The Effects of Plyometric Versus Dynamic Stabilization and Balance Training on Lower Extremity Biomechanics

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Background: Neuromuscular training that includes both plyometric and dynamic stabilization/balance exercises alters movement biomechanics and reduces ACL injury risk in female athletes. The biomechanical effects of plyometric and balance training utilized separately are unknown.

Hypothesis: A protocol that includes balance training without plyometric training will decrease coronal plane hip, knee, and ankle motions during landing, and plyometric training will not affect coronal plane measures. The corollary hypothesis was that plyometric and balance training effects on knee flexion are dependent on the movement task tested.

Study Design: Controlled laboratory study.

Methods: Eighteen high school female athletes participated in 18 training sessions during a 7-week period. The plyometric group ($n = 8$) performed maximum-effort jumping and cutting exercises, and the balance group (n = 10) used dynamic stabilization/balance exercises during training. Lower extremity kinematics were measured during the drop vertical jump and the medial drop landing before and after training using 3D motion analysis techniques.

Results: During the drop vertical jump, both plyometric and balance training reduced initial contact ($P = .002$), maximum hip adduction angle ($P = .015$), and maximum ankle eversion angle ($P = .020$). During the medial drop landing, both groups decreased initial contact ($P = .002$) and maximum knee abduction angle ($P = .038$). Plyometric training increased initial contact knee flexion ($P = .047$) and maximum knee flexion ($P = .031$) during the drop vertical jump, whereas the balance training increased maximum knee flexion ($P = .005$) during the medial drop landing.

Conclusion: Both plyometric and balance training can reduce lower extremity valgus measures. Plyometric training affects sagittal plane kinematics primarily during a drop vertical jump, whereas balance training affects sagittal plane kinematics during single-legged drop landing.

Clinical Relevance: Both plyometric and dynamic stabilization/balance exercises should be included in injury-prevention protocols.

Keywords: neuromuscular training; plyometrics; balance; ACL injury prevention

Female athletes are currently reported to be 4 to 6 times more likely to sustain a sports-related noncontact ACL injury than are male athletes.[1,27,38] Altered or decreased neuromuscular strategies during the execution of sports movements result in lower limb joint mechanics (motions and loads) that may increase the risk of ACL injury in girls and women.[4,9,10,17,31] Hewett et al[17] prospectively

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demonstrated that measures of lower extremity valgus, including knee abduction and related hip adduction motion and torque, during jump-landing tasks predicted ACL injury risk in young female athletes. Female athletes also exhibit increased lower extremity valgus movement and loads compared with male athletes during landing and pivoting movements.[4,9,16,30] In addition, increased coronal plane ankle motion during similar movements may also be associated with ACL injury in female athletes.[10,24]

Sagittal plane movement and load patterns during dynamic tasks may also contribute to the current gender disparity in noncontact ACL injury rates.[4,26] Specifically, the relative decreases in knee flexion typically observed in female athletes at initial contact and throughout the stance during sports movements are proposed to elicit anterior tibial shear loads large enough to injure the ACL.[8,29] Therefore, improved lower extremity movement strategies during high-risk sports movements, in particular those that contribute to decreased sagittal plane motion and increased coronal plane motions and load, may reduce risk and possibly prevent ACL injuries in female athletes.[3,17,39]

The established links between lower limb mechanics and noncontact ACL injury risk have led to the development of specific neuromuscular training interventions designed to prevent ACL injury, particularly in female athletes. These interventions were originally developed through empirical evidence from coaching and training female athletes and from performance-enhancement protocols.[19,20] More recent interventions have used comprehensive training strategies developed from injury mechanism and training studies, combining multiple components of plyometric power and dynamic stabilization/balance training.[18,28,36,37,44] Initial evidence suggests that these programs likely reduce the potential for ACL injury in the female athlete.[28,37,44] However, it is unclear whether the combination of multiple neuromuscular training components provides additive effects or whether a single component is responsible for biomechanical adaptations and subsequent reduction of ACL injuries in female athletes.[17,20,36] Combined plyometric and dynamic stabilization/balance training can reduce lower extremity valgus measures, contralateral limb asymmetries, and impact forces.[20,36] In contrast, protocols that focused solely on plyometrics were reported to increase measures related to lower extremity valgus (increased hip adductor activation) measures in female athletes.[6] Current evidence suggests that although combined plyometric and dynamic stabilization training can improve dangerous lower extremity mechanics related to ACL injury risk,[17,20,36] isolated plyometric protocols may not be beneficial to female athletes.[6]

Assessment of the relative efficacy of plyometric and dynamic stabilization/balance training interventions alone and in combination, is important to optimize the potential positive effects on ACL injury prevention. The comprehensive interventions currently used in ACL injury–prevention programs often involve large time commitments that may deter coaches from including them in preseason conditioning programs.[15,28,37] In addition, the increased volume of training, especially plyometric training, may place undue stress on young female athletes attempting to prepare for an injury-free season. Thus, if a single training component were found to alter the biomechanical risk factors related to the female athlete's increased risk of ACL injury, more effective and efficient preseason training programs could be implemented.

There are no published comparisons of the effects of isolated plyometric and dynamic stabilization/balance training on the biomechanical motions purported to be linked to increased ACL injury risk in female athletes. The purpose of the current study was to compare the effects of maximum effort plyometric jumping versus dynamic stabilization/balance exercises on lower extremity kinematics during landing tasks in female athletes. Specifically, the separate effects of plyometric and balance training on resultant frontal and sagittal plane motions were examined during a plyometric landing task and a single-limb stabilization task that incorporate the potential high-risk mechanisms. The first hypothesis was that a protocol that included dynamic stabilization/balance exercises without maximum-effort plyometrics would decrease coronal plane hip adduction, knee abduction, and ankle eversion during landing. The second hypothesis was that isolated plyometric training without dynamic stabilization/balance exercises would not reduce lower extremity coronal plane measures at the hip, knee, and ankle. The corollary hypotheses were that plyometric and balance training effects on knee flexion would be dependent on the movement task tested.

MATERIALS AND METHODS

Subjects

Coronal and sagittal plane kinematic data from ACL-injured and ACL-uninjured female athletes were used to determine the clinically significant minimum expected changes for the current study groups.[17] Based on these data, a power analysis revealed that to achieve 80% statistical power in the current study, with an exploratory α level of .05, a minimum of 8 subjects per group (plyometric group and balance group) were required. We recruited a team with a minimum of 16 athletes to be randomized into 2 groups.

Subjects (n = 23) from an area high school volleyball team were recruited to participate in this study and were subsequently randomly assigned to 1 of the 2 training groups. One group performed a protocol that involved plyometric training, whereas the other group performed a protocol that focused on dynamic stabilization and balance. The preestablished compliance criterion required that each subject participate in at least two thirds (12 of 18) of the training sessions to be included in the study. One subject made only 11 sessions because of competitive club season travel, which excluded her from the analyses. Three subjects did not complete the required number of training sessions or participate in posttesting because of injuries sustained during outside sport activities (1 acute fibula fracture from ankle eversion injury while wearing a rigid ankle orthosis, 1 grade 2 inversion ankle sprain, and 1 grade 3 inversion ankle sprain). No acute injuries occurred during the training sessions. One subject was excluded from the 3D motion statistical analysis because of an error during the data collection session. The 5 excluded subjects

TABLE 1
Protocol for Plyometric Training Group (PLYO)[a]

PLYO Training, Week 1	Time, s	Reps	Total Reps
Athletic position		5	
Wall jumps	15		
Squat jumps	10		
Tuck jump, with thighs parallel	10		
Line jumps, side to side	10		
Line jump lateral maximum vertical		5	
Lunge jump	10		
180° jumps, height	15		
Broad jump vertical + step[b]		8	
Bounding in place	20		
Forward jumps over barriers + step[b]		6	
Forward barrier jumps, with middle box + step[b]		6	
Box drop maximum vertical + step[b]		10	
Box drop + step[b]		10	
PLYO Training, Week 3	**Time, s**	**Reps**	**Total Reps**
Wall jumps	15		
Squat jumps	15		
Tuck jump, with abdominal crunch	15		
Tuck jump, with butt kick	15		
Barrier jumps, front to back	15		
Barrier jumps, side to side	15		
Hop, hop, hop—athletic position + step[b]		6	
180° jumps, height	15		
Broad jump, jump, jump vertical + step[b]		6	
Bounding for distance		6	
Lateral barrier hops with staggered box reaction[b]		6	
Back drop-box touch–maximum vertical + step[b]		10	
Lateral box drop maximum vertical		5	
Power steps		8	
PLYO Training, Week 5	**Time, s**	**Reps**	**Total Reps**
Squat-tuck jumps	12		
Barrier hops flat, front to back	12		
Barrier hops flat, side to side	12		
Crossover hop, hop, hop—athletic position + step[b]		10	
180° jumps, height	15		
Broad jump, jump, jump vertical + step[b]		6	
3 barrier hop–reaction, 3-way		3	
Forward/backward hops over barriers + step[b]		6	
Box drop–180°–box drop–maximum vertical + step[b]		8	
Box drop–180° + step[b]		8	
Lateral box drop–broad jump + step[b]		6	
Box drop maximum vertical–broad jump + step[b]		6	
Approach maximum vertical		4	
Crossover step–ski stop maximum vertical		4	

[a]Reps, repetitions.
[b]Exercise ends with a quick unanticipated reaction cut or step.

from the original 23 initially recruited left 18 (plyometric group, n = 8; balance group, n = 10) subjects to be evaluated for the effects of training. The mean completed sessions for both study groups was approximately 16 (plyometric group, 16.4 ± 1.5; balance group, 15.6 ± 1.4) and was not different between the study groups (*P* = .029).

The mean ± SD age of the participants was 15.9 ± 0.8 years in the plyometric group and 15.6 ± 1.2 years in the balance group, with a combined range of 14 to 17 years. All the subjects listed their primary sport as volleyball, whereas 12 listed secondary sports including 5 basketball, 2 soccer, 2 softball, and 1 swimming. Height and body mass were assessed at the pretraining test date and the posttraining test date. The initial height (mean ± SD) of the participants in the plyometric group was 169.5 ± 6.1 cm, and body mass was 61.4 ± 7.3 kg. In the balance group, the initial height and body mass (mean ± SD) were 168.0 ± 7.3 cm and 66.4 ± 11.8 kg. Follow-up assessment of height and body mass at the posttest date revealed a significant increase in both mean height (0.7 cm, *P* = .016) and body mass (1.1 kg, *P* = .028), but neither change was significantly different between groups. The dominant limb was documented by asking the athlete which foot she would use to kick a ball as far as possible.[11] The subjects' parents or guardians signed informed consent forms approved by the Institutional Review Board before the subjects' participation in the study.

All subjects had 3D lower limb (hip, knee, and ankle) joint kinematics recorded both before and after training. Pretesting occurred 1 week before training, whereas posttesting was performed approximately 8 weeks after the pretest on all subjects (4 days after the final training session). The training sessions were conducted with at least a 1:3 trainer-to-athlete ratio by National Strength and Conditioning Association–certified professionals and staff members.

Training Procedures

The 2 isolated neuromuscular training protocols used in this study were derived from a combined training protocol previously shown to reduce biomechanical measures related to ACL injury and to increase measures of performance.[17,36,43] The original protocol was modified to include either maximum-effort plyometric jumping and cutting maneuvers or dynamic lower extremity stabilization/balance exercises. Each training session lasted for approximately 90 minutes. Before each training session, an active warm-up that included 5 agility ladder runs was performed. Tables 1 and 2 depict the specific protocols for the plyometric and balance sessions respectively, taken from the first session of the week in weeks 1, 3, and 5. Table 3 depicts the corresponding resistance-training protocols used in conjunction with both groups.

The plyometric training emphasized jumping movements with maximum effort and power and performance of cutting techniques with quick reactions and maximum effort. The athletes received before, during, and/or after each exercise frequent oral feedback regarding the technical performance of their jumping and cutting movements. Specifically, the athletes were instructed to perform maximum-effort jumps without lower extremity valgus, with a focus on improving the efficiency and the power of the jump. During performance of the unanticipated cutting maneuvers, the athletes were again instructed to decrease lower extremity valgus motion, maintain proper knee and foot alignment, and attempt to improve the speed and efficiency of the technique. The exercise intensity was progressed by adding complexity to the movements and by adding single-limb maneuvers. The exercises performed by the plyometric group did not include any form of stabilization, hold, or balance.

In contrast, the balance group followed a protocol that emphasized dynamic stabilization and balance. The athletes were instructed on methods to dampen the landing force through sagittal plane flexion while avoiding positions of lower extremity valgus. During the exercise, the balance group received frequent and simultaneous oral feedback regarding the technical performance, improving postural and lower extremity alignment and control. Specifically, the athletes were instructed to perform the selected exercise with increased knee flexion without lower extremity valgus. As this protocol progressed, it increased in difficulty by moving from stable ground surfaces to relatively unstable surfaces, such as Airex pads (Perform Better Inc, Cranston, RI), both sides up (BOSU) trainers (TEAM BOSU, Canton, Ohio), and Swiss balls (Perform Better Inc). In addition, this group performed exercises that focused on maintaining dynamic stabilization and balance, with movements designed to strengthen the core musculature of the body. These exercises included torso flexion, torso extension, and rotational strength maneuvers. Dynamic balance exercises progressed by forced movement of the athletes' center of gravity through perturbations or addition of external mass to the movement or by the use of single-limb maneuvers.

Kinematic Testing

Movements. To test the effects of the balance and plyometric training on resultant lower limb 3D kinematics, 2 movement tests that may be related to increased risk of ACL injury were chosen.[3,13,39] The drop vertical jump was adopted from our earlier studies and consisted of the subject on top of a box (31 cm in height) with her feet positioned 35 cm apart (distance measured between toe markers). Each subject was instructed to drop directly down off the box and immediately perform a maximum vertical jump, raising both arms as though jumping for a basketball rebound.[9] Two force platforms (AMTI, Watertown, Mass) were positioned so that each foot would contact a different platform during the maneuver. The first contact on the platforms (ie, the drop from the box) was used to analyze the stance phase of the drop vertical jump task (Figure 1).[9,17,31] Three successful trials were recorded for each subject.

The second exercise chosen for evaluation was the single-legged medial drop landing task. For the medial drop landing, subjects were instructed to balance on 1 leg on a 13.5-cm block positioned adjacent to the force plate. They were then instructed to drop off the block medially from the stance limb, land on the same leg, and hold the landing (Figure 2). The subjects were not given feedback about their posture. Three successful trials on each limb were recorded for each subject, and the limb tested first was randomized for each subject. Again, the first contact on the platforms (ie, the drop from the box) was used to analyze the stance phase of the medial drop landing task.

Injury to the ACL occurs when joint motions or loads become extreme.[29,30,52] With this in mind, evaluating the effects of 2 training methods on resultant "maximum" joint kinematics appears to be a logical course of action. Furthermore, noncontact ACL injury likely occurs very early in the stance (approximately 50 milliseconds after initial contact),[21] suggesting that the risk of injury is already determined as the athlete contacts the ground.[12] Evaluating training effects on initial contact joint postures also appears warranted because it is possible to train athletes to land in positions that minimize the likelihood of ensuing hazardous control patterns.[20]

Instrumentation. Eight high-speed Eagle video cameras (Motion Analysis Corp, Santa Rosa, Calif) were positioned in the laboratory that defined an optimized capture volume of 4.5 × 2 × 2.5 m. Video and force data were time–medial drop landing synchronized and collected at 240 Hz and 1200 Hz, respectively (EVaRT, Motion Analysis Corp). Before each data collection session, the motion analysis system was calibrated to manufacturer recommendations.

Lower limb kinematic data were generated for each trial from the 3D coordinates of precisely attached external skin markers, as recorded via the high-speed video system. Specifically, each subject was instrumented with 37 retro reflective markers placed on the sacrum, left posterior superior iliac spine, sternum, and bilaterally on the shoulder, elbow, wrist, anterior superior iliac spine, greater trochanter, midthigh, medial and lateral knees, tibial tubercle, midshank, distal shank, medial and lateral ankles, heel, dorsal surface of the midfoot, lateral foot (fifth metatarsal), and toe (between second and third metatarsals) (Figure 3). A static trial was first collected as the subject was instructed to stand still and was aligned with the laboratory (global) coordinate system. This measurement was used to define each subject's neutral (zero) alignment, with subsequent dynamic kinematic measures quantified relative to this position.

Data Analyses. From the standing trial, a kinematic model composed of 9 skeletal segments (1 pelvis and thigh, shank, talus, and foot for both limbs) and 22 degrees of freedom was defined using Mocap Solver 6.17 (Motion Analysis Corp). This same method has been presented in detail previously.[32] Briefly, Mocap Solver performs model-based kinematic analysis through global least-squares optimization[25] and has been used to successfully quantify 3D lower limb (hip, knee, and ankle) joint motions associated with the stance phase of sidestepping, jump landing, and shuttle-run tasks.[31,33] For the current study, the pelvis was assigned 6 degrees of freedom relative to the global (laboratory) coordinate system, with the hip, knee, and ankle joints of each limb defined locally and assigned 3 rotational degrees of freedom,[53] 3 rotational degrees of freedom,[14] and 2 rotational degrees of freedom,[22,48] respectively (Figure 3). Hip, knee, and ankle joint centers were defined according to the

TABLE 2
Protocol for Balance Training Group (BAL)[a]

BAL Training, Week 1	Time, s	Reps	Total Reps
Deep hold position		5	
Box butt touch		8	
Line jump, forward–deep hold		8	
Line jump, lateral–deep hold		4	
Box drop–deep hold		10	
Single leg squat–deep hold		6	
BOSU (F) deep hold	5	8	
BOSU (F) drop squats		8	
BOSU (R) jump stick landing–deep hold		10	
BOSU (R) both knees–deep hold	20		
BOSU (R) crunches		35	
BOSU (R) swivel crunch, feet planted		40	
BOSU (R) single leg pelvic bridges		12	
BOSU (R) supermans		12	
BAL Training, Week 3	**Time, s**	**Reps**	**Total Reps**
BOSU (F) drop stick–deep hold		10	
BOSU (F) deep hold partner perturbations	20		
Box drop, lateral–deep hold		4	
Single-legged line hop, front/back–deep hold		8	
Single-legged line hop, side/side–deep hold		8	
Single-legged squat–heel touches		10	
Swiss ball, both knees–deep hold	20		
BOSU (R) single-legged step–stick deep hold		6	
Double crunch		25	
Table double crunch		15	
Table double swivel crunch		8	
Table reverse hyperextensions		12	
BOSU (R) lateral crunch		10	
BOSU (R) swimmers		10	
BAL Training, Week 5	**Time, s**	**Reps**	**Total Reps**
Double BOSU (F) deep hold, partner perturbations	10	5	
BOSU (F) drop single-legged Airex stick deep hold		5	
BOSU (R) single-legged deep partner ball toss	25		
Swiss ball, both knees, deep hold, partner perturbations	20		
BOSU (R) single-legged (4 + way) hop stick deep hold		8	
BOSU (F) single-legged ball pick up		8	
Airex walking lunges		5	
BOSU (F) single-legged squats		8	
BOSU (F) single-legged, deep hold, partner perturbations	30		
Straight leg lifts with toe punch		15	
Straight leg lateral double crunch		12	
BOSU (R) double crunch		15	
BOSU (R) opposite swivel crunch, feet up		12	
Swiss ball reverse back hyperextensions		12	

[a]Reps, repetitions; BOSU (F), BOSU both sides up balance trainer, flat side up; BOSU (R), BOSU both sides up balance trainer, round side up.

work of Bell et al,[2] Vaughan et al,[49] and Isman and Inman,[22] respectively. The 3D marker trajectories recorded during the test trials for each subject were processed by the Mocap Solver software to solve the generalized coordinates for each frame, that is, the 22 degrees of freedom of the skeletal model. Joint rotations in the hip, knee, and ankle were expressed relative to a neutral position where all segment axes were aligned.[31] These data were then low-pass filtered with a cubic smoothing spline at a 15-Hz cut-off frequency.[51]

Initial ground contact for each test trial was defined as the instance when the vertical ground reaction force (GRF) first exceeded 10 N. For the drop vertical jump movement, for which a definite stance phase was evident, toe-off was similarly defined as the instance when GRF data went below 10 N. Filtered kinematic data for each trial were subsequently resampled through linear interpolation at 1-millisecond time increments from 200 milliseconds before initial contact to either toe-off for the drop vertical jump (Figure 1) or 500 milliseconds after initial contact for the medial drop landing (Figure 2).

Statistical Analyses

For each trial, initial contact and peak (maximum) stance phase values of each lower limb kinematic parameter were determined. Statistical means and standard deviations for each variable were then calculated for each group. A mixed-design repeated measures analysis of variance ($2 \times 2 \times 2$) was used to test for the main effect and interactions of training, training group, and side (dominant versus nondominant) on the dependent variables of hip, knee, and ankle coronal and sagittal plane kinematics during the drop vertical jump and medial drop landing. An exploratory α level of .05 was used to determine statistical significance in all comparisons. Statistical analyses were conducted in SPSS for Windows, version 12.0 (SPSS Inc, Chicago, Ill).

RESULTS

Statistically significant training effects were observed in coronal plane kinematic data during both drop vertical jump and medial drop landing movements. During the drop vertical jump (Figure 1), both plyometric and balance training protocols decreased the initial contact (P = .002) and the maximum hip adduction angle (P = .015). Posttest measures of the maximum ankle eversion angle were also significantly

TABLE 3
Resistance Training Protocol Used by Both Groups[a]

Resistance Training, Week 1	Sets	Reps	AW/R
Dumbbell hang snatch	2	12	
Bench butt touch	1	10	
Barbell squat	2	12	
Bench press	2	12	
Lying leg curl	2	10	
Lateral pull-downs	1	15	
Ball squat dumbbell floor touches	1	10	
Dumbbell shoulder press	1	15	
Russian hamstring curl	1	10	
Seated cable row	1	15	
Hip ad/abd at 60 deg/s and 120 deg/s	1	10	
Double crunch	2	20	
Resistance Training, Week 3	**Sets**	**Reps**	**AW/R**
Hang clean	2	8	
Leg press	2	10	
Dumbbell incline press	2	8	
Front lunges + press	2	10	
Inverted lying pull-ups	1	10	
Stretch dumbbell dead lift	1	10	
3-way dumbbell shoulder circuit	1	12	
Bench reverse hyperextensions	1	10	
Knee flex/ext at 120 deg/s and 300 deg/s	1	12	
Band good mornings	1	10	
Back extensions	1	20	
Ankle circuit	1	12	
Resistance Training, Week 5	**Sets**	**Reps**	**AW/R**
Dumbbell hang snatch	3	5	
Barbell squat	2	5	
Single leg band assisted squat	1	8	
Bench press	2	5	
Lying leg curl	2	8	
Lateral pull-downs	1	8	
Dumbbell shoulder press	1	8	
Band shoulder press	1	8	
Russian hamstring curl	1	15	
Standing cable row	1	8	
Hip ab/abd at 60 deg/s and 120 deg/s	1	8	
Double crunch	2	30	

[a]Reps, repetitions; AW/R, actual weight and repetitions used; ad/abd, adduction/abduction; flex/ext, flexion/extension.

(P = .02) reduced in both training (balance and plyometric) groups. The mean coronal plane measures for the initial contact and the maximum angle for the hip, knee, and ankle during the drop vertical jump are detailed in Table 4. Although the drop vertical jump testing was sensitive to coronal plane changes from training at the hip and ankle, the medial drop landing test demonstrated coronal plane improvements at the knee. Specifically, when performing the medial drop landing (Figure 2), both training groups decreased the initial contact (P = .002) and the maximum knee abduction angle during stance (P = .038). The mean coronal plane lower extremity measures associated with medial drop landing execution are detailed in Table 5.

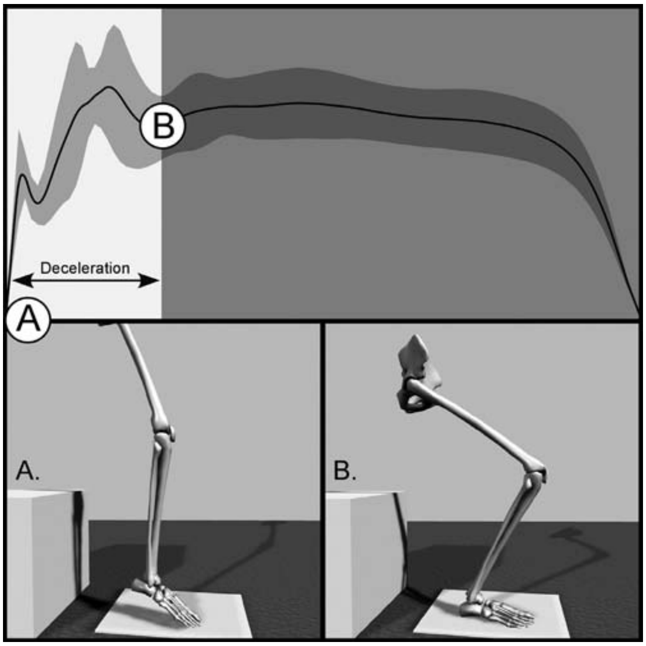

Figure 1. Representative stance force over time graph during the drop vertical jump outlaid with corresponding model depicting relative positioning of the athlete. Kinematic measures were taken from initial contact and maximum values during stance.

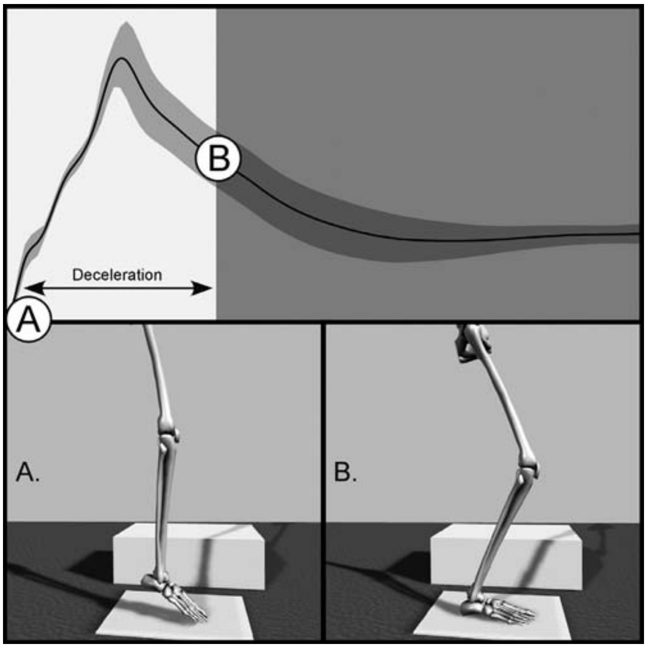

Figure 2. Representative force over time graph during the medial drop landing outlaid with corresponding model depicting relative positioning of the athlete. Kinematic measures were taken from initial contact and maximum values during stance.

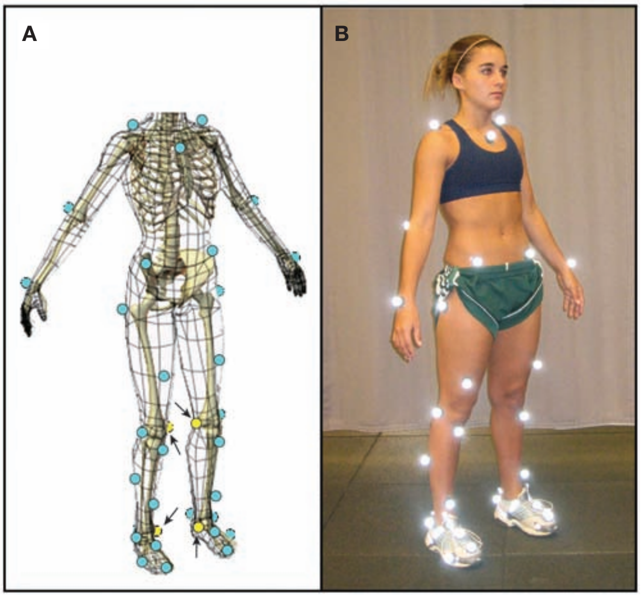

Figure 3. A, dynamic marker set: medial knee and ankle markers (arrows) were removed after collection of the static trial to prepare the athlete for testing. B, static marker set: locations of the reflective markers used for data collection. Sacrum, left posterior superior iliac spine, left midtibial, and right heel markers are not visible in this view. External marker locations used to generate lower limb 3D joint kinematic data. The kinematic model was assigned 22 degrees of freedom, 6 degrees of freedom at the pelvis and bilaterally 3 degrees of freedom at the hip, 3 degrees of freedom at the knee, and 2 degrees of freedom at the ankle.

TABLE 4
Mean Coronal Plane Measures With 95% Confidence Interval (CI) During the Drop Vertical Jump (DVJ) for Both Balance (BAL) and Plyometric (PLYO) Groups[a]

	DVJ	
	Pretraining, deg	Posttraining, deg
Hip adduction (IC)[b]	–4.6; CI, –6.3 to –2.9	–5.7; CI, –7.6 to –3.8
Hip adduction (MAX)[b]	–2.1; CI, –4.4 to 0.2	–3.4; CI, –5.7 to –1.1
Knee abduction (IC)	–0.1; CI, –1.8 to 1.6	0.1; CI, –1.4 to 1.6
Knee abduction (MAX)	–3.7; CI, –6.7 to –0.7	–3.6; CI, –5.7 to –1.5
Ankle eversion (IC)	6.9; CI, 3.9 to 9.9	7.4; CI, 4.0 to 10.8
Ankle eversion (MAX)[b]	–7.3; CI, –10.0 to –4.6	–4.4; CI, –7.6 to –1.2

[a]IC, initial contact; MAX, maximum.
[b]Main effect of training.

TABLE 5
Mean Coronal Plane Measures With 95% Confidence Interval (CI) During the Medial Drop Landing (MDL) for Both Balance (BAL) and Plyometric (PLYO) Groups[a]

	MDL	
	Pretraining, deg	Posttraining, deg
Hip adduction (IC)	–3.6; CI, –6.1 to –1.1	–5.3; CI, –7.2 to –3.4
Hip adduction (MAX)	8.4; CI, 5.7 to 11.1	7.7; CI, 5.0 to 10.4
Knee abduction (IC)[b]	–0.4; CI, –1.7 to 0.9	0.6; CI, –0.7 to 1.9
Knee abduction (MAX)[b]	–2.9; CI, –4.8 to –1.0	–1.9; CI, –3.4 to –0.4
Ankle eversion (IC)	8.1; CI, 4.9 to 11.3	8.3; CI, 5.1 to 11.5
Ankle eversion (MAX)	–16.5; CI, –20.5 to –12.5	–14.5; CI, –18.1 to –10.9

[a]IC, initial contact; MAX, maximum.
[b]Main effect of training.

Although plyometric and balance training protocols had similar effects on coronal plane measures of dynamic knee control, distinct training mode differences were observed in the sagittal plane (training × group interaction). Specifically, plyometric training significantly increased knee flexion at the initial contact (P = .047) (Figures 4 A and B) and the maximum angle (P = .031) (Figures 5 A and B), whereas balance training did not affect knee flexion during the drop vertical jump. In contrast to the drop vertical jump testing, the plyometric training did not affect sagittal plane measures during the medial drop landing task. The measured changes during the medial drop landing were specific to balance training (Figures 6 A and B), with increased maximum knee flexion (P = .005) observed for this group.

DISCUSSION

Comprehensive neuromuscular training can lead to improvements in athletic performance and movement biomechanics and reduce ACL injury risk in female athletes.[18,28,36,37,44] The 2 training protocols evaluated in the present study used abridged versions of a comprehensive training protocol shown previously to alter biomechanical factors that were related to increased ACL injury risk in female athletes.[17,36,43] Specifically, the balance and plyometric training groups adopted the respective dynamic balance or maximum-effort plyometric exercises typically incorporated within these combined training regimens.[35,36,43] Both training modes produced significant changes in lower extremity coronal plane mechanics parameters during both the drop vertical jump and medial drop landing movements. However, as hypothesized, the sagittal plane effects of plyometric and balance protocols were task specific with respect to the plyometric and dynamic stabilization/balance tests.

Increased neuromuscular control of dynamic lower extremity valgus (hip adduction, knee abduction, and ankle eversion) is critical when landing with knee angles close to full extension.[17,31,39] Cadaveric studies have shown that relatively large lower extremity valgus excursions at low knee

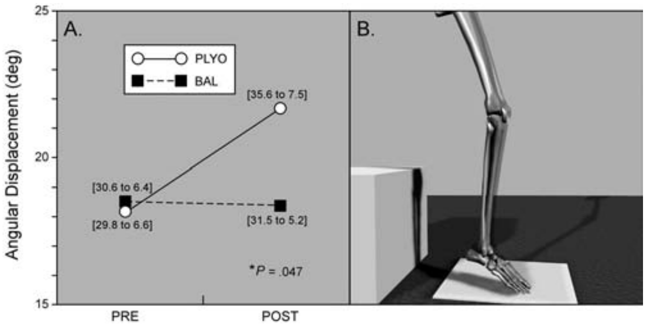

Figure 4. A, plot depicting mean pretest and posttest initial contact knee flexion values (95% confidence intervals) during the drop vertical jump for plyometric (PLYO) and balance (BAL) training groups. Plyometric training significantly increased knee flexion at initial contact during the drop vertical jump. Balance training did not affect knee flexion at initial contact during the drop vertical jump. B, biomechanical model comparing actual mean knee flexion at initial contact during the drop vertical jump after training for the plyometric (solid figure) and the balance (transparent figure) groups.

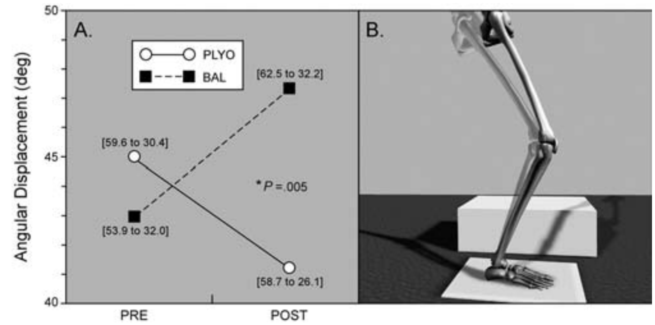

Figure 6. A, plot depicting mean pretest and posttest maximum knee flexion values (95% confidence intervals) during the medial drop landing for the plyometric (PLYO) and balance (BAL) training groups. Balance training significantly increased maximum knee flexion during the medial drop landing. Plyometric training did not affect maximum knee flexion during the medial drop landing. B, biomechanical model comparing actual mean maximum knee flexion during the medial drop landing after training for the plyometric (solid figure) and the balance (transparent figure) groups.

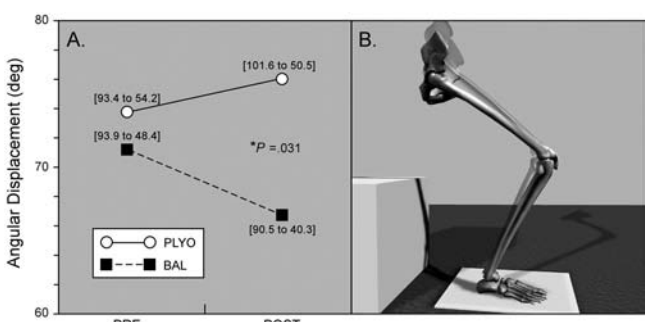

Figure 5. A, plot depicting mean pretest and posttest maximum knee flexion values (95% confidence intervals) during the drop vertical jump for plyometric (PLYO) and balance (BAL) training groups. Plyometric training significantly increased knee flexion at maximum effort during the drop vertical jump. Balance training did not affect maximum knee flexion during the drop vertical jump. B, biomechanical model comparing actual mean maximum knee flexion during the drop vertical jump after training for the plyometric (solid figure) and the balance (transparent figure) groups.

flexion angles, in conjunction with forceful quadriceps contractions, elicit large ACL loads.[29] Dynamic lower extremity valgus is also directly linked to ACL injury risk,[17] which suggests that interventions aimed specifically at reducing this kinematic parameter are important for injury prevention.[35] Therefore, a primary goal of interventional training should be to focus on teaching female athletes to land with reduced valgus motion. In the current study, both the plyometric group and the balance group demonstrated this effect. A commonality between the 2 tested training protocols was their use of athlete awareness and trainer feedback techniques to reduce dynamic lower extremity valgus. However, the teaching modes to improve lower extremity coronal plane strategies were different in each case. For example, the balance group was given immediate and concurrent feedback based on observational coronal plane control while performing the training with dynamic stabilization/balance tasks. This type of feedback allowed for postural and lower extremity adjustments to be made simultaneously with the task on which the chosen feedback was based. Conversely, the dynamic and fast-paced nature of the plyometrics and cutting technique training for the plyometric group did not facilitate voluntary active postural and lower extremity corrections secondary to observational-based cueing during the exercise. Thus, a majority of the feedback for the plyometric group was given after the task was performed, when it was more conducive for the athlete to make a cognitive response. The plyometric group could then apply the feedback on subsequent exercise attempts. Because of differences in the way that feedback was applied to the 2 groups during training and the evidence that isolated plyometric training increases hip adductor activation,[6] it was hypothesized that balance training would more effectively facilitate lower extremity control in the coronal plane, particularly during the dynamic stabilization testing. The findings only partially support this hypothesis, as decreased lower extremity valgus after training was observed for both the balance group and the plyometric group during both tasks. These results might suggest that although improvements in lower extremity valgus may be related to feedback and adjustments made during training, they are not dependent on the associated mode of exercise. Onate et al[40,41] demonstrated that the use of videotape feedback can also result in safer landing biomechanics. The results of the current study suggest that improved lower extremity coronal plane control may be possible through either a plyometric or balance training mode. Although we can only speculate at this point, these results suggest that further success may be possible if augmented (videotape) feedback techniques and exercise modes used for the plyometric and balance groups are combined.

It is interesting that the effects of training in the coronal plane were found to be task specific. During the drop vertical jump, for example, a 2-footed plyometric activity, posttraining results showed that lower extremity valgus was reduced at the hip and the ankle. Conversely, during the medial drop landing, a single-legged landing task, the most significant modifications occurred at the knee. These results might suggest resultant lower extremity valgus is governed primarily by hip and ankle motions during a 2-footed landing, whereas for single-legged tasks, it is displayed by knee motions. Previous studies suggest that increased coronal plane control at both the hip[5,42] and the ankle[24,31] may be necessary to reduce ACL injury risk. Although hip abduction strength was not assessed in the current study, both groups of athletes improved their hamstring strength and hamstring-to-quadriceps ratio.[34] These increases in hamstring strength and hamstrings-to-quadriceps ratio may be related to the improved coronal plane control.[20,34] The association between ACL injury and relatively large knee motions in the coronal plane is also well documented.[17,30] In addition, lower extremity coronal joint motions linked to ACL injury risk are often correlated, suggesting that lower extremity valgus control requires a synergistic and antagonistic contribution from the hip, knee, and ankle.[17] Considering the potential contributions of each lower limb joint to dynamic lower extremity valgus and resultant ACL loading, current results suggest that training with both single-support and double-support exercises is warranted.[17,30,35,36]

In addition to limiting lower extremity coronal plane motion, a reduction in female sports-related ACL injury rates appears dependent on improved control of sagittal plane biomechanics, especially knee flexion.[3,39] A sagittal position of the knee close to full extension when landing or cutting is nearly always observed in video analysis of ACL injuries in female athletes.[3,39] In addition, a prospective study has shown that female athletes who subsequently sustained ACL injuries demonstrated significantly less (10.5°) knee flexion when performing a drop vertical jump than did those who did not sustain injury.[17]

In direct support of our corollary hypotheses, the results of this study demonstrated that training effects on sagittal plane knee kinematics were largely task sensitive. Specifically, plyometric training increased knee flexion during the drop vertical jump, whereas balance training increased knee flexion during the medial drop landing. The increased maximum knee flexion observed in each case may indicate increased range of knee motion in the sagittal plane throughout the landing. The increases in knee flexion after training during landing observed for both movements may reduce the potential for ACL injury stemming from an overextended landing position.[3,39] As noted earlier, landing at relatively low knee flexion angles (0° to 30° of knee flexion) in conjunction with relatively large quadriceps contractions may elicit anterior tibial shear forces that are large enough to rupture the ACL.[4,8] These potentially hazardous effects may be even more pronounced without balanced knee flexor (hamstring and gastrocnemius) co-contraction.[4,7] Muscle activation patterns were not examined in the current study; hence, the impact of the 2 training methods on these neuromuscular parameters is not known. Combining electromyographic analyses with kinematic measures in future studies may provide further insight into the relative effects of these 2 training modes. The findings indicate that both plyometric and balance training should be used to increase knee flexion during respective double-legged and single-legged landing tasks in female athletes.

Injury to the ACL is likely not caused by either an isolated coronal or sagittal plane loading mechanism but, rather, by a combination of the 2 mechanisms.[30,45] Therefore, the finding that increased dynamic knee joint control is possible in both planes through combined training protocols is an important one.[3,17,20,36,39] Female athletes often demonstrate a predominately coronal plane strategy to control dynamic knee motion, which has been shown to be ineffective for adequate force dissipation during landing tasks.[17,20] Both balance and plyometric training appear to enhance sagittal plane control by relatively large and powerful muscle groups, which may in effect reduce the need to rely on less effective coronal plane control during these movements.

Clinical Relevance

Considering the significant short-term and long-term debilitation associated with noncontact ACL injury, prevention of such injury is crucial. The current article addresses the prevention of ACL injuries directly by examining the effects of well-established training strategies on lower limb mechanical parameters suggested to predict ACL injury risk. Specifically, we have taken steps in determining the most effective and efficient means of modifying potentially high-risk movement patterns in the female athlete. To this point, although high-risk movement and load patterns have been identified in the literature, their manifestation within precise injury mechanisms remains largely unclear. For example, how much of a particular movement or load is too much, and further, whether injury-causing load magnitudes are largely subject specific. Considering the potential for individual variations in joint anatomy[23,47] and ligament or laxity properties,[46,50] such a scenario seems plausible. Elucidation of the precise mechanisms of ACL injury is obviously beyond the scope of the current investigation. Until such information is available, however, positive modifications in potentially high-risk movement strategies should be considered clinically significant.

A reduction in ACL injury risk via coronal or sagittal plane mechanisms may not occur through implementation of an isolated plyometric or dynamic stabilization/balance training program. It appears that successful training adaptations, in particular those experienced in the sagittal plane, vary from task to task. If the goal of training is to reduce female injury risk across a variety of movement tasks, as required during sport competition, training including both plyometric and dynamic stabilization components appears desirable. The significant time and labor-intensive requirements of comprehensive ACL-prevention training programs may detract from their ultimate success because of decreased initiation or compliance. Further work may be necessary to identify which components of both the plyometric and dynamic balance training modes are the key contributors to changes in sagittal and coronal plane kinematics during landing tasks. In addition, further investigation into the role of feedback and athlete awareness of potentially dangerous positions during dynamic tasks is warranted.

Limitations

A potential limitation of the current study is that individual variations in training undertaken outside of this study may have confounded comparisons of the 2 isolated (plyometric and balance) training components. To control for this possibility, athletes were instructed to follow team guidelines for training, which included no outside neuromuscular training (resistance, speed, agility, dynamic balance, or plyometric). In addition, the other components of the protocols, which may have had biomechanical effects on dynamic knee control, were identical between the plyometric and balance groups. Another potential limitation to the interpretation of the study results may be that the number of subjects was relatively low, even though the number reached the minimum dictated by power analysis. We are currently conducting several studies that incorporate larger subject populations, which should provide further insight into the efficacy of these training modalities. Although an assumption of a standard (subject-to-subject) joint coordinate system is likely feasible for the hip and knee joint, it may be less appropriate for the ankle joint. Individual differences in foot morphologic characteristics are common, and hence, a great deal of variability exists in the segment's true 3D rotational axes.[22,48] In the current study, the talocrural axis was defined in accordance with mean population data presented previously.[22] Hence, for the population tested, it is possible that individual differences in the true orientation of this axis affected inversion-eversion calculations. To address this fact, our future work will continue to explore the possibility of accounting for individual morphological differences within coordinate system definitions. The findings of this study may also be limited without the inclusion of a negative control group or a combined plyometric and balance protocol. However, the effects of a combined plyometric and balance protocol have been previously demonstrated, and the current purpose of this study was to perform a comparison of the effects of plyometric and balance training, not to demonstrate the relative effects compared to baseline.

CONCLUSION

- Both plyometric and balance training can reduce lower extremity valgus measures at the hip and at the ankle during a 2-footed plyometric activity.
- Both plyometric and balance training can reduce lower extremity valgus measures at the knee during a single-limb dynamic stabilization task.
- In the sagittal plane, training increases in knee flexion may be dependent on the interaction between training mode and movement task. Thus, to improve knee flexion during a broad range of sports-related activities, it may be necessary to utilize both plyometric and balance modes of training.
- The results of the current study do not support the exclusion of either plyometric or dynamic stabilization/balance exercises from an injury-prevention protocol.

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