the intervention sessions, and all participants in the core stability group completed at least 9 of 12 (9.5 ± 0.5) sessions. One participant in the plyometric group did not return for posttesting after completing the entire program. The combined feedback from the ATs observing the intervention program is reported in Table 1. Findings that were different and effect sizes for within-group comparisons between pretest and posttest where the CI bands did not overlap are reported in Table 5. Pretest and posttest group means at initial contact, the peak point in the first 25% of

the stance phase, and the average value of the entire stance phase (0%–100%), are reported in Table 6 for the dependent variables that were not different.

Control Group

The external-rotation knee moment of the control group was smaller at posttest (mean difference = 0.06 ± 0.008) between 12% and 24% of landing but remained an external-rotation moment (Figure 2A). Furthermore, this window had a strong effect size (Cohen $d = 1.34$, 95% CI = 0.09, 2.60).

Plyometric Group

We found a mean difference of $-18.5^\circ \pm 3.6^\circ$ for knee-flexion angle from 13% to 25% of the landing phase. This represented a decrease in the knee-flexion angle after the 4-week intervention (Cohen $d = -1.79$, 95% CI = -2.89 , -0.70 ; Figure 2B). Similarly, the knee internal-rotation angle decreased from 1% to 25% of the landing phase, with a mean difference of $-18.5 \pm 2.7^\circ$ (Cohen $d = -3.68$, 95% CI = -5.20 , -2.16 ; Figure 2C). In addition, the knee-flexion moment was notably lower from 16% to 25% of the landing phase, when the mean difference was -0.33 ± 0.04 Nm/kg-m (Cohen $d = 2.04$, 95% CI = 0.90, 3.18; Figure 2D). The knee-abduction moment decreased at 10% of the landing phase, which corresponded with the timing of the peak abduction knee moment (Figure 2E). The mean difference between pretest and posttest at the 10% point was 0.1 Nm/kg-m with a strong effect size (Cohen $d = 1.52$, 95% CI = 0.47, 2.57). No other differences were found within the plyometric group.

Core Stability Group

Knee-flexion angle decreased from 10% to 25% of the landing phase, with a mean difference of $-16.3^\circ \pm 3.4^\circ$ (Cohen $d = -1.88$, 95% CI = -3.06 , -0.70 ; Figure 2F). Knee internal-rotation angle increased after the core stability intervention at 1% to 2% of the landing phase, with a mean difference of $12.2^\circ \pm 1.1^\circ$ (Cohen $d = 1.65$, 95% CI = 0.52, 2.79; Figure 2G). Hip-joint moments were altered after the core stability intervention program. The hip-flexion moment decreased from 19% to 25%; the mean

Table 5. Drop Vertical Jump Kinematic and Kinetic Findings That Were Different for All Groups

Group	Landing Phase, %	Mean Difference (Pooled SD)	Effect Size (Confidence Interval) ^a
Control			
Knee internal-rotation moment, Nm/kg-m	12–24	0.04 (0.03)	1.34 (0.09, 2.6)
Plyometric			
Knee-flexion angle, °	13–25	−18.5 (3.6)	−1.79 (−2.89, −0.70)
Knee internal-rotation angle, °	1–25	−18.5 (2.7)	−3.68 (−5.20, −2.16)
Knee-flexion moment, Nm/kg-m	16–25	−0.33 (0.04)	2.04 (0.90, 3.18)
Knee-valgus moment, Nm/kg-m	10	0.09	1.52 (0.47, 2.57)
Core stability			
Knee-flexion angle, °	10–25	−16.3 (3.4)	−1.88 (−3.06, −0.70)
Knee internal-rotation angle, °	1–2	12.2 (1.1)	1.65 (0.52, 2.79)
Hip-flexion moment, Nm/kg-m	19–25	−0.33 (0.05)	−1.51 (−2.62, −0.40)
Hip internal-rotation moment, Nm/kg-m	9–12	−0.06 (0.02)	−1.99 (−3.19, −0.79)
Hip internal-rotation moment, Nm/kg-m	20–24	−0.06 (0.01)	−2.21 (−3.46, −0.97)

^a Cohen d effect sizes were calculated at the point in the landing phase where the confidence interval bands did not cross and the mean difference was the largest. Negative values indicate a decrease after the intervention, and positive values indicate an increase after the intervention. For all findings shown, there was a strong effect size: the confidence interval did not cross 0.

Table 6. Drop Vertical Jump Kinematic and Kinetic Mean Findings That Were not Different for All Groups^a

Group	Pretest			Posttest		
	Initial Contact	Peak ^b	Average ^c	Initial Contact	Peak ^b	Average ^c
Control						
Knee-flexion angle, °	15.52	69.39	63.74	16.11	46.52	49.68
Knee-abduction angle, °	2.88	−0.40	−1.19	2.91	1.61	−0.39
Knee internal-rotation angle, °	6.40	25.46	26.30	5.29	16.07	17.14
Hip-flexion angle, °	32.90	53.20	50.92	25.24	36.13	39.42
Hip-abduction angle, °	−9.98	−10.21	−6.33	−7.34	−5.66	−5.35
Hip internal-rotation angle, °	−0.80	3.94	−0.38	4.58	4.58	−0.05
Spine lateral-flexion angle, °	5.38	5.42	1.85	1.80	2.01	2.30
Knee-flexion moment, Nm/kg·m	−0.08	0.79	0.57	−0.16	0.42	0.31
Knee-abduction moment, Nm/kg·m	−0.08	−0.12	0.14	−0.09	−0.09	0.08
Hip-flexion moment, Nm/kg·m	−0.02	0.56	0.32	0.13	0.38	0.27
Hip-abduction moment, Nm/kg·m	−0.12	−0.24	−0.05	−0.09	−0.11	0.02
Hip internal-rotation moment, Nm/kg·m	0.01	0.11	0.09	0.02	0.06	0.06
Plyometric						
Knee-abduction angle, °	3.79	−0.08	−0.22	0.77	−2.08	−1.62
Hip-flexion angle, °	24.39	48.20	46.15	27.28	43.13	45.04
Hip-abduction angle, °	−9.58	−9.58	−8.17	−8.77	−7.83	−7.54
Hip internal-rotation angle, °	−1.83	−0.66	−1.73	−3.04	−1.18	−3.49
Spine lateral-flexion angle, °	0.67	1.55	0.93	1.83	2.31	2.77
Hip-flexion moment, Nm/kg·m	0.06	0.59	0.43	0.04	0.44	0.32
Hip-abduction moment, Nm/kg·m	−0.01	−0.20	−0.01	−0.02	−0.16	0.01
Hip internal-rotation moment, Nm/kg·m	0.01	0.14	0.11	0.01	0.07	0.09
Knee external-rotation moment, Nm/kg·m	0.01	−0.05	−0.05	0.006	−0.03	−0.03
Core stability						
Knee-abduction angle, °	4.02	3.55	3.84	−0.49	−0.49	−1.29
Hip-flexion angle, °	28.17	54.0	51.18	26.0	41.08	43.1
Hip-abduction angle, °	−8.18	−8.61	−4.45	−7.04	−7.33	−2.98
Hip internal-rotation angle, °	−0.63	3.44	3.60	−5.07	−4.13	−4.89
Spine lateral-flexion angle, °	0.37	4.18	3.07	2.08	3.37	3.24
Knee-flexion moment, Nm/kg·m	−0.13	0.68	0.48	−0.14	0.57	0.44
Knee-abduction moment, Nm/kg·m	−0.07	−0.11	0.07	−0.05	−0.07	0.15
Knee external-rotation moment, Nm/kg·m	−0.003	−0.06	−0.06	0.001	−0.06	−0.06
Hip-abduction moment, Nm/kg·m	−0.10	−0.16	−0.10	−0.03	−0.13	0.01

^a Positive values indicate flexion, adduction, and internal-rotation directions.

^b Indicates the peak within the first 25% of the stance phase.

^c Indicates an average over the entire stance phase (range, 0%–100%).

difference was -0.33 ± 0.05 Nm/kg·m (Cohen $d = -1.51$, 95% CI = $-2.62, -0.40$; Figure 2H). In addition, the hip internal-rotation moment decreased at posttest between 9% to 12% and 20% to 24% of landing, with a mean difference of -0.06 ± 0.02 Nm/kg·m (Cohen $d = -1.99$, 95% CI = $-3.19, -0.79$) and -0.06 ± 0.01 Nm/kg·m (Cohen $d = -2.21$, 95% CI = $-3.46, -0.97$), respectively (Figure 2I). No other differences were found within the core stability group.

DISCUSSION

In a recent meta-analysis, Yoo et al²⁴ concluded that ACL injury-prevention programs are most effective in people younger than age 18 years. The individuals in our study were all high school-aged athletes participating at the junior varsity level, which may indicate a participant pool with diminished neuromuscular coordination and, therefore, a higher ceiling for improvement.²⁵ We hypothesized that we would see changes in trunk, hip, and knee biomechanics after completion of a neuromuscular training program focused on either plyometric or core stability. Our findings partially confirmed our hypotheses, indicating that changes in lower extremity biomechanics during a DVJ can be seen after 4 weeks of coach-supervised training in female

athletes. The plyometric group demonstrated differences for knee-joint kinematic and kinetic variables only; however, the core stability group had altered hip- and knee-joint variables, and the control group had 1 altered kinematic variable.

Griffin et al²⁶ indicated that the common denominator in successful ACL injury-prevention programs was the inclusion of plyometric exercises. We incorporated exercises shown to effectively decrease the risk of ACL injury or improve biomechanical variables associated with increased injury risk. Contrary to the literature in which researchers examined kinematic variables at peak vertical ground reaction force during a maximal vertical jump¹⁰ and assessed total sagittal-plane motion during a DVJ,⁸ we found a decrease in knee-flexion angle after the plyometric training intervention. Pollard et al,¹¹ who studied high school female soccer teams, also reported a nonsignificant decrease in knee flexion after an in-season intervention program.

The finding of decreased knee-flexion angle was contrary to our hypothesis and poses a concern about the potential for ACL injury. Hewett et al⁶ reported that after prospective testing, their group with injured ACLs had a peak knee-flexion angle that was 10.5° less than that of the healthy group; however, this variable did not fit into the predictor

model for ACL injury. A decrease in knee-flexion motion may increase the relative strain on the ACL.²⁷ Furthermore, a decrease in knee-flexion angle will affect the angle of contraction for the hamstrings muscles, altering the effectiveness of this muscle group in limiting anterior translation of the tibia.²⁸ The changes shown in our study may have resulted from the program's being led by the coaching staff rather than a more qualified clinician. In future studies, investigators may incorporate more extensive training of the individuals involved in leading the intervention program, as Mandelbaum et al²⁹ did. The most effective and efficient method for implementing neuromuscular control training programs in an athletic environment is unknown. However, it seems logical that if the individuals responsible for implementing the training programs are more informed, the quality of instruction given to the athletes will be better.

We found a decreased knee internal-rotation angle for the entire landing phase after plyometric training (Figure 2C). Knee internal rotation is believed to increase the stress placed on the ACL.³⁰ Therefore, if knee rotation is decreased, the stress placed on the ACL also should decrease, thus minimizing the risk for noncontact injury. No known evidence has indicated that the knee internal-rotation angle is solely related to tibiofemoral joint movement during landing. Therefore, a change in foot positioning during landing may have influenced the average 18.5° decrease in internal-rotation angle at the knee, but we do not have specific data to support this theory. The handout provided to the coaching staff did not emphasize that athletes should point their toes straight ahead, yet it did state that the knee should be centered over the toes when performing each exercise. The athletes might have changed the position of the foot under the tibia instead of making a proximal adjustment to account for this landing error. This was the only dependent variable that was different between groups at pretest. The plyometric group had a larger knee internal-rotation angle than the core stability group, and after the intervention, this difference was no longer present.

The plyometric group also demonstrated changes in knee-joint moments that partially supported our initial hypotheses. We found a decrease in the external knee-flexion moment, which corresponded to the internal knee-extensor moment, from 16% to 25% of the landing phase, spanning the late deceleration phase of the DVJ. Quadriceps dominance is a proposed risk factor for ACL injury and has been associated with an increase in the internal knee-extensor moment over the internal knee-flexor moment, potentially leading to long-term imbalances in strength and muscle activation coordination.³¹ Therefore, we believe the decrease in external knee-flexor moment represents a shift toward a more balanced neuromuscular pattern. In addition, an overreliance on the quadriceps musculature can mean individuals are placing added anterior shear stress on the ACL during dynamic activities, increasing their risk for noncontact injury. Ligament dominance occurs when the ligament and not the surrounding joint musculature is used to attenuate the energy transferred from a ground reaction force.³² Ligament-dominant females have increased medial knee motion and larger knee-abduction moments and ground reaction forces.³³ The decreased knee-abduction moment at 10% of the landing phase, which corresponded with the peak knee-abduction moment, may indicate that

the plyometric intervention was beneficial in reducing the participants' reliance on the static stabilizers to attenuate the force transferred during the landing task. Furthermore, both kinetic changes had strong effect sizes, demonstrating that the mean difference found over time was clinically meaningful.

Similar to the plyometric group, the core stability group also demonstrated a decrease in knee-joint flexion. This finding may suggest that increases in neuromuscular coordination of the hip and trunk musculature may decrease the participant's reliance on quadriceps muscle function. Lawrence et al³⁴ found that participants with greater hip external-rotation strength had smaller knee-flexor moments during a single-legged drop landing and attributed this to requiring less quadriceps activation during landing. Our core stability group performed open chain exercises to isolate the hip external rotators and performed forward lunges and squats to reinforce stabilization of the femur in the closed chain position. The intervention handout encouraged the athletes to perform the exercises in a slow, controlled manner to instruct eccentric quadriceps and gluteal function. Ekstrom et al¹² examined muscle activation during a forward lunge and found that this exercise elicited, on average, 76% of the maximal voluntary isometric contraction for the vastus medialis oblique. Therefore, specific exercises, such as the forward lunge and double-limb squat performed by the core stability group, possibly improved eccentric strength and neuromuscular control of the quadriceps; however, we have no strength or muscle activation data to confirm that this occurred in a 4-week period within this participant population. As mentioned when referring to the decrease in knee-flexion angle after plyometric training, a smaller knee-flexion angle during landing is considered a risk factor for ACL injury.⁶ Further research is needed to clarify whether the decrease in knee-flexion angle after the intervention is due to a change in neuromuscular function or to the personnel conducting the intervention sessions.

The knee internal-rotation angle was higher for the first 2% of the landing phase after the implementation of the core stability training. To our knowledge, no researchers have examined the effect of core stability training in isolation on lower extremity biomechanics during a DVJ. Chappell and Limpisvasti⁵ incorporated some of the same exercises that we used as part of a global neuromuscular training program and found a nearly significant difference ($P = .06$) for increased knee internal rotation at initial contact. We propose that the differences may be due to the change in force management of hip internal rotation. Researchers^{34,35} believe that inducing changes at the hip will cause a cascade of adaptations to occur down the kinetic chain. The timing of the change in knee internal rotation may be explained by preparatory muscle activity when the athlete may be adjusting the positioning of the lower extremity during the flight phase of landing rather than adapting an internally rotated position to better eccentrically control the loading response phase of landing. Unfortunately, we did not collect electromyographic data as part of this data set, so we cannot confirm this theory.

Unlike the plyometric group, the core stability group showed adaptations in hip-joint kinetics. This finding was not surprising because the exercises performed for 4 weeks focused on improving trunk and hip neuromuscular

coordination. The decrease in hip-flexion and internal-rotation moments may be associated with increased ability of the hip extensors and external rotators to eccentrically control hip flexion and internal rotation, respectively. Investigators have shown that the side-plank exercise, which was among the core stability exercises, can activate up to 74% of the maximal voluntary isometric contraction of the gluteus medius,¹² which substantially contributes to eccentrically controlling knee-joint positioning.³⁶ Furthermore, Lephart et al¹⁰ designed a basic neuromuscular program for high school female athletes that incorporated some of the same trunk exercises that we used and found similar results for changes in the peak hip-flexion moment. Differences between intervention programs and levels of supervision must be noted when drawing comparisons among these studies.

Few researchers have reported changes in transverse-plane hip moments. However, Paterno et al³⁷ found that an increase in the internal moment for hip internal rotation resulted in a risk for ACL injury that was 8 times greater in those who had sustained an ACL injury. These researchers advocated targeting hip external-rotation strength to decrease hip internal-rotation range of motion during landing. Finally, all changes that were different for hip-joint kinetics had strong effect sizes, indicating that the magnitudes of difference were meaningful. Changes related to force management at the hip may have translated to changes in joint range of motion at the knee, further suggesting the link in the kinetic chain within the lower extremity.⁹

Contrary to our hypothesis, neither the plyometric nor the core stability group demonstrated changes in lateral trunk flexion after the intervention period. We initially hypothesized we would find a difference in this kinematic variable for both intervention groups because the plyometric group performed exercises with an emphasis on avoiding trunk lean during landing and the core stability group performed exercises that targeted the lateral trunk musculature. The DVJ used during testing entails primarily sagittal-plane movement, and a very small amount (peak means of less than 5° in each group at each testing period) of lateral trunk flexion occurred. Zazulak et al,⁹ who laid the groundwork for this specific hypothesis, found that lateral trunk displacement due to perturbation was a predictor of ACL injury. Therefore, we believe the testing protocol did not challenge the participants enough to require implementation of potentially learned strategies. In future studies, researchers should consider requiring a multiplanar task or adding a controlled perturbation to better determine if plyometric or core stability training is an effective intervention to minimize lateral trunk displacement during a dynamic task.

Clinical Relevance

One goal in designing this study was to keep the intervention programs feasible for implementation outside of a research setting. The exercises chosen required no equipment beyond what is available at a typical soccer or lacrosse practice. The coaches were responsible for instructing the athletes in proper technique during the exercises through the use of a guided handout without the involvement of outside support staff. Yoo et al²⁴ suggested

that feedback from a qualified instructor plays a large role in the success of injury-prevention programs, so in the future, researchers should consider this variable when planning a clinical intervention. To encourage compliance and promote feasibility, we designed the intervention programs to be completed in 4 weeks, with each session lasting less than 20 minutes. In previous intervention studies,^{5,7,10,11,14,16,25} investigators used exercise programs that required 6 to 12 weeks and lasted for 15 to 90 minutes per session. The optimal duration (overall intervention time frame and individual session length) for implementing an ACL injury-prevention program has not been determined. Despite the simplicity of the interventions, our results were clinically meaningful and echoed many of the findings of more involved research studies.^{5,8,38}

The length of our program was shorter than most neuromuscular control training and ACL injury-prevention programs.^{5,7,10,16,38–40} The changes seen over a relatively short period of training may reflect the age and skill level of the athletes included in our study (athletes at the high school junior varsity level). Myer et al³¹ noted that less-skilled or less-developed athletes are more adept at changing movement patterns than are high-level athletes. Therefore, the included participants may have been more adept at changing and may have had more potential to improve strength and neuromuscular control.

The plyometric training program produced kinematic and kinetic changes at the knee joint only, whereas the core stability program produced changes at both the hip and knee joints. Because we did not include injury incidence data, determining which intervention program may be more successful in reducing ACL injuries is difficult. However, both types of exercises appear to be capable of altering biomechanical patterns of a DVJ. Decreases in sagittal-plane knee motion occurred after both interventions, which may be of concern because a smaller peak knee-flexion angle has been shown to be related to an increased risk for ACL injury.⁶ Therefore, we recommend that comprehensive ACL injury-prevention programs incorporate components of both plyometric and core stability training and that these programs be instructed by a qualified individual to ensure that proper technique is enforced to minimize harm. We also recommend assessment of an intervention that uses both plyometric and core stability components to identify the biomechanical changes associated with a combination training program.

Limitations and Future Research

Our study had limitations. The intervention groups were not randomly assigned to the schools, so the control group had fewer participants than the intervention groups. Furthermore, despite great efforts to recruit participants, the plyometric group consisted solely of lacrosse players, whereas the core stability and control groups comprised both lacrosse and soccer athletes. This homogeneity may have decreased the within-group variability for the plyometric group, and involving only 1 team meant that more consistency existed in the coach-directed training sessions. This is in contrast to the core stability group, which included 2 teams from different sports, potentially leading to more variability in biomechanical patterns and intervention implementation.

Further limitations include the amount of formal training given to the coaches and athletes in the intervention groups about correctly performing the exercises. Given that standardized instruction was provided only in the exercise manual that each team received, the exercises may not have been performed correctly, and the intervention groups may not have benefited fully. This decision was made to create an intervention that could be implemented realistically into a secondary school setting and used minimal amounts of resources (time, supplies).

The objective of our study was to determine if biomechanical changes could be seen with either type of intervention and was not to determine whether core stability training was more beneficial than plyometric training in altering biomechanical patterns associated with ACL injury risk. A combination group may provide more information about whether performing both types of exercises has an additive effect. To make intervention programs more feasible to implement, further research is needed to determine which specific exercises are most successful in eliciting a change in lower extremity biomechanics during a DVJ. Researchers need to understand the duration of training required before important changes in biomechanical variables occur.

CONCLUSIONS

The implementation of an in-season, 4-week training program for high school female athletes resulted in kinematic and kinetic changes. The plyometric group demonstrated changes solely at the knee joint, whereas the core stability group showed alterations in kinetics at the hip joint and kinematics at the knee joint. Our results suggest that both types of exercises are warranted in ACL injury-prevention programs because they contribute different biomechanical adaptations.

REFERENCES

- Agel J, Arendt EA, Bershadsky B. Anterior cruciate ligament injury in National Collegiate Athletic Association basketball and soccer: a 13-year review. *Am J Sports Med.* 2005;33(4):524–530.
- Boden BP, Dean GS, Feagin JA Jr, Garrett WE Jr. Mechanisms of anterior cruciate ligament injury. *Orthopedics.* 2000;23(6):573–578.
- Blackburn JT, Padua DA. Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. *Clin Biomech (Bristol, Avon).* 2008;23(3):313–319.
- Griffin LY, Agel J, Albohm MJ, et al. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg.* 2000;8(3):141–150.
- Chappell JD, Limpisvasti O. Effect of a neuromuscular training program on the kinetics and kinematics of jumping tasks. *Am J Sports Med.* 2008;36(6):1081–1086.
- Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med.* 2005;33(4):492–501.
- Myer GD, Ford KR, McLean SG, Hewett TE. The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. *Am J Sports Med.* 2006;34(3):445–455.
- Myer GD, Ford KR, Palumbo JP, Hewett TE. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *J Strength Cond Res.* 2005;19(1):51–60.
- Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. *Am J Sports Med.* 2007;35(7):1123–1130.
- Lephart SM, Abt JP, Ferris CM, et al. Neuromuscular and biomechanical characteristic changes in high school athletes: a plyometric versus basic resistance program. *Br J Sports Med.* 2005;39(12):932–938.
- Pollard CD, Sigward SM, Ota S, Langford K, Powers CM. The influence of in-season injury prevention training on lower-extremity kinematics during landing in female soccer players. *Clin J Sport Med.* 2006;16(3):223–227.
- Ekstrom RA, Donatelli RA, Kenji CC. Electromyographic analysis of core trunk, hip, and thigh muscles during 9 rehabilitation exercises. *J Orthop Sports Phys Ther.* 2007;37(12):754–762.
- Distefano LJ, Blackburn JT, Marshall SW, Padua DA. Gluteal muscle activation during 36 common therapeutic exercises. *J Orthop Sports Phys Ther.* 2009;39(7):532–540.
- Herman DC, Weinhold PS, Guskiewicz KM, Garrett WE, Yu B, Padua DA. The effects of strength training on the lower extremity biomechanics of female recreational athletes during a stop-jump task. *Am J Sports Med.* 2008;36(4):733–740.
- Hewett TE, Myer GD, Ford KR, Slaughterbeck JR. Preparticipation physical examination using a box drop vertical jump test in young athletes: the effects of puberty and sex. *Clin J Sport Med.* 2006;16(4):298–304.
- 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.
- Myer GD, Chu DA, Brent JL, Hewett TE. Trunk and hip control neuromuscular training for the prevention of knee joint injury. *Clin Sports Med.* 2008;27(3):425–448, ix.
- Pfeiffer RP, Shea KG, Roberts D, Grandstrand S, Bond L. Lack of effect of a knee ligament injury prevention program on the incidence of noncontact anterior cruciate ligament injury. *J Bone Joint Surg Am.* 2006;88(8):1769–1774.
- Akuthota V, Ferreiro A, Moore T, Fredericson M. Core stability exercise principles. *Curr Sports Med Rep.* 2008;7(1):39–44.
- Willson JD, Dougherty CP, Ireland ML, Davis IM. Core stability and its relationship to lower extremity function and injury. *J Am Acad Orthop Surg.* 2005;13(5):316–325.
- Krosshaug T, Nakamae A, Boden BP, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med.* 2007;35(3):359–367.
- Monaghan K, Delahunt E, Caulfield B. Ankle function during gait in patients with chronic ankle instability compared to controls. *Clin Biomech (Bristol, Avon).* 2006;21(2):168–174.
- Pollard CD, Davis IM, Hamill J. Influence of gender on hip and knee mechanics during a randomly cued cutting maneuver. *Clin Biomech (Bristol, Avon).* 2004;19(10):1022–1031.
- Yoo YS, Jeong WS, Shetty NS, Ingham SJ, Smolinski P, Fu F. Changes in ACL length at different knee flexion angles: an in vivo biomechanical study. *Knee Surg Sports Traumatol Arthrosc.* 2010;18(3):292–297.
- 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.
- Griffin LY, Albohm MJ, Arendt EA, et al. Understanding and preventing noncontact anterior cruciate ligament injuries: a review of the Hunt Valley II meeting, January 2005. *Am J Sports Med.* 2006;34(9):1512–1532.
- Withrow TJ, Huston LJ, Wojtys EM, Ashton-Miller JA. The relationship between quadriceps muscle force, knee flexion, and anterior cruciate ligament strain in an in vitro simulated jump landing. *Am J Sports Med.* 2006;34(2):269–274.

28. Markolf KL, O'Neill G, Jackson SR, McAllister DR. Effects of applied quadriceps and hamstrings muscle loads on forces in the anterior and posterior cruciate ligaments. *Am J Sports Med.* 2004;32(5):1144–1149.
29. Mandelbaum BR, Silvers HJ, Watanabe DS, et al. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. *Am J Sports Med.* 2005;33(7):1003–1010.
30. Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GA, Slauterbeck JL. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res.* 1995;13(6):930–935.
31. Myer GD, Ford KR, Hewett TE. Rationale and clinical techniques for anterior cruciate ligament injury prevention among female athletes. *J Athl Train.* 2004;39(4):352–364.
32. Ford KR, Myer GD, Toms HE, Hewett TE. Gender differences in the kinematics of unanticipated cutting in young athletes. *Med Sci Sports Exerc.* 2005;37(1):124–129.
33. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc.* 2003;35(10):1745–1750.
34. Lawrence RK III, Kernozek TW, Miller EJ, Torry MR, Reuteman P. Influences of hip external rotation strength on knee mechanics during single-leg drop landings in females. *Clin Biomech (Bristol, Avon).* 2008;23(6):806–813.
35. Zazulak BT, Ponce PL, Straub SJ, Medvecky MJ, Avedisian L, Hewett TE. Gender comparison of hip muscle activity during single-leg landing. *J Orthop Sports Phys Ther.* 2005;35(5):292–299.
36. Carcia C, Eggen J, Shultz S. Hip-abductor fatigue, frontal-plane landing angle, and excursion during a drop jump. *J Sport Rehabil.* 2005;14(4):321–331.
37. Paterno MV, Schmitt LC, Ford KR, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med.* 2010;38(10):1968–1978.
38. Myer GD, Ford KR, Brent JL, Hewett TE. The effects of plyometric vs dynamic stabilization and balance training on power, balance, and landing force in female athletes. *J Strength Cond Res.* 2006;20(2):345–353.
39. Myer GD, Ford KR, Hewett TE. The effects of gender on quadriceps muscle activation strategies during a maneuver that mimics a high ACL injury risk position. *J Electromyogr Kinesiol.* 2005;15(2):181–189.
40. Peterson W, Braun C, Bock W, et al. A controlled prospective case control study of a prevention training program in female team handball players: the German experience. *Arch Orthop Trauma Surg.* 2005;125(9):614–621.

SUPPLEMENTAL MATERIAL

Appendix S1. Plyometric Training Program

Found at: <http://dx.doi.org/10.4085/1062-6050-48.4.06.S1> (831 KB PDF).

Appendix S2. Core Stability Training Program

Found at: <http://dx.doi.org/10.4085/1062-6050-48.4.06.S1> (1416 KB PDF).

Address correspondence to Kate R. Pfile, PhD, ATC, College of Charleston, 66 George Street, Charleston, SC 29424. Address e-mail to pfilekr@cofc.edu.