The effect of different exercise training interventions on lower extremity biomechanics and quality of movement in high school female athletes

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APPROVAL OF THE DISSERTATION

This dissertation, "The effect of different exercise training programs on lower extremity biomechanics and quality of movement in adolescent female athletes", has been approved by the Graduate Faculty of the Curry School of Education in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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The effect of different exercise training interventions on the biomechanics of a drop vertical jump in high school female athletes

ABSTRACT

Context: Anterior cruciate ligament (ACL) injuries are common in adolescent and adult female athletes and are believed to be related to poor neuromuscular control. Neuromuscular deficits manifest through biomechanics during dynamic tasks such as landing from a jump. Alterations in biomechanical patterns have been shown as a result of neuromuscular training programs. It is unknown which component of these programs are responsible for the neuromuscular alterations. **Objective:** To assess the efficacy of either a 4 week core stability program or plyometric program on altering lower extremity and trunk kinetics and kinematics during a drop vertical jump (DVJ). **Design:** Cohort study. **Setting:** High school athletic field and motion analysis laboratory. **Patients or Other Participants:** 23 junior varsity female lacrosse and soccer players. **Intervention(s):** Independent variables were group (core stability, plyometric, control) and time (pre-test, post-test). Subjects performed five trials of a DVJ prior to and after completion of a four week period during which intervention subjects engaged in a core stability or plyometric program. **Main Outcome Measures:** Dependent variables were 3-dimensional hip, knee, and trunk kinetics and kinematics during the landing phase of a DVJ. Group means and associated 95% confidence intervals were calculated via bootstrapping across the entire landing phase. Curve analysis using an alpha level of $P<0.05$ was performed to identify time periods where the confidence interval bands for the groups did not cross. **Results:** Significant within group differences were shown for lower extremity kinematic and kinetic variables for both intervention groups. No differences were shown for trunk kinematics. The control group had a decrease in knee external rotation moment. The plyometric group had a decrease in knee flexion and knee internal rotation angles in addition to a decrease in knee flexion and knee valgus moments. The plyometric group also had an increase in knee valgus angle and knee external rotation moment at the end of landing phase. The core stability group had decreases in hip internal rotation and knee flexion angles while also increasing the knee internal rotation angle. There were several kinetic changes including a decrease in hip flexion and internal rotation moments as well as an increase in hip abduction moment. Finally there was a decrease in the knee valgus moment. All significant kinetic changes had a strong effect size. **Conclusions:** An in-season, four week training program at the junior varsity level for female athletes resulted in significant changes in kinematic and kinetic findings related to increased ACL injury risk. The plyometric group was limited to changes found only at the knee joint while the core stability group had alterations at the hip and knee joint. The results of this study suggest that both types of exercise are warranted in ACL injury prevention programs.

INTRODUCTION

The rate of noncontact anterior cruciate ligament (ACL) injury is more than three times higher in adult and adolescent females as compared to their male counterparts.[1] Noncontact ACL injuries commonly occur during dynamic activities where the individual is decelerating, such as landing from a jump or changing direction.[2] Laboratory based studies examining the biomechanics of landing tasks have identified commonalities in adolescent and adult female populations believed to be associated with an increased risk for ACL injury. The biomechanical patterns believed to be associated with greater risk for injury are increased extension in the sagittal plane as well as increased frontal and transverse plane motion.[3] A study comparing high school male and female basketball players during a drop vertical jump (DVJ) found females landed with greater total knee valgus motion and greater knee valgus angles [4] Similarly, collegiate female soccer and basketball athletes demonstrated greater knee valgus angles at instant contact and peak as well as greater total coronal hip motion compared to males when performing a single-leg landing task.[5] A study also demonstrated there were greater knee valgus angles during a DVJ following isolated hip abductor fatigue. This finding is an indication that eccentric hip abductor function influences the position of the femur resulting in an increased knee valgus angle.[6] Moreover, Salci et al[7] showed that female college volleyball players had decreased hip and knee flexion angles during spike and block landings compared to male volleyball players.

These common patterns were echoed in a prospective study that identified landing patterns in adolescent females who later suffered an ACL injury.[8] Previous research[9] has shown that those who experienced an injury had greater knee valgus angles at contact and at peak compared to the uninjured group. Joint forces were also a factor in increased risk for injury where greater amounts of valgus loading at the knee resulted in increased stress placed on the ACL.[10] Hewett et al[9] also found that individuals who sustained an ACL injury had larger external knee abduction moments; furthermore, abduction moment at the knee significantly correlated to hip adduction moments. In addition, a prospective study examining knee injuries linked the relationship between poor trunk neuromuscular control and ACL injury risk in female athletes. This study suggests that females who had greater lateral trunk displacement in response to sudden force were more likely to incur an ACL injury.[11] Therefore, it appears that noncontact ACL injuries are related to forces at the knee as well as decreased neuromuscular control of more proximal structures such as the hip and trunk.

Theories providing an explanation for the gender bias in ACL injuries include differences in anatomical and hormonal profiles as well as biomechanical and neuromuscular characteristics.[3] Biomechanical and neuromuscular control patterns have been shown to be modifiable in response to relatively brief periods of training.[12-15] Various intervention programs focused on altering lower extremity and trunk mechanics during dynamic activities. Successful programs have utilized a broad approach by incorporating balance, lower extremity strength, plyometric, and agility components in an attempt to address all aspects of neuromuscular control.[13, 15-17] However, it is unknown which types of exercises are effective in altering biomechanical patterns, and it may be possible that the number and volume of the exercises included in an intervention program can be reduced to make it more manageable in various athletic settings. By gaining a better understanding of what exercises are effective in altering neuromuscular patterns we may potentially be more effective in preventing injury. Therefore, the aim of this study was to determine whether kinematic and kinetic patterns during a drop vertical jump (DVJ) can be altered following an intervention program that incorporates either core stability or plyometric training in isolation. We hypothesized that the plyometric group would have a decrease in lateral trunk flexion, hip adduction, hip internal rotation, knee valgus and knee internal rotation angles as well as an increase in hip and knee flexion angles. Additionally, the plyometric group would decrease their hip flexion, abduction and external rotation moments as well as their knee flexion, valgus and internal rotation moments. We further hypothesized that the core stability group would show a decrease in lateral trunk flexion as well as hip internal rotation and adduction angles and joint moments. Finally, we hypothesized that we would not see any changes in kinematic or kinetic patterns for the control group.

METHODS

This study utilized a cohort design where the independent variables tested were group (core stability, plyometric and control) and time (pre- and post-test). The dependent variables were lower extremity kinematic and kinetic mean values over the entire stance phase at the pre and post-test time points. The kinematic variables assessed were lateral trunk flexion angle; hip flexion, internal rotation and adduction angles; and knee flexion, internal rotation and valgus angles. External joint moments for hip flexion, internal rotation and adduction, and knee flexion, internal rotation and valgus were also collected.

Subjects

Twenty four females from three local area high schools volunteered for this study. One subject was excluded for have current low back pain during activity. Twenty three subjects (14.8 ± 0.8 yrs, 1.7 ± .07 m, 57.7 ± 8.5 kg) were actively participating on a junior varsity lacrosse or soccer team, had no history of trunk or lower extremity surgery and no previous injury within the past 6 weeks that limited participation in athletics or physical activity. Furthermore, subjects had no neurological disorders that may affect balance and had not previously participated in a formal core stability or plyometric training program as reported by the subject and their parents. The study was approved by the Institutional Review Board for Health Sciences Research (IRB-HSR #14039). A parent or guardian of the subject signed an informed consent form and the subject read and signed an informed assent form for this study.

Instrumentation

Kinematic data were obtained using a 10 camera Vicon 624 motion analysis system (Vicon Peak, Lake Forest, CA, USA). Synchronized kinetic data was captured using a conventional in-ground AMTI force plate (AMTI, Watertown, MA, USA). Kinematic data were captured at 250 Hz and the kinetic data were captured at 1000 Hz and time synched with the kinematic data.

Testing Procedures

Subjects reported to the motion analysis laboratory for pre-testing within the first third of the high school spring athletic season. Anthropometric measurements including height, mass, leg length, knee and ankle width were taken and recorded. Subjects were fitted with Brooks running shoes (Brooks® Sports, Inc., Bothell, Washington, USA) model Radius 06 and had retroreflective markers placed bilaterally on the following anatomic landmarks to represent the lower extremity segments in accordance with the Vicon Clinical Manager (Vicon, Oxford Metrics, London, UK) protocol: 2nd metatarsal head, calcaneus, lateral malleolus, lateral midshank, lateral femoral condyle and lateral midthigh. A four marker cluster was secured around the hips over the sacrum using elastic tape. To capture trunk motion, markers were also placed on the sternum, xiphoid process, C7 and T10 spinous processes and bilateral acromion processes.

Subjects were instructed on 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, subjects were directed to stand on a 25 cm box and leading with their right leg step off the box landing equally on both feet. The right and left foot contacted separate embedded force plates and immediately upon contacting the ground the subject performed a maximal vertical jump off both legs. Each subject was allowed to practice the task until she felt comfortable, then 5 test trials were collected for analysis. The height of the box was chosen because it is the average maximum vertical jump height achieved by adolescent females when performing a DVJ.[18] Kinetic and kinematic data were collected for all subjects and the mean values were used for analyses.

Each subject repeated the testing following the four week intervention. All subjects completed testing within a 10 day period following the final session of intervention exercises. Subjects were re-instructed on how to perform the DVJ and allowed to re-acquaint themselves with the task. Following the completion of the post-testing session subjects were dismissed from the study (see Figure 1).

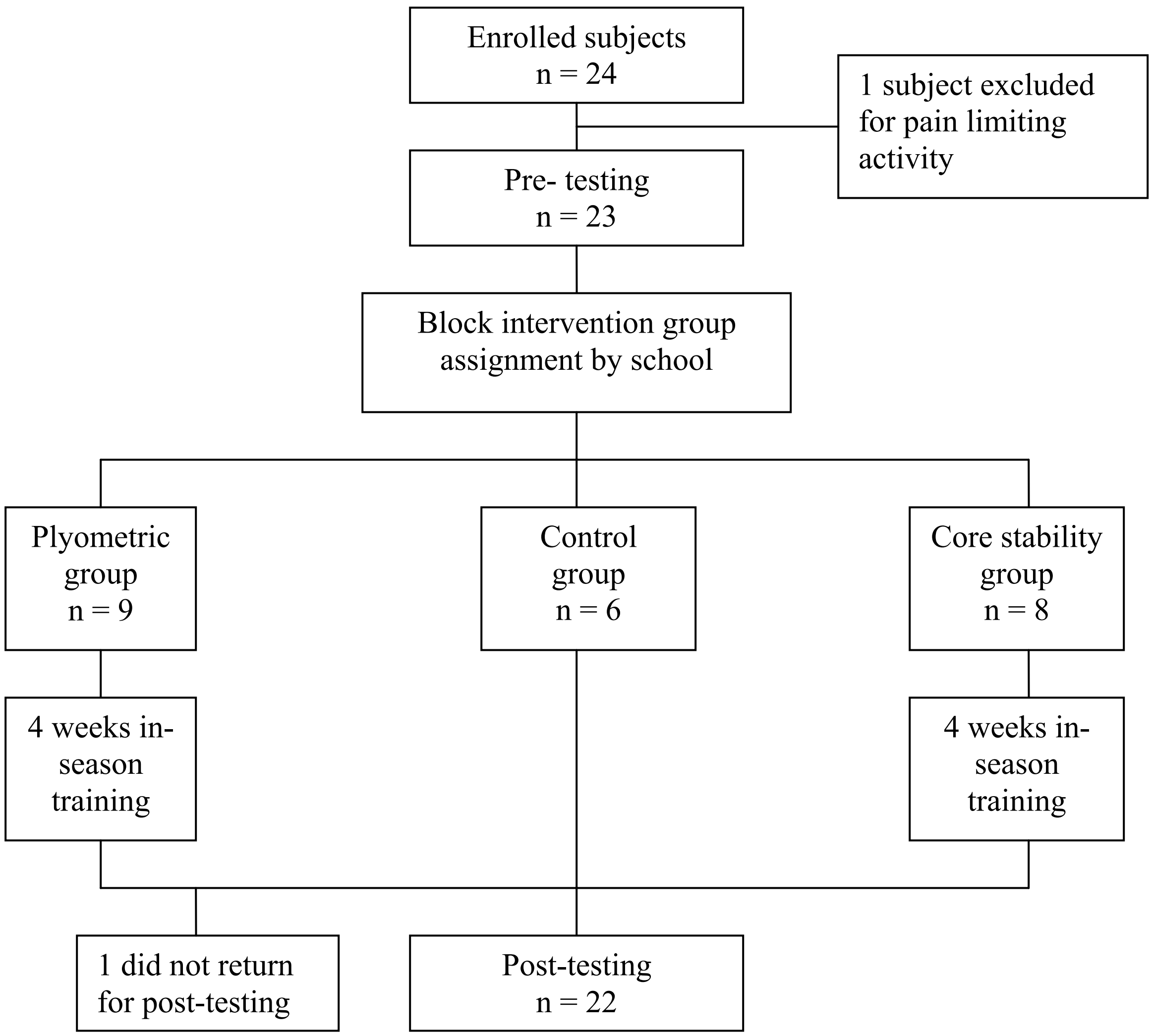

Figure 1. CONSORT flowchart outlining the progression of testing order and subject dropout.

Intervention programs

Teams were allocated to one of 3 groups and subjects participated as an entire team in either the plyometric or core strength program 3 times a week for 4 weeks, or continued their normal team activities for 4 weeks (control).[19] The coaches were given an attendance log to monitor compliance of the athletes enrolled in the study. They were also provided an exercise protocol to follow which included directions to give the athletes on how to perform the exercises as well as pictures and visual keys to look for while they supervised the sessions. Additionally, a certified athletic trainer from each school observed one session a week and filled out an assessment form to subjectively determine how the coaches and athletes responded to the intervention program. The plyometric and core stability programs were designed to be completed in no more than 20 minutes and with no additional exercise or rehabilitation equipment required.

The plyometric program (see Table 1) consisted of a series of double and single limb jumps as well as skipping exercises focused on quality takeoff and landing form. The exercises included were adapted from various ACL prevention and neuromuscular training programs where the emphasis was placed on soft, balanced, and controlled landing.[12, 13, 20-22] The plyometric program was divided into two phases, with a progression occurring after the sixth session that increased the difficulty level by incorporating more single-leg landings and multi-planar movements. The program included supervision from the coaching staff throughout implementation. Additionally, the subjects performed the exercises in pairs to reinforce the use of correct form to each other. Exercises for the core stability group (see Table 2) were targeted at improving coordination of the abdominal and lumbar stabilizers, and hip extensors, external rotators and abductors.[23-25] After completion of 6 sessions, subjects progressed to a second phase of exercises that incorporated more challenging positions and combined maneuvers from phase one that focused on increasing trunk stability with more traditional strength gain exercises. Subjects were included in the data analysis if they participated in at least 9 of the 12 sessions.

Table 1. Plyometric Group Exercise Progression

Phase	Sets / Reps
1 (Weeks 1 & 2)	
Forward / backward single-leg line jumps	30 forward / backward
Side to side single-leg line jumps	30 side / side
High skips	Field length
Distance skips	Field length
Broad jumps*	2 x 10
Tuck jumps*	2 x 10
Alternating single-leg lateral jumps	2 x 10
Phase 2 (Weeks 3 & 4)	
Forward single-leg hop, hop, hop & stick*	10
Squat jumps*	2 x 10
Single-leg max vertical jump*	10
Single-leg jump for distance*	10
Broad jump, jump, jump, vertical jump*	5
180 jumps*	10
R/L only single-leg lateral jumps*	10

** Denotes partner watching*

Table 2. Core Stability Group Exercise Progression

Phase 1	Sets / Reps
(Weeks 1 & 2)	
Abdominal draw-in	10 x 5 seconds
Side plank knee bent	2 x 20 seconds
Side lying hip abduction	3 x 10
Side lying hip external rotation (clam shells)	3 x 10
Crunches	3 x 15
Lumbar extension hands on head	3 x 10
Walking lunges hands on hips	Field length
Phase 2 (Weeks 3 & 4)	
Hamstring bridge with abdominal draw-in	3 x 20 seconds
Side plank legs extended with abdominal draw-in	2 x 10 seconds
Quadruped hip extension/external rotation/abduction	2 x 10
Crunches opposite elbow to knee	3 x 15
Lumbar extension arms straight	3 x 10
Squats with arms overhead*	3 x 10
Lunges with ball toss*	3 x 10

* Denotes partner watching

Data Analysis

A force platform (AMTI OR 6-7, Watertown, MA, USA) was used to collect raw ground reaction forces at 1080 Hz and interfaced with a 10 camera (M2 series) motion analysis system (Oxford Metrics Ltd, Oxford, UK) to capture the 3-D position of markers at 120 Hz. Kinematic data were collected at 250 Hz. A Woltring filtering technique was applied to the marker data with a predicted MSE value of 20 according to recommended Vicon processing protocols (Vicon Peak, Centennial, CO, USA). Ground reaction force data were synchronized with the Vicon system for simultaneous collection. The ground reaction forces were collected at 1000 Hz frequency and filtered using a low-pass, anti-aliasing filter with a cutoff frequency of 30 Hz. Points of initial contact and toe-off were visually identified using the ground reaction force and all data were normalized to 101 data points for the landing phase. The ground reaction force data was time synchronized and processed using Plug-in Gait to determine hip and knee joint moments. Moments were normalized to a product of mass and height and reported in Newton-meters per kilogram·meter (Nm/kgm). Joint moment calculations were based on the following parameters: 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.

Statistical analysis

Comparisons within groups were made on pre-test, post-test change scores for all dependent variables. Group means and associated 95% confidence intervals (CI) were calculated for each percent of the landing phase. Curve analysis was used to determine points during landing where significant differences were present within groups. An alpha level of $P<0.05$ was performed across the landing phase to identify time periods where the CI bands for the two groups did not cross[26]. Confidence interval comparison allows for comparisons to be made throughout the duration of the landing phase rather than comparing peak points as these tend to represent only a discrete minimum or maximum value of the landing phase. Effect sizes were calculated for joint moments on the point where the mean difference between pre- and post-test scores were the largest and where the CI bands did not cross. Cohen's d was calculated by taking the mean difference (from pre and post-tests in this case) and dividing by the standard deviation of the control group. An effect size of >0.8 with a confidence interval does not cross 0 is considered a strong effect that can be interpreted as clinically meaningful.

All graphs were created using Microsoft Excel 2003 (Microsoft Corporation, Redmond, WA, USA) The kinematic dependent variables were mean joint angles for trunk lateral flexion (the position of the trunk relative to the pelvis), hip flexion, internal rotation and adduction, knee flexion, valgus and internal rotation. The kinetic dependent variables were mean external moments for the sagittal, frontal and transverse planes at the hip and knee. Furthermore, descriptive statistics for age, height and mass were compared between groups using separate ANOVA models with Tukey post-hoc comparisons.

RESULTS

There was a significant difference between groups for mass at post-test ($F_{2,20} = 3.52$, $p = 0.049$). Tukey post-hoc testing revealed the plyometric group had a significantly greater mass than the control group ($F_{2,20} = 3.25$, $P = 0.049$) (see Table 3). All subjects enrolled in the plyometric group completed 100% of the intervention sessions and all subjects in the core stability group completed at least 9 out of 12 (9.5 $\pm$

0.5 sessions). Significant findings for within group comparisons between pre- and post-test where the CI bands did not overlap are reported in Table 4.

Table 3. Group demographic means and standard deviations (SD) at pre- and post-test.

	Control	Plyometric	Core Stability
Pre-test			
Age (yr)	14.8 (0.4)	15.1 (1.1)	14.5 (0.8)
Height (cm)	168.6 (4.5)	172.1 (8.0)	169.2 (7.3)
Mass (kg)	52.1 (6.1)	62.6 (8.8)	56.8 (7.9)
Post-test			
Age (yr)	14.8 (0.4)	15.3 (1.04)	14.5 (0.8)
Height (cm)	168.9 (4.4)	172.5 (8.4)	169.3 (7.4)
Mass (kg)	52.0 (5.7)*	64.0 (9.1)*	57.4 (7.8)

* Indicates a statistically significant difference between groups at post-test, $F_{(2,20)} = 3.52$, $P = 0.049$.

Table 4. DVJ kinematic and kinetic change scores for all groups. Angles were reported in degrees and moments in Nm/kgm. Cohen's d effect sizes were calculated at the point in the landing phase where the CI bands did not cross and the mean difference was the largest. Effect sizes were only calculated for the kinetic variables to enhance the clinical interpretation of the data.

Group	Variable	% Landing Phase	Mean Difference (SD)	Effect Size: d (CI)
Control	Knee internal rotation moment	12-24	0.06 (0.008)	1.83 (0.37, 3.0)*
		70-87	0.06 (0.003)	1.75 (0.31, 2.92)*
Plyometric	Knee flexion angle	13-58	-24.1 (4.5)	
Plyometric	Knee valgus angle	98-101	-5.3 (0.03)	
Plyometric	Knee internal rotation angle	1-93	-17.9 (3.2)	
Plyometric	Knee flexion moment	16-31	-0.32 (0 .04)	-2.04 (-3.06, -0.82)*
Plyometric	Knee valgus moment	10	0.1	1.56 (0.44, 2.53)*
Plyometric	Knee internal rotation moment	39-57	0.06 (0.008)	1.48 (0.38, 2.44)*
Core Stability	Hip internal rotation angle	36-42	-15.3 (0.4)	
		61-65	-13.1 (0.4)	
Core Stability	Knee flexion angle	10-56	-21.0 (4.2)	
		96-101	14.9 (2.8)	
Core Stability	Knee internal rotation angle	1-2	12.2 (1.1)	
		82-101	16.5 (2.9)	
Core Stability	Hip flexion moment	19-25	-0.33 (0.05)	-1.02 (-2.0, 0.07)
		32-43	-0.25 (0.04)	-1.79 (-2.84, -0.055)*
		48-61	-0.35 (0.05)	-2.81 (-4.0, -1.31)*
		65-80	-0.28 (0.05)	-2.23 (-3.33, -0.89)*
Core Stability	Hip abduction moment	37-48	0.23 (0.01)	2.35 (0.97, 3.47)*

Core Stability	Hip internal rotation moment	9-12	-0.06 (0.02)	-1.89 (-2.95, -0.63)*
		20-24	-0.06 (0.01)	-2.21 (-3.31, -.87)*
		28-81	-0.07 (0.02)	-3.34 (-4.69, -1.73)*
		89-94	-0.4 (0.005)	-1.8 (-2.85, -0.56)*
Core Stability	Knee valgus moment	50-72	0.19 (0.01)	1.68 (0.46, 2.71)*

* Represents a strong effect size where the CI did not cross 0.

Control Group

The transverse plane knee moment of the control group significantly increased but remained an external rotation moment. There were 2 windows where the CI bands did not overlap, between 12-24% of the landing phase and again from 70-87%. During both of these intervals the control group had a smaller hip external rotation moment at post-test compared to pre-test with a mean difference of 0.06 $\pm$ .008 and 0.06 $\pm$ .003 Nm/kgm respectively (see Figure 2). Furthermore these 2 windows both had a strong effect size as represented by Cohen's d =1.83 (0.37, 3.0) and d = 1.75 (0.31, 2.92).

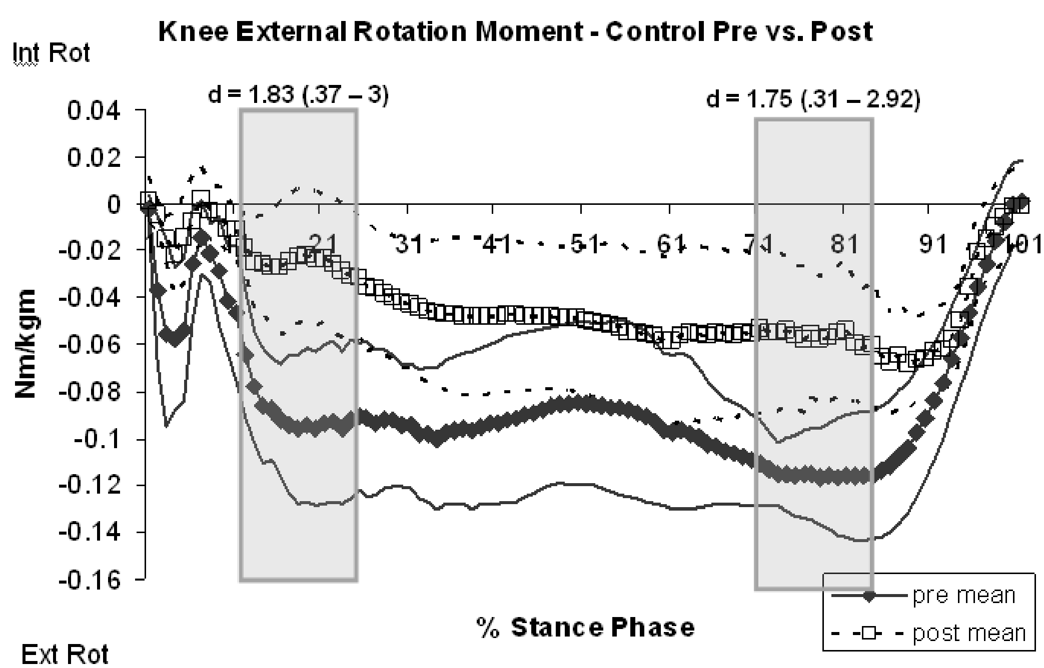

Figure 2. Control Group Change Scores for DVJ Knee Rotation Moment
The control group change score from pre-test to post-test for knee rotation moment. The lines surrounding the mean scores represent the 95% confidence intervals. The post-test

mean was significantly higher from 12-24% of the landing phase and then again from 70-87%. The mean difference for these windows were 0.06 ± 0.008 and 0.06 ± 0.003 Nm/kgm respectively, *P*<0.05. Both windows had a strong effect size that did not cross 0 as represented by a Cohen's d =1.83 (0.37, 3.0) and d = 1.75 (0.31, 2.92).

Plyometric Group

There were 6 significant findings for time for the plyometric group, all occurring at the knee joint. The knee flexion angle had a significant window from 13-58% of landing phase that represented a decrease in the knee flexion angle following the four week intervention. The mean difference for the knee flexion window was -24.1 ± 4.5 degrees, *P*<0.05 (see Figure 3). Similarly the knee internal rotation angle decreased significantly from 1-93% of the landing phase with a mean difference of -17.9 ± 3.2 degrees, *P*<0.05 (see Figure 4). The final kinematic finding for the plyometric group was a decrease in the knee frontal plane angle from the 98-101% of landing phase. At post-test the plyometric group moved from a varus to valgus position close to the point of take off. The mean difference for this significant window was -5.3 ± 0.03, *P*<0.05 (see Figure 5).

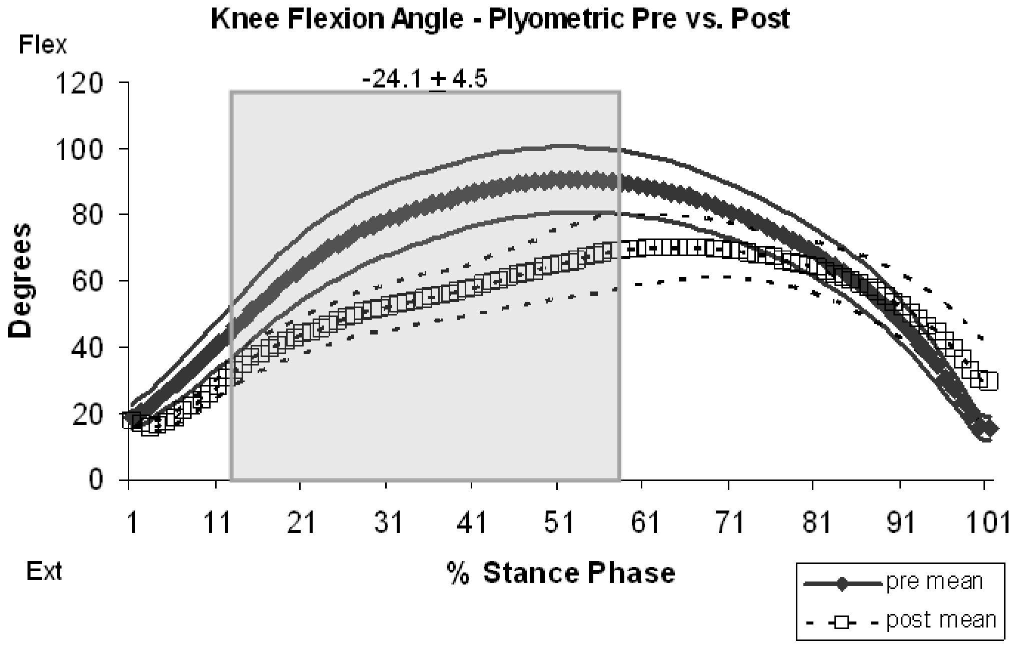

Figure 3. Plyometric Group Change Scores for DVJ Knee Flexion Angle
The plyometric group change score from pre-test to post-test for knee flexion angle. The lines surrounding the mean scores represent the 95% confidence intervals. The post-test mean was significantly lower from 13-58% of the landing phase. The mean difference for this window was -24.1 $\pm$ 4.5 degrees, $P < 0.05$.

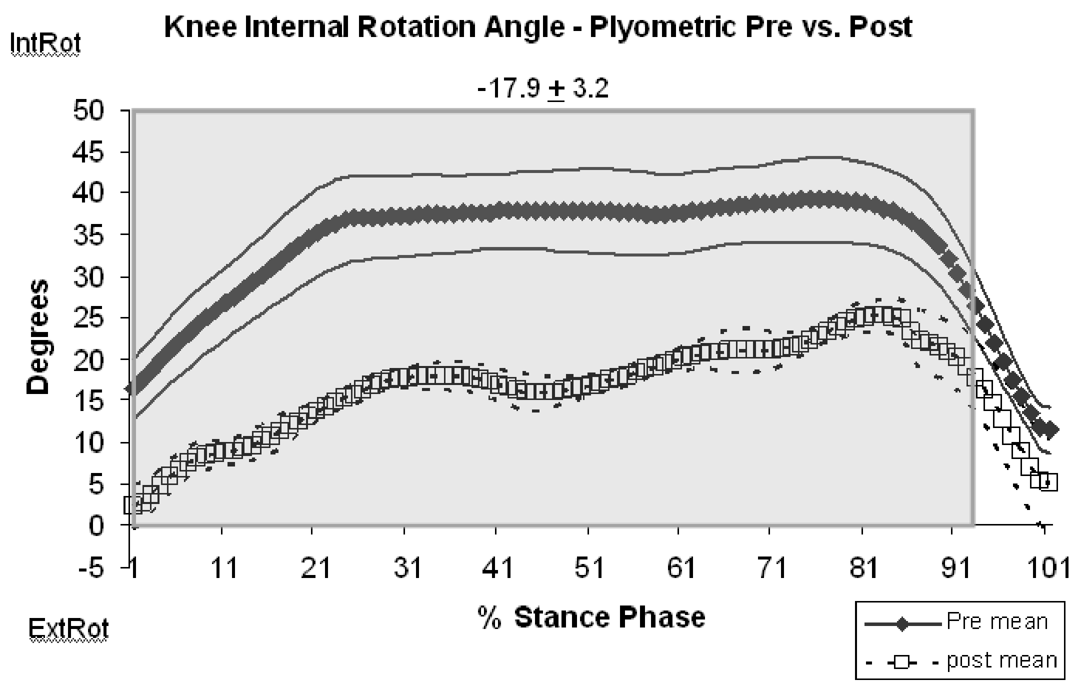

Figure 4. Plyometric Group Change Scores for DVJ Knee Internal Rotation Angle

The plyometric group change score from pre-test to post-test for knee internal rotation angle. The lines surrounding the mean scores represent the 95% confidence intervals. The post-test mean was significantly lower from 1-93% of the landing phase. The mean difference for the window was -17.9 ± 3.2 degrees, $P<0.05$.

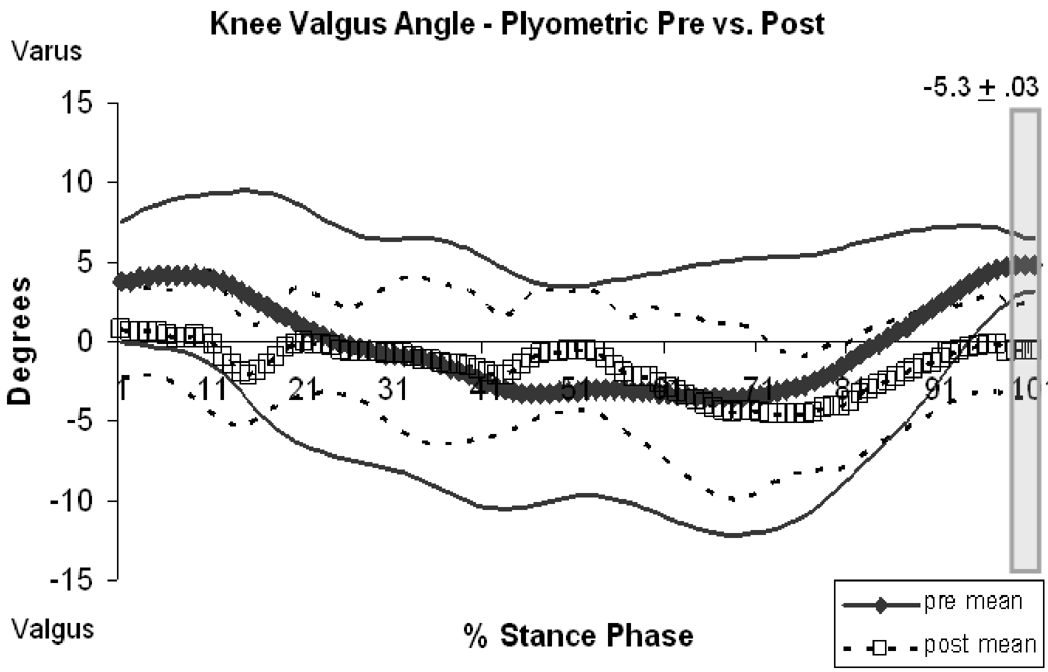

Figure 5. Plyometric Group Change Scores for DVJ Knee Valgus Angle
The plyometric group change score from pre-test to post-test for knee valgus angle. The lines surrounding the mean scores represent the 95% confidence intervals. The post-test mean was significantly lower from 98-101% of the landing phase. The mean difference for the window was -5.3 ± 0.03 degrees, $P<0.05$.

The plyometric group had significant differences between pre- and post-test knee kinetics in all 3 planes. The knee flexion moment was notably lower between 16-31% of the landing phase where the mean difference was -0.32 ± .04 (see Figure 6). Furthermore there was a strong effect size and the CI did not cross 0, d = -2.04 (-3.06, -0.82). The knee valgus moment decreased at 10% of the landing phase which corresponded with the lowest dip in the valgus/varus knee moment curve (see Figure 7). The mean difference between pre- and post-test at the 10% point was 0.1 Nm/kgm with a strong effect size of d = 1.56 (0.44, 2.53). The plyometric group also decreased the external rotational moment at the knee by a mean difference of 0.06 ± .008 between 39-57% of the landing phase (see Figure 8).

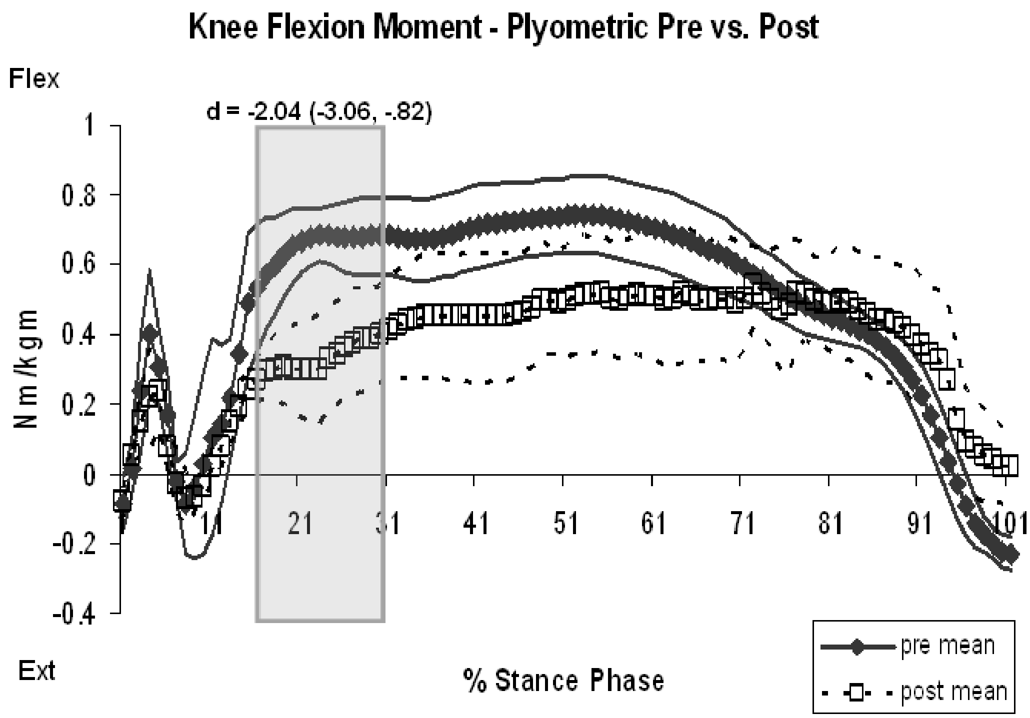

Figure 6. Plyometric Group Change Scores for DVJ Knee Flexion Moment
The plyometric group change score from pre-test to post-test for knee flexion moment. The lines surrounding the mean scores represent the 95% confidence intervals. The post-test mean was significantly lower from 16-31% of the landing phase. The mean difference for the window was -0.32 ± 0.04 Nm/kgm, P <0.05. This window had a strong effect size that did not cross 0 as represented by a Cohen's d = -2.04 (-3.06, -0.82).

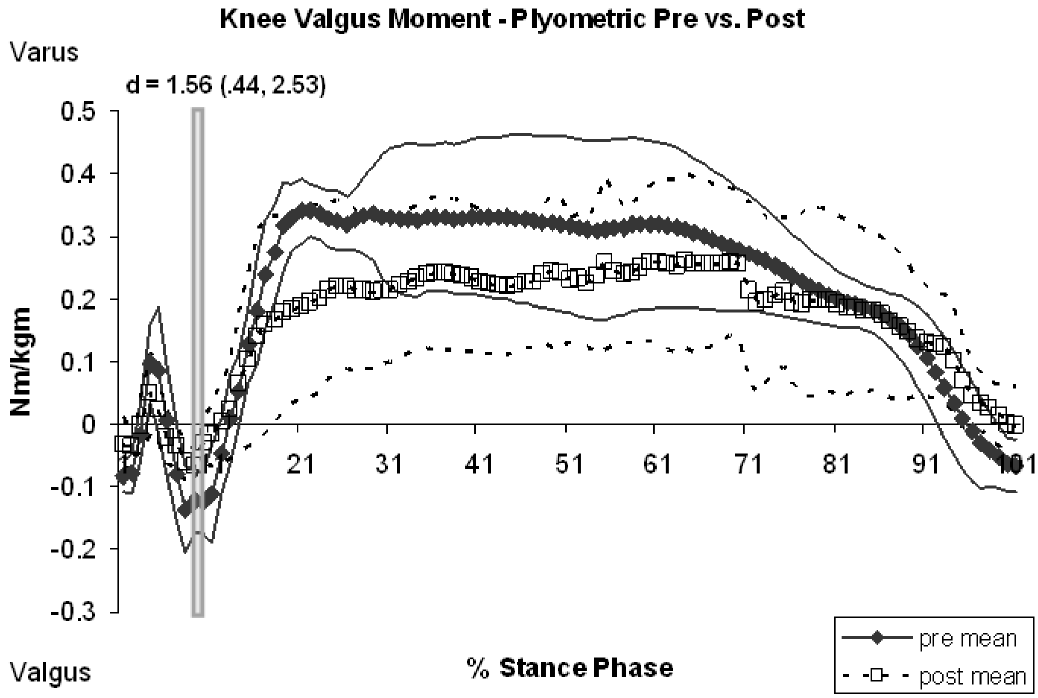

Figure 7. Plyometric Group Change Scores for DVJ Knee Valgus Moment
The plyometric group change score from pre-test to post-test for knee valgus moment. The lines surrounding the mean scores represent the 95% confidence intervals. The post-test mean was significantly higher at 10% of the landing phase. The mean difference for the window was 0.1 Nm/kgm, *P*<0.05. This window had a strong effect size that did not cross 0 as represented by a Cohen's d =1.56 (0.44, 2.53).

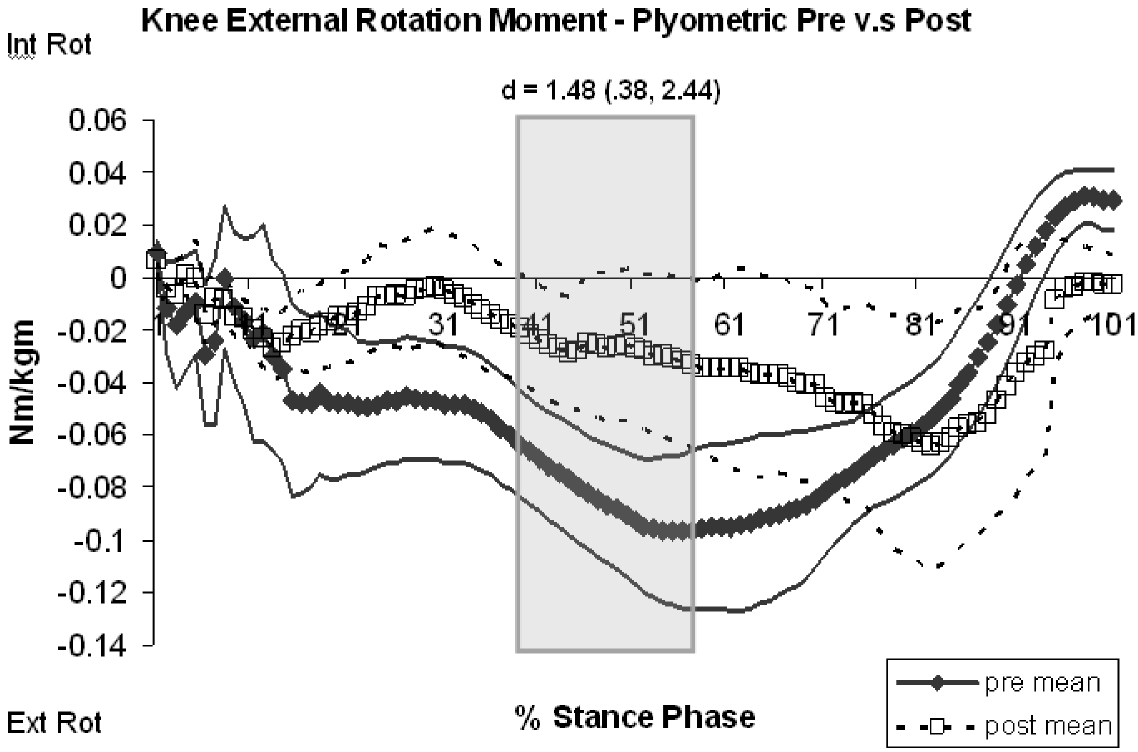

Figure 8. Plyometric Group Change Scores for DVJ Knee Rotation Moment
The plyometric group change score from pre-test to post-test for knee rotation moment. The lines surrounding the mean scores represent the 95% confidence intervals. The post-test mean was significantly higher from 39-57% of the landing phase. The mean difference for the window was 0.06 $\pm$ 0.008 Nm/kgm, P <0.05. This window had a strong effect size that did not cross 0 as represented by a Cohen's d =1.48 (0.38, 2.44).

Core Stability Group

The core stability group had 7 different variables that showed significant differences following the intervention sessions. Hip internal rotation angle decreased significantly during two separate intervals from 36-42% and 61-65% of the landing phase, P <0.05. The mean differences for these two windows were -15.3 $\pm$ .4 and -13.1 $\pm$ .4 degrees, respectively (see Figure 9). Knee flexion angle significantly changed from pre-test to post-test from 10-56% and 96-101% of the landing phase, P <0.05. Knee flexion decreased in the first window where the group mean difference decreased -21.0 $\pm$ 4.2 degrees while the in the second window the group mean difference increased 14.9 $\pm$

2.8 degrees (see Figure 10). Knee internal rotation angle significantly increased following the core stability intervention at 1-2% of the landing phase with a mean difference of 12.2 ± 1.1 degrees and again from 82-101% where the mean difference was 16.5 ± 2.9 degrees, *P <0.05*(see Figure 11).

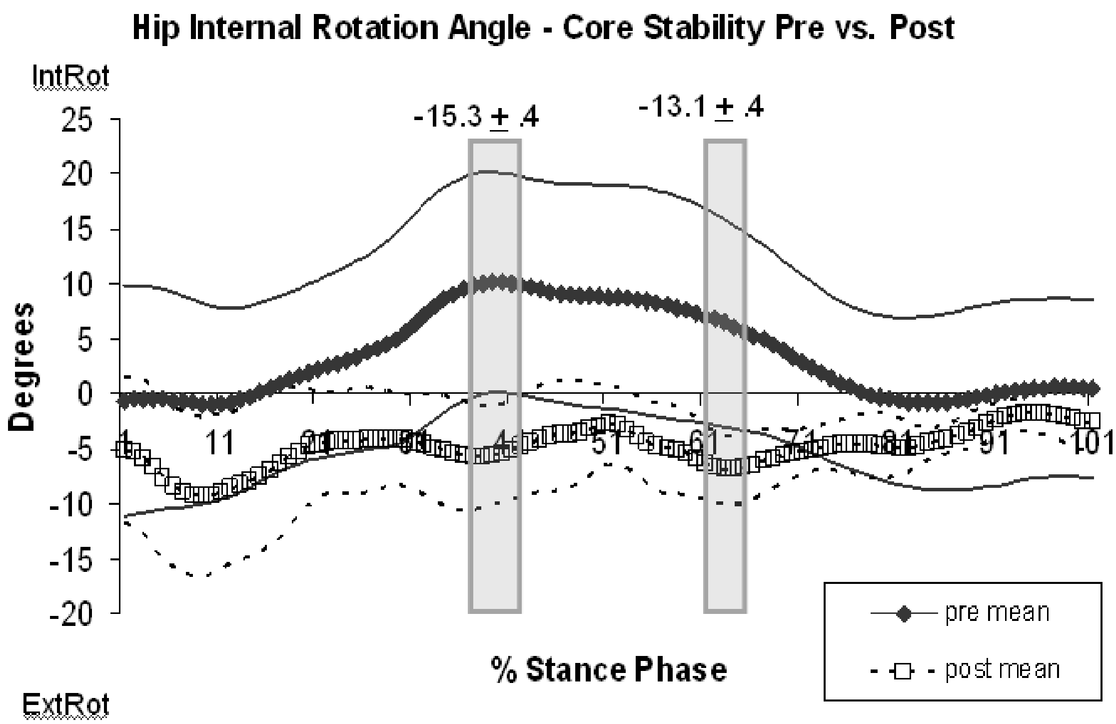

Figure 9. Core Stability Group Change Scores for DVJ Hip Internal Rotation Angle
The core stability group change score from pre-test to post-test for hip rotation angle. The lines surrounding the mean scores represent the 95% confidence intervals. The post-test mean was significantly lower from 36-42% of the landing phase and then again from 61-65%. The mean difference for the windows were -15.3 ± 0.4 and -13.1 ± 0.4 degrees respectively, *P* <0.05.

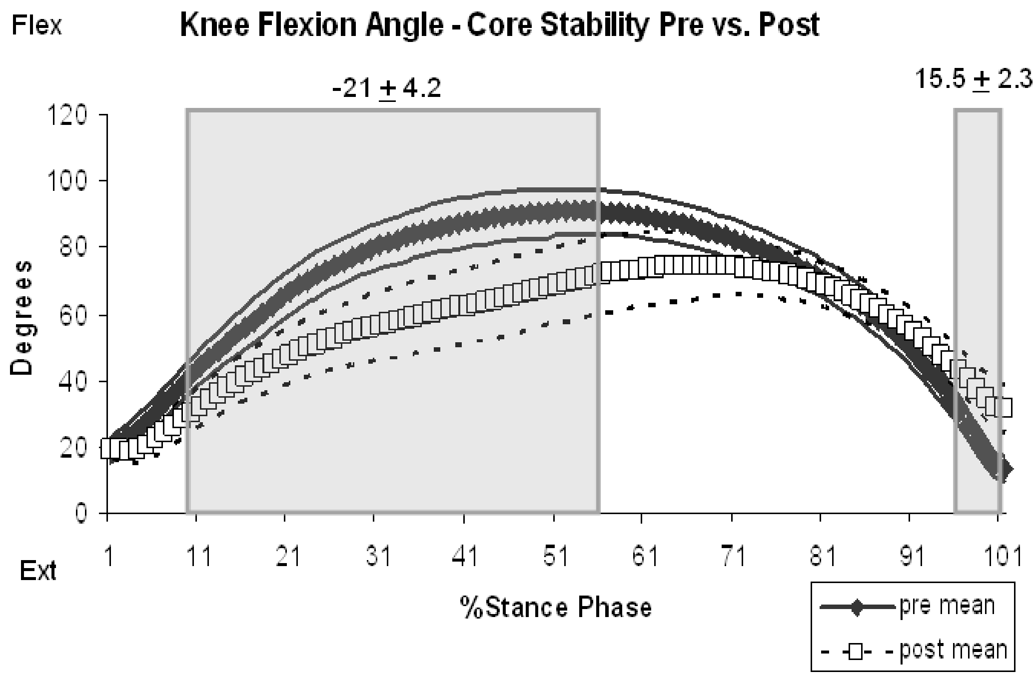

Figure 10. Core Stability Group Change Scores for DVJ Knee Flexion Angle
The core stability group change score from pre-test to post-test for knee flexion angle. The lines surrounding the mean scores represent the 95% confidence intervals. The post-test mean was significantly different from 10-56% of the landing phase and then again from 96-101%. The mean difference for these windows were -21.0 ± 4.2 and 15.5 ± 2.3 degrees respectively, $P < 0.05$.

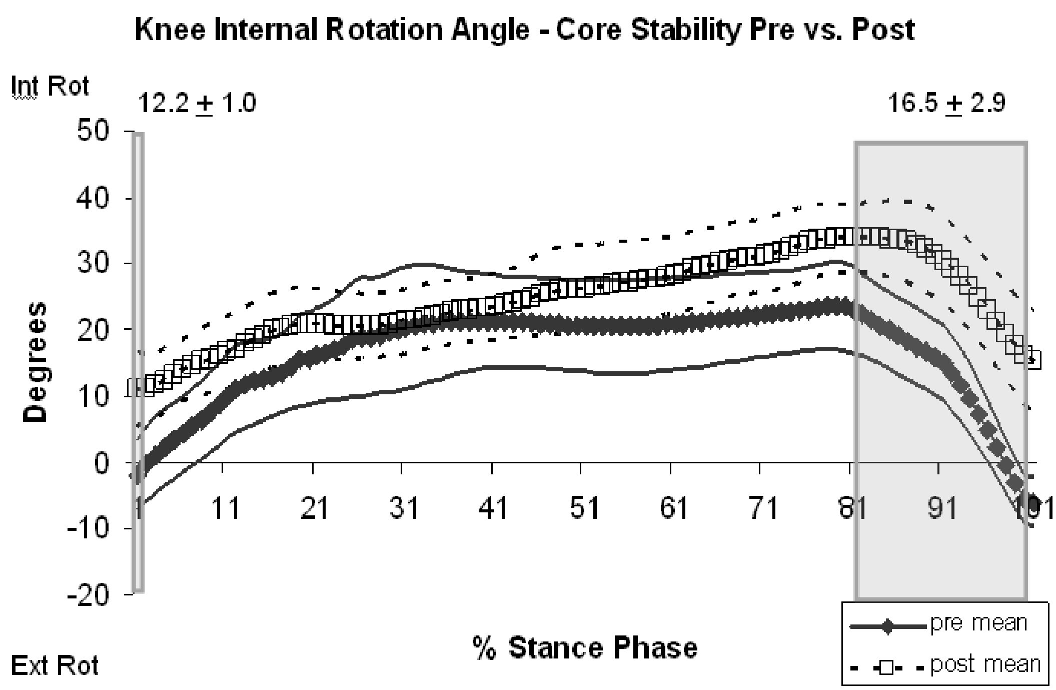

Figure 11. Core Stability Group Change Scores for DVJ Knee Internal Rotation Angle The core stability group change score from pre-test to post-test for knee internal rotation angle. The lines surrounding the mean scores represent the 95% confidence intervals. The post-test mean was significantly higher from 1-2% of the landing phase and then again from 82-101%. The mean difference for these windows were 12.2 ± 1.0 and 16.5 ± 2.9 degrees respectively, *P* <0.05.

Hip joint moments were significantly altered for all 3 planes of motion following the core stability intervention program. The hip flexion moment decreased at four separate intervals of the landing phase (see Figure 12). The first window was from 19-25% where the mean difference was -0.33 ± .05 Nm/kgm, *P* <0.05. However the CI for the effects size crossed the 0 point making it clinically inconclusive. The second window from 32-43% had a mean difference of -0.25 ± .04 Nm/kgm, *P* <0.05 and a strong effect size where d = -1.02 (-2.0, -0.07). The third window from 48-61% of the landing had a decrease of the hip flexion moment for the post-test with a mean difference of -0.35 ± .05 and a clinically meaningful and strong effect size of d = -2.81 (-4.0, -1.31). The final window spanned 65-80% of the landing phase where the mean difference of -0.28 ± .05 over time was statistically significant at *P*<0.05 resulting in a strong effect size of -2.23 (-3.33, -0.89). The hip abduction moment significantly increased from 37-48% of landing phase, *P* <0.05 (see Figure 13). The mean difference was 0.23 ± .01 Nm/kgm and a strong, clinically meaningful effect size was found, d = 2.35 (0.97, 3.47). Additionally the hip internal rotation moment decreased at post-test at four windows, *P* <0.05 (see Figure 14). The first window had a mean difference of -0.06 ± .02 Nm/kgm between 9-12% of landing with a strong effect size d = -1.89 (-2.95, -0.63). The second small window spanned from 20-24% and had a mean difference of -0.06 ± .01 Nm/kgm statistically significant at *P* <0.05, and a strong effect size d = -2.21 (-3.31, -.87). A decrease of -0.07 ± .02 Nm/kgm was found between 28-81% of the landing phase where a strong effect size was found, d = -3.34 (-4.69, -1.73). Additionally the post-test hip internal rotation moment was significantly smaller than pre-test from 89-94% of landing. The group mean difference was -0.04 $\pm$ 0.005 Nm/kgm and had a strong effect size where the CI did not cross 0, d = -1.8 (-2.85, -0.56). Finally, there was a significant increase in the knee varus moment from 50-72% of the landing phase (see Figure 15). The core stability group increased a mean difference of 0.19 $\pm$ .01 Nm/kgm indicating a strong, clinically meaningful effect, d = 1.68 (0.46, 2.71). No other within group differences were found, *P* >0.05.

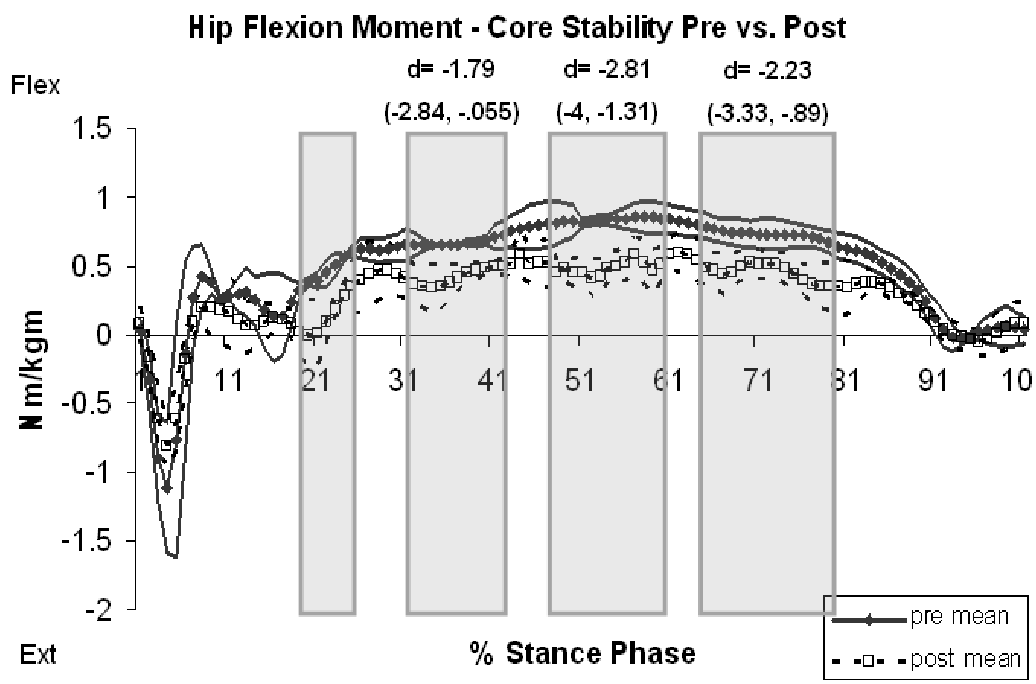

Figure 12. Core Stability Group Change Scores for DVJ Hip Flexion Moment
The core stability group change score from pre-test to post-test for hip flexion moment. The lines surrounding the mean scores represent the 95% confidence intervals. The post-test mean was significantly lower at four separate intervals of the landing phase from 19-25%, 32-45%, 48-61%, 65-80%. The first window had a mean difference of -0.33 $\pm$ 0.05 Nm/kgm, *P* <0.05 but a non-significant effect size. The second window had a mean difference of -0.25 $\pm$ .04 Nm/kgm, *P* <0.05 and a strong effect size that did not cross 0 as represented by a Cohen's d = -1.79 (-2.84, -0.055). The third window had a mean difference of -0.35 $\pm$ .05 Nm/kgm, *P* <0.05 and a strong effect size that did not cross 0 as represented by a Cohen's d = -2.81 (-4.0, -1.31). The final window had a mean difference

of -0.28 ± .05 Nm/kgm, *P* <0.05 and a strong effect size that did not cross 0 as represented by a Cohen's d = -2.23 (-3.33, -0.89).

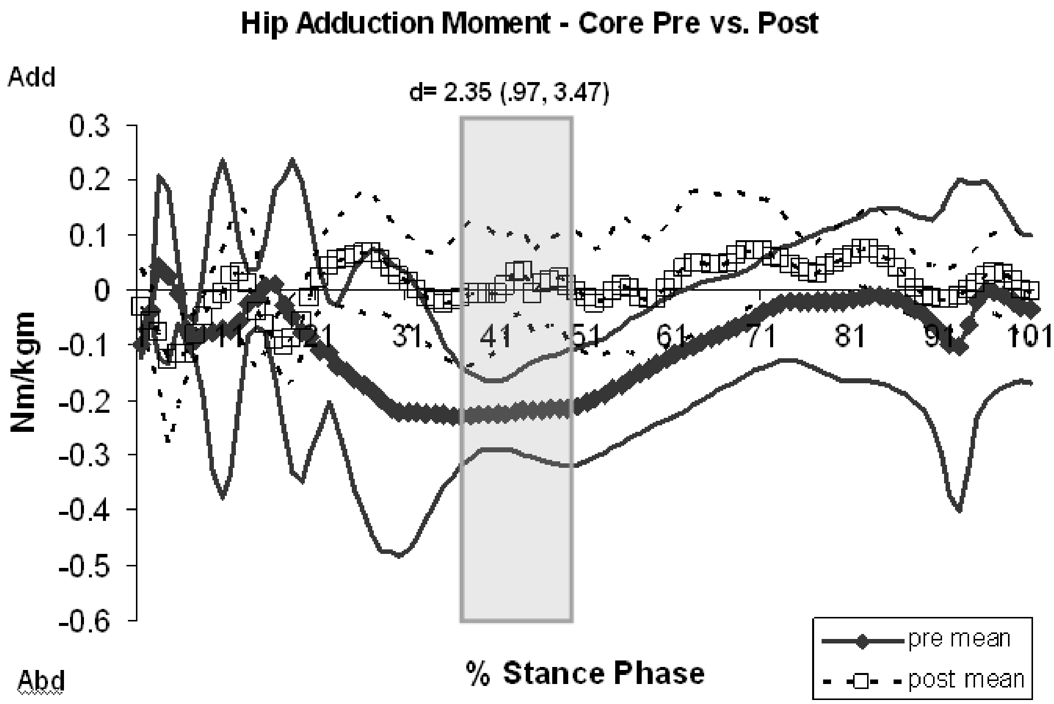

Figure 13. Core Stability Group Change Scores for DVJ Hip Abduction Moment
The core stability group change score from pre-test to post-test for hip adduction moment. The lines surrounding the mean scores represent the 95% confidence intervals. The post-test mean was significantly higher from 37-48% of the landing phase. The mean difference for the window was 0.23 ± 0.01 Nm/kgm, *P* <0.05. This window had a strong effect size that did not cross 0 as represented by a Cohen's d =2.35 (0.97, 3.47).

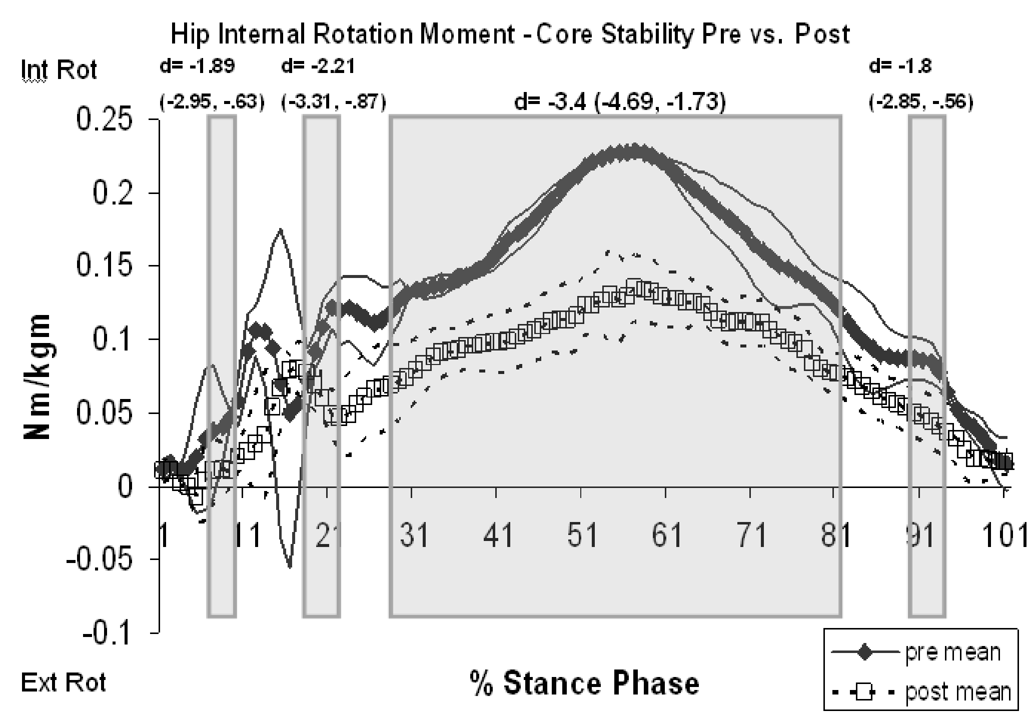

Figure 14. Core Stability Group Change Scores for DVJ Hip Internal Rotation Moment The core stability group change score from pre-test to post-test for hip internal moment. The lines surrounding the mean scores represent the 95% confidence intervals. The post-test mean was significantly lower at four separate intervals of the landing phase from 9-12%, 20-24%, 28-82%, 89-94%. The first window had a mean difference of -0.06 $\pm$ 0.02 Nm/kgm, *P* <0.05 and a strong effect size that did not cross 0 as represented by Cohen's d = -1.89 (-2.95, -0.63). The second window had a mean difference of -0.06 $\pm$ .01 Nm/kgm, *P* <0.05 and a strong effect size that did not cross 0 as represented by a Cohen's d = -3.4 (-4.69, -1.73). The third window had a mean difference of -0.07 $\pm$ .02 Nm/kgm, *P* <0.05 and a strong effect size that did not cross 0 as represented by a Cohen's d = -3.4 (-4.69, -1.73). The final window had a mean difference of -0.04 $\pm$ .005 Nm/kgm, *P* <0.05 and a strong effect size that did not cross 0 as represented by a Cohen's d = -1.8 (-2.85, -0.56).

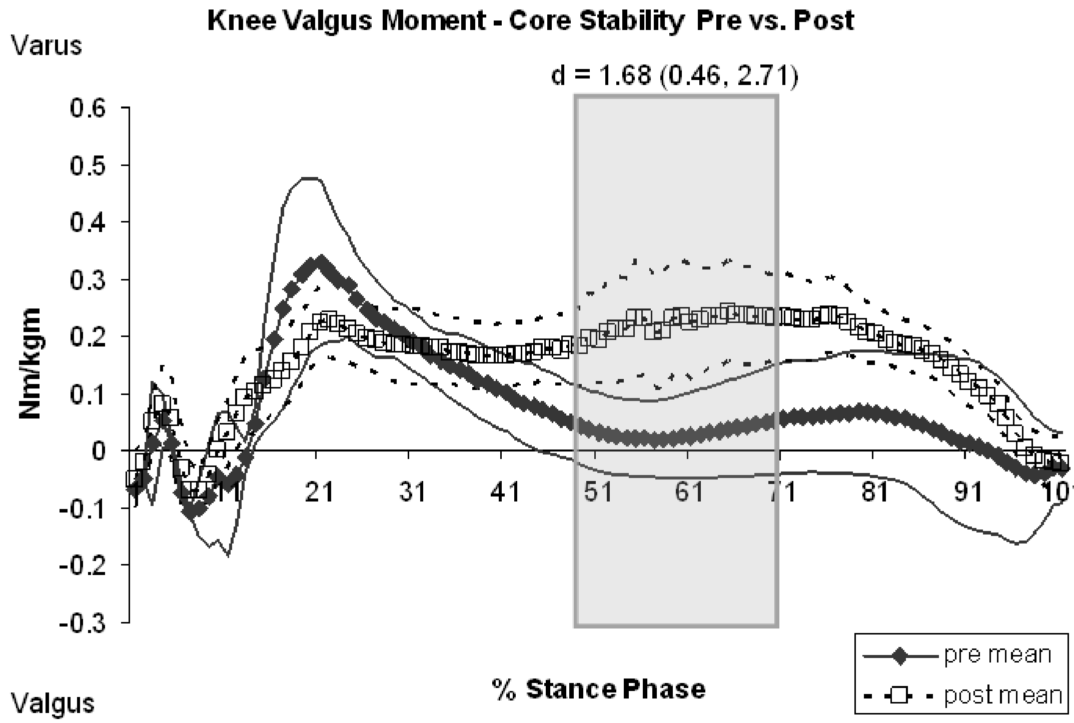

Figure 15. Core Stability Group Change Scores for DVJ Knee Valgus Moment
The core stability group change score from pre-test to post-test for knee valgus moment. The lines surrounding the mean scores represent the 95% confidence intervals. The post-test mean was significantly higher from 50-72% of the landing phase. The mean difference for the window was 0.19 $\pm$ 0.01 Nm/kgm, $P < 0.05$. This window had a strong effect size that did not cross 0 as represented by a Cohen's d =1.68 (0.46, 2.71).

DISCUSSION

It was hypothesized that changes in trunk, hip and knee kinematics and kinetics would be found following completion of a neuromuscular training program focused either on plyometric or core stability. The findings of this study partially confirm our hypotheses indicating that changes in lower extremity biomechanics during a DVJ are present following 4 weeks of coach-supervised training in junior varsity female athletes. The plyometric group demonstrated significant differences for knee joint kinematic and kinetic variables only while the core stability group had altered hip and knee joint variables while the control group showed no substantial changes.

Plyometric Intervention

Kinematics

Previous research[3] has indicated that the common denominator in successful ACL injury prevention programs is the inclusion of plyometric exercises. This study incorporated exercises from the literature shown to either decrease ACL injury risk or decrease the biomechanical variables associated with increased injury risk. Contrary to published literature,[13, 16] this study found a decrease in knee flexion angle following the plyometric training intervention. A decrease in knee flexion following an in-season intervention program (although not significant) was also reported in a study conducted using high school female soccer teams.[15] We attribute this significant decrease in flexion range of motion to the group's improved efficiency to absorb force during landing [27] If muscles are more adept at absorbing external forces then there is a diminished need to move through a large knee flexion range of motion in order to increase the time over which external forces can be managed. The window from 13-58% in which the significant difference in knee flexion change scores occurred represents the period of time where the subject is transitioning from deceleration to force generation.[17] Additionally, decreasing the amount of knee flexion upon landing may help to decrease the amortization phase between jumps[13] potentially leading to improved athletic performance.

The finding of decreased knee flexion angle was contrary to our hypothesis and poses a concern in regards to the potential for ACL injury. Hewett[9] reported that following prospective testing the ACL injured group had a peak knee flexion angle that was 10.5 degrees less than the healthy group however this variable did not fit into the predictor model for ACL injury. The decrease in knee flexion may result in an increase in the relative strain on the ACL.[28] Furthermore, a decrease in knee flexion angle will impact the angle of pull of the hamstring, altering the effectiveness of this muscle group in limiting anterior translation of the tibia.[29] The changes shown following the intervention program may be a result of the programs being led by the coaching staff rather than more qualifed personnel. Future study may incorporate training of the individuals involved in leading the intervention program to improve the quality of instruction given to the athletes.

The plyometric group also demonstrated a change in the knee valgus angle; however, it did not confirm the initial hypothesis that there would be a decrease in knee valgus. The significant change noted came in the final stages of the landing phase leading into takeoff (see Figure 5) where the post-test mean moved from a varus knee joint position into a just slightly valgus position. The clinical significance of this finding in relation to ACL injury mechanism is questionable. A prospective research study[9] found female athletes who suffered a noncontact ACL injury had a significantly greater knee valgus angle at initial contact compared to female athletes who did not sustain an injury. Of notable interest was the decrease in the CI surrounding the post-test mean indicating a decrease in variability for frontal plane knee motion. Pollard[15] and Myer[30] both suggest the theory of responders where the greatest changes occur in individuals who display the greatest risk for injury. Application of this theory to our data may indicate that there is a decrease in knee valgus angle primarily for the subjects who had the greatest valgus angle at pre-test. A more in-depth analysis of the data set is needed to determine whether this theory is valid.

A significant decrease for knee internal rotation angle was found throughout almost the entire landing phase (93%) following plyometric training (see Figure 4). Knee internal rotation is believed to place greater stress on the ACL.[8] Therefore, by decreasing the amount of knee rotation the amount stress placed on the ACL should also decrease, thus minimizing the risk for noncontact injury.

Kinetics

The plyometric group also demonstrated significant changes in knee joint moments that were partially in agreement with our initial hypotheses. We found a decrease in the knee flexion moment from 16-31% of the landing phase spanning the late deceleration phase of the DVJ (see Figure 6). Similarly we found a decrease in the knee valgus moment at 10% of the landing phase which corresponded with the peak knee valgus moment. Both windows had a strong effect size indicating that the mean difference found over time was a clinically meaningful finding.

These 2 results suggest that the core stability program was beneficial in altering the athlete's tendencies away from a quadriceps and/or ligament dominant pattern. An individual with quadriceps dominance has an increase in her internal knee extensor moment over her internal knee flexor moment potentially leading to long term imbalances in strength and muscle activation coordination.[31] Secondly, an over-reliance on the quadriceps musculature can mean individuals are placing added anterior shear stress to the ACL during dynamic activities, placing them at greater risk for noncontact injury. Ligament dominance is exhibited when the ligament rather than the surrounding joint musculature is used to absorb a ground reaction force.[32] Ligament dominant females have an increase in medial knee motion and larger valgus knee moments and ground reaction forces.[4] Therefore, by decreasing variables associated with both quadriceps and ligament dominance the plyometric training intervention appeared successful in decreasing potentially injurious knee joint torques.

Finally, our results show a significant increase in the knee external rotation moment. We initially hypothesized that at pre-test there would be an internal rotation knee moment. However, this was not the case and in fact the group mean was externally rotated at pre-test and moved towards a more neutral rotation moment at post-test (see Figure 8). This change may be due to an alteration of the transverse plane knee kinematics. A result was found in a study examining the effect of a neuromuscular training program on female college athletes where the peak knee rotational moment significantly increased from an external rotation moment to an internal rotation moment.[12] It may be that plyometric training helps to maintain a more neutral joint position by reducing the amount of joint torque.[33] Further research is needed to gain a better understanding of how plyometric training affects transverse plane knee joint moments.

Core Stability Intervention

Kinematics

The core stability group showed significant changes in joint angles at both the hip and knee. However, no change in lateral trunk flexion angle was found following the 4 week intervention. A significant decrease for hip internal rotation angle was found at two separate intervals during the landing phase (see Figure 9). As depicted in the figure, the post-test mean remained in an externally rotated position throughout the duration of the landing phase with a much tighter CI band indicating a decrease in the group variability.

The exercise program targeted the hip external rotators in either an isolated plane or in combination with other hip musculature while attempting to maintain a neutral femur position. Few studies have examined the effect of core stability training in isolation on lower extremity biomechanics during a DVJ. Chappell et. al.[12] incorporated some of the same exercises used in this study in part of a global neuromuscular training program and found no significant differences for hip kinematics including internal rotation.

Similar to the plyometric group, the core stability group had a significant decrease in knee flexion angle following four weeks of training. This finding suggests that increases in neuromuscular coordination of the hip and trunk musculature may improve the efficiency with which the quadriceps muscle group functions. Lawrence et al.[34] found that subjects with greater hip external rotation strength had a significantly decreased knee flexor moment requiring less quadriceps activation during landing. Our core stability group performed closed chain exercises such as forward lunges and squats as part of their intervention program emphasizing slow controlled lowering into knee flexion to encourage eccentric quadriceps and gluteal function.

Significant changes were seen for knee internal rotation between pre- and post-test in the core stability group. The post-test group mean was higher at initial contact for the first 2% of landing phase and then again towards the propulsion phase. No other studies have reported an increase in knee internal rotation angle following core stability training. We propose that the differences seen may be a result of the change in hip internal rotation position. It is thought that by inducing changes at the hip there will be a cascade of adaptations made down the kinetic chain.[34, 35] The increase shown during the final 20% of landing in the propulsion phase of the landing may be related to anecdotal patterns noted where the subjects dropped into a more internally rotated position to generate hip and knee extension. The differences seen here are unlikely to be important for ACL injury prevetion however more research is needed in this area to provide a rationale for why core stability training increases knee internal rotation just prior to take off from a DVJ.

Kinetics

Unlike the plyometric group, the core stability group showed significant adaptations in all 3 planes for hip joint kinetics, as well as a change in the knee varus moment. This finding is not surprising as the exercises performed for 4 weeks focused on improving trunk and hip neuromuscular coordination. All 3 hip joint kinetic findings are associated with increased efficiency of the hip extensors, abductors and external rotators to eccentrically control hip flexion, adduction and internal rotation, respectively. Lephart et al.[13] designed a “basic” neuromuscular program that incorporated some of the same trunk exercises as this study and found similar results for the peak hip flexion moment. However, their results are not entirely similar because no difference was shown for the peak hip abduction moment. Differences between intervention programs and level of supervision must be noted when drawing comparisons between these studies.

Hip external rotation strength has been linked to changes found for peak hip abduction moment during a single leg landing.[34] Subjects classified as having strong hip external rotators had significantly smaller hip abduction moments when compared to those with weak hip external rotators. Therefore, while our study did not specifically measure strength outcomes it may be reasonable to say that the core stability training program improved neuromuscular control patterns that elicited positive adaptations in external force management. Finally, all the significant changes found for hip joint kinetics had strong effect sizes indicating the magnitude of difference is clinically meaningful however the timing of the events may not take place duing a point in the landing phase associated with ACL injury risk.

The only significant difference shown for knee joint kinetics within the core stability group occurred in the frontal plane. The mean post-test knee varus moment increased between 50-72% of the landing phase (see Figure 15). This finding suggests a protective effect as the subjects moved into the force generation period of the DVJ. Lawrence et al.[34] also demonstrated that individuals with stronger hip external rotators had significantly smaller external knee valgus moments. These results may be indicative of eccentric control of the external rotators limiting the degree of hip internal rotation. This is important because it further establishes the theory that control of the hip musculature leads to more control of forces at the knee joint.[21, 25, 34] Furthermore, it relates to ACL injury prevention as a shift in the torque curve away from an external knee valgus moment may be considered protective.[9]

Clinical Relevance

One of the goals in designing the methods for this study was to keep the intervention programs feasible to implement outside of a research setting. The exercises chosen required no additional equipment other than what is available at a soccer or lacrosse practice. The coaches were responsible for instructing the athletes on proper technique during the exercises through the use of a guided handout (see Table C5 and C6) with no outside medical staff involved. Finally the amount of time required to complete the programs was limited to 20 minutes to keep it manageable and improve compliance. Despite the simplicity of the interventions, the results of this study were clinically meaningful and echoed many of the results found in more involved research studies.[12, 16, 36]

The length of program used in this study was shorter than most used in previously reported neuromuscular control training and ACL prevention studies.[12 13, 17, 20, 36-38] This finding may be related to the level of athletes used in this study where all participants were involved with junior varsity level sports. The changes seen over a relatively short period of training may be a factor of the age and skill level of the athletes included. It is thought that less skilled and/or developed athletes are more adept to change movement patterns in comparison to high level athletes.[31]

The plyometric training program produced kinematic and kinetic changes at the knee joint only while the core stability group saw significant changes at both the hip and knee joint. Because no injury incidence data was included as part of this study it is difficult to say which intervention program may be more successful in reducing ACL injuries. However, it appears that both types of exercises are valuable in altering biomechanical patterns associated with ACL injury risk. Therefore we recommended that comprehensive ACL prevention programs incorporate components of both plyometric and core stability training.

Limitations and Future Research

This study had many significant findings for both groups despite a small sample size. Much of the current body of literature proposes the use of neuromuscular training interventions in female athletes during the adolescent stage of development or younger.[12, 21, 31, 39] The subjects in this study were all high school aged athletes; however, they were participating at the junior varsity level which may indicate a subject pool with diminished neuromuscular coordination. The level of competition may also play a role as to why many of the dependent variables were significant as compared to other studies with similar sample sizes.[12, 13]

The intervention groups were not randomly assigned to the schools, and because of this the control group ended up with fewer subjects than the intervention groups. Furthermore, despite great efforts to recruit subjects the plyometric group consisted solely of lacrosse players while the core stability and control groups were comprised of both lacrosse and soccer athletes. This fact may have decreased the within group variability for the plyometric group. Using only one team for the plyometric group meant that there was more consistency in the coach-directed training sessions. This is in contrast to the core stability group that included 2 separate teams from 2 different sports potentially leading to greater differences in kinematic and kinetic patterns.

The objective of this study was not to determine whether core stability training was more beneficial than plyometric training in decreasing ACL injuries. A combination group may provide more information as to whether there is an additive effect by performing both types of exercises. Finally, further research is needed to determine which specific exercises are most successful in eliciting a change in lower extremity biomechanics during a DVJ and the necessary duration required before significant changes in movement patterns are found.

The statistical analysis used in this study is rather unique to this area of research making it more difficult to compare findings to the current body of literature. Graphing the group mean and CI over the course of the landing phase provides information beyond a discrete point regarding changes from an intervention program. Myer et al.[36] included aspects of this in a study where the confidence intervals were reported around the group means as well as a few representative force graphs. Future studies should continue to report curve analysis findings as well as peak means. Curve analysis provides an overall picture of how specific biomechanical variables are acting over a course of time rather than at a peak. It enables researchers and clinicians to make conclusions on whether intervention programs are resulting in neuromuscular adaptations leading to larger scale changes in movement patterns.

Conclusion

In conclusion, the implementation of an in-season, four week training program at the junior varsity level for female athletes resulted in significant changes in kinematic and kinetic findings. The plyometric group demonstrated changes solely at the knee joint while the core stability group showed alterations in kinematics and kinetics at both the hip and knee joint. The results of this study suggest that both types of exercises are warranted in ACL injury prevention programs. Core stability training may add benefit above and beyond plyometric training because it influenced movement patterns and force distribution at the hip joint.

MANUSCRIPT 2

THE EFFECT OF DIFFERENT EXERCISE TRAINING INTERVENTIONS ON THE BIOMECHANICS OF A SIDESTEP CUTTING TASK IN HIGH SCHOOL FEMALE ATHLETES

ABSTRACT

Context: Anterior cruciate ligament (ACL) injuries are more common in adolescent and adult female athletes than males and are believed to be related to poor neuromuscular control. Neuromuscular deficits manifest through biomechanics during dynamic tasks such as sidestep cutting (SSC). Alterations in biomechanical patterns have been shown as a result of neuromuscular training programs. It is unknown which component of these programs are responsible for the neuromuscular alterations. **Objective:** To assess the efficacy of 4 week core stability program and plyometric program on altering lower extremity and trunk kinetics and kinematics during a SSC task. **Design:** Cohort study. **Setting:** High school athletic field and motion analysis laboratory. **Patients or Other Participants:** 23 healthy junior varsity female lacrosse and soccer players. **Intervention(s):** Independent variables were group (core stability, plyometric, control) and time (pre-test, post-test). Subjects performed five trials of a SSC prior to and after completing a four week core stability or plyometric program. **Main Outcome Measures:** Dependent variables were 3-dimensional lower extremity and trunk kinetics and kinematics during the stance phase of a SSC. Group means and associated 95% confidence intervals were calculated via bootstrapping across the entire stance phase. Curve analysis using an alpha level of $P < 0.05$ was performed to identify time periods where the confidence interval bands for the groups did not cross. **Results:** All groups had a decrease in hip flexion angle at the initial stage of the stance phase. Control: -21.5 ± 0.5 degree mean difference from 1-19%; plyometric: mean difference was -13.5 ± 0.3 from

1-12%; core stability: -16.5 ± 0.3 mean difference 1-15%. Significant changes in knee flexion patterns were found throughout the stance phase, P <0.05. The control group decreased from 25-35% -9.7 ± 0.2 and then increased 16.1 ± 2.9 degrees from 85-101. The plyometric group increased 18.8 ± 3.1 degrees from 84-101% and the core stability group decreased 8.9 ± 1.0 degrees from 13-49% and then increased 12.9 ± 1.9 degrees from 88-101% of stance phase. The only kinetic change was found in the core stability group where there was a decrease of 0.54 ± 0.05 Nm/kgm in the external hip flexor moment from 19-21% of stance phase, P <0.05. This reduction had a strong effect size (d = -1.54 (-2.56, -0.36)). **Conclusions:** Overall, no independent changes were found resulting from a plyometric training intervention. The SSC used in this study may not provide a significant enough challenge to the neuromuscular system to implement new motor patterns gained in jump landing training. The core stability group improved the management of sagittal plane kinetics at the hip through increased eccentric gluteal function. The minimal amount of frontal plane focused exercises may be a factor in the limited findings of this study because the SSC is a frontal plane oriented task.

INTRODUCTION

Females who participate in sports that involve pivoting, cutting, and jumping are over three times more likely to sustain a noncontact anterior cruciate ligament (ACL) injury than males participating in the same activities.[1] Potential factors related to the increase in ACL injury risk for females are categorized into hormonal, anatomical and biomechanical and neuromuscular factors. Biomechanical and neuromuscular factors are of particular interest as decreases in ACL injury risk have been shown following training aimed at correcting poor biomechanical and neuromuscular control patterns.[20, 40-42]

Noncontact ACL injuries frequently occur when performing a dynamic activity such as cutting that involves deceleration coupled with a sudden change in direction.[2] Researchers investigating the gender bias in ACL injury have examined biomechanical characteristics during cutting. Although there have been no prospective studies of a sidestep cut (SSC) linking specific biomechanical findings to ACL injury risk, there is a body of literature that examines common patterns believed to be associated with increased injury risk. Studies have repeatedly demonstrated that adolescent and adult females appear to exhibit increased amounts of knee valgus, decreased hip and knee flexion, and decreased hip abduction angles when changing direction. [43-46]

There are less data describing the kinetics of a SSC; however, both McLean et al[47, 48] and Sigward et al[33, 49] identified females as having larger normalized knee abduction moments. This finding is significant as it echoes the association found between larger knee abduction moments and ACL injury risk for adolescent females that is described in the jump landing literature.[9]

ACL prevention programs focusing on improving neuromuscular control have proven effective in reducing injury incidence.[20, 40-42] A common component of these programs is plyometric training because it is thought that the stretch-shortening cycle activates the neural, muscular, and elastic components ultimately improving joint stability through enhanced dynamic stiffness.[3] One study[16] showed individuals who displayed "high risk" biomechanical patterns made significant improvements after an intervention that included plyometric, core strength, balance and resistance training. A study utilizing a similar program demonstrated a significant decrease in ACL injury incidence for the trained group versus the control.[20] However, these effective programs are time consuming and require large amounts of individual attention, thus increasing the difficulty of implementation on a wide-scale. Furthermore, it is unknown whether one or all of the components included are necessary to see such desired results.

Core stability is becoming an increasingly popular concept in relation to lower extremity injury prevention. Leetun et al[50] found that hip abduction and external rotation strength were significantly different between male and female athletes who went on to suffer a back or lower extremity injury. It has been proposed that individuals who have weaker hip abductors and external rotators may not be able to eccentrically control the position of the femur leading to increased hip adduction and knee valgus angles as well as joint forces, thereby increasing the risk for ACL injury.[46] A prospective study found that females who suffered an ACL injury had greater lateral trunk displacement in response to a sudden force.[11] This finding further demonstrates the link between decreased core neuromuscular control and increased risk for a distal lower extremity injury. However, there are no studies in the literature investigating the effects of an intervention focused on core stability in altering trunk and lower extremity control.

The purpose of this study was to determine whether a four week intervention utilizing either plyometric training or core stability could alter females' kinematic and kinetic patterns while performing a SSC. We hypothesized that the core stability group would have a decrease in lateral trunk flexion, hip adduction, and internal rotation angles as well as decrease in the external hip joint moments for flexion, adduction, and internal rotation following the intervention. Additionally, the plyometric group would show significant decreases in lateral trunk flexion, hip adduction, and internal rotation angles as well as decreases in knee valgus and internal rotation kinematics. Furthermore, we hypothesized the plyometric group would also have increased hip and knee flexion angles. We believed there would be significant differences in flexion, adduction and internal rotation moments at the hip in addition to kinetic changes seen for knee flexion, valgus and internal rotation. Finally, we believed there would be no significant differences between intervention groups in kinematic or kinetic patterns during the SSC.

METHODS

This study utilized a cohort design where the independent variables tested were group (core stability, plyometric and control) and time (pre- and post-test). The dependent variables were mean within group change scores of lower extremity kinematic and kinetic variables. The kinematic variables assessed were lateral trunk flexion, hip flexion, internal rotation and adduction as well as knee flexion, internal rotation and valgus. External joint moments for hip flexion, internal rotation and adduction, knee flexion, internal rotation and valgus were also collected.

Subjects

Twenty four females volunteered for this study from three local area high schools. One subject was excluded for have current low back pain during activity. Twenty three subjects (14.8 ± 0.8 yrs, 1.7 ± .07 m, 57.7 ± 8.5 kg) were actively participating on a junior varsity lacrosse or soccer team, had no history of trunk or lower extremity surgery and no previous injury within the past 6 weeks that limited participation in athletics or physical activity. Furthermore subjects had no neurological disorders that may affect balance and had not participated in a formal core stability or plyometric training program as determined by parent and subject self-report. The study was approved by the Institutional Review Board for Health Sciences Research (IRB-HSR #14039). All subjects' parent or guardian signed an informed consent form and the subject read and signed an informed assent form for this study.

Instrumentation

Kinematic data was obtained using a 10 camera Vicon 624 motion analysis system (Vicon Peak, Lake Forest, CA, USA). Synchronized kinetic data was captured using a conventional in-ground AMTI force plate (AMTI, Watertown, MA, USA). Kinematic data were captured at 250 Hz and the kinetic data were captured at 1000 Hz and time synched.

Testing Procedures

Subjects reported to the motion analysis laboratory for pre-testing. Anthropometric measurements including height, mass, leg length, knee and ankle width were taken and recorded. Subjects were fitted with Brooks running shoes (Brooks® Sports, Inc., Bothell, Washington, USA) model Radius 06 and had retroreflective markers placed bilaterally on the following anatomic landmarks to represent the lower extremity segments: 2nd metatarsal head, calcaneus, lateral malleolus, lateral midshank, lateral femoral condyle and lateral midthigh in accordance with the Vicon Clinical Manager (Vicon, Oxford Metrics, London, UK) protocol. A four marker cluster was secured around the hips over the sacrum using elastic tape. To capture trunk motion markers were also placed on the sternum, xiphoid process, C7 and T10 spinous processes and bilateral acromion processes.

Subjects performed the SSC by running at 4.0-5.0 m/s pace down a 10 meter runway, contacting their right foot on an embedded force plate, and changing direction to the left. Tape was placed on the ground between 35-55 degrees creating an alley for subjects to run through. Approach speed was calculated by measuring the velocity of the sacral cluster marker as a representation of center of mass velocity. Subjects performed five acceptable trials requiring a clean strike of the foot on the force plate, visualization of all markers, and an approach speed in the pre-determined velocity range. Kinetic and kinematic data were collected for all subjects and the mean values were used for analyses.

Each subject repeated the testing following the four week intervention. All subjects completed testing within a 10 day period following the final session of intervention exercises. Subjects were re-instructed on how to perform the SSC and allowed to re-acquaint themselves with the task. Following the completion of the post-testing session subjects were dismissed from the study (see Figure 16).

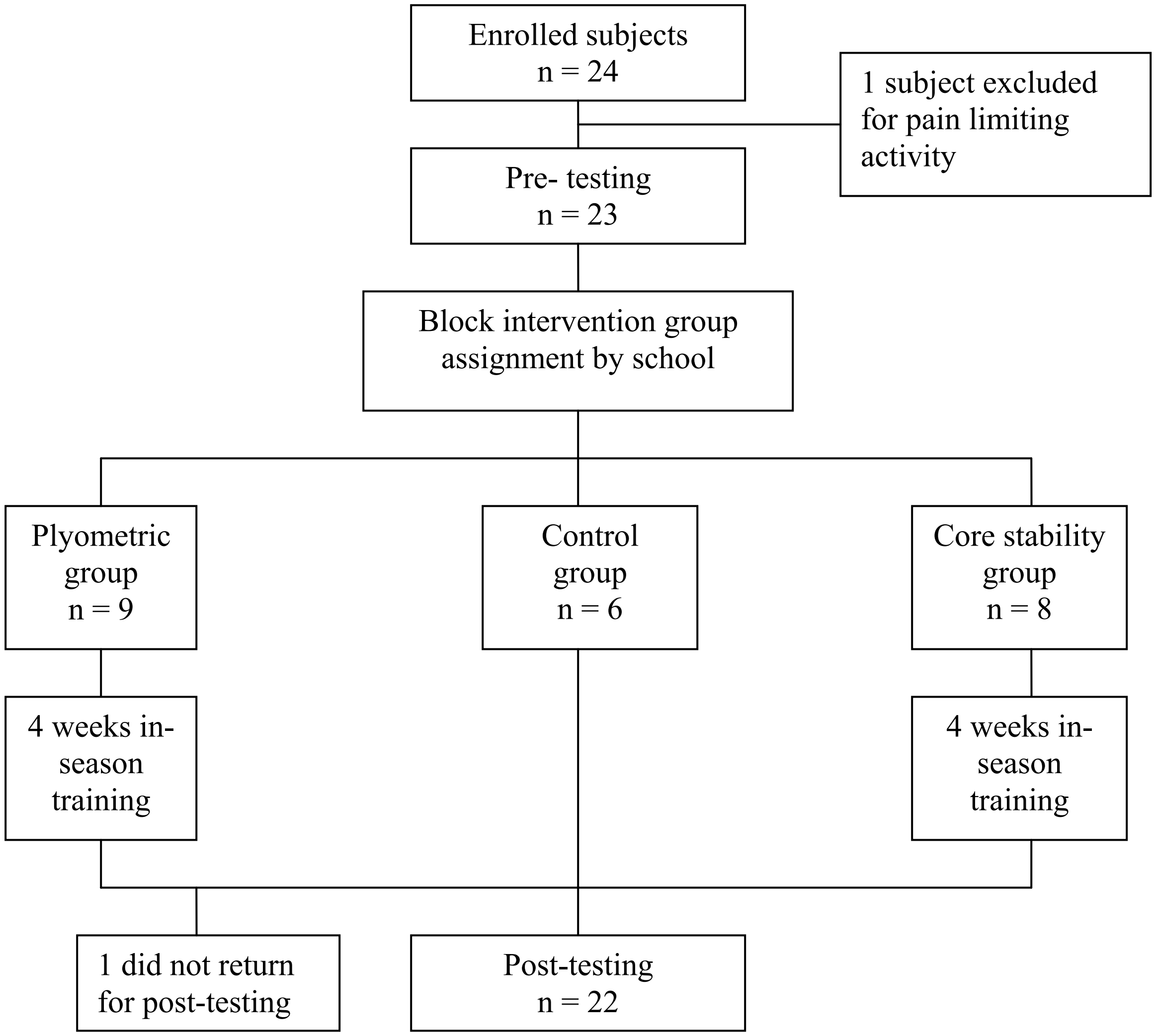

Figure 16. CONSORT flowchart outlining the progression of testing order and subject dropout.

Intervention programs

Teams were allocated to one of three intervention groups and subjects participated as an entire team in either the control, plyometric or core stability program three times a week for four weeks.[19] The coaches were given an attendance log to monitor compliance of the athletes enrolled in the study. They were also provided an exercise protocol to follow which included directions to give the athletes on how to perform the exercises as well as pictures and visual keys to look for while they supervised the sessions. Additionally, a certified athletic trainer from each school observed one session a week and filled out an assessment form to subjectively determine how the coaches and athletes responded to the intervention program. The plyometric and core stability programs were designed to be completed in no more than 20 minutes and with no additional exercise or rehabilitation equipment required.

The plyometric program (see Table 5.) consisted of a series of double and single limb jumps as well as skipping exercises focused on quality takeoff and landing form. The exercises included were adapted from various ACL prevention and neuromuscular training programs where the emphasis was placed on soft, balanced, controlled landing.[12, 13, 20-22] The plyometric program was divided into two phases with a progression occurring after the sixth session where the difficulty level increased by incorporating more single-leg landings and multi-planar movements. The program included supervision from the coaching staff throughout in addition to the subjects performing the exercises in pairs to reinforce the use of correct form. Exercises for the core stability group (see Table 6.) were targeted at improving coordination of the abdominal and lumbar stabilizers, hip extensors, external rotators and abductors.[23-25] After completion of six sessions subjects progressed to a second set of exercises that incorporated more challenging positions and combining maneuvers from phase one that focused on increasing trunk stability with more traditional strength gain exercises.

Table 5. Plyometric Group Exercise Progression

Phase 1 (Weeks 1 & 2)	**Sets / Reps**
Forward / backward single-leg line jumps	30 forward / backward
Side to side single-leg line jumps	30 side / side
High skips	Field length
Distance skips	Field length

Broad jumps*	2 x 10
Tuck jumps*	2 x 10
Alternating single-leg lateral jumps	2 x 10
Phase 2 (Weeks 3 & 4)	
Forward single-leg hop, hop, hop & stick*	10
Squat jumps*	2 x 10
Single-leg max vertical jump*	10
Single-leg jump for distance*	10
Broad jump, jump, jump, vertical jump*	5
180 jumps*	10
R/L only single-leg lateral jumps*	10

* Indicated exercises where the athletes worked in partners to help increase awareness of correct landing posture.

Table 6. Core stability group exercise progression.

Phase 1 (Weeks 1 & 2)	**Sets / Reps**
Abdominal draw-in	10 x 5 seconds
Side plank knee bent	2 x 20 seconds
Side lying hip abduction	3 x 10
Side lying hip external rotation (clam shells)	3 x 10
Crunches	3 x 15
Lumbar extension hands on head	3 x 10
Walking lunges hands on hips	Field length
Phase 2 (Weeks 3 & 4)	
Hamstring bridge with abdominal draw-in	3 x 20 seconds
Side plank legs extended with abdominal draw-in	2 x 10 seconds
Quadruped hip extension/external rotation/abduction	2 x 10
Crunches opposite elbow to knee	3 x 15
Lumbar extension arms straight	3 x 10
Squats with arms overhead*	3 x 10
Lunges with ball toss*	3 x 10

* Indicated exercises where the athletes worked in partners to help increase awareness of correct form.

Data Analysis

A force platform (AMTI OR 6-7, Watertown, MA, USA) was used to collect raw ground reaction forces at 1000 Hz and interfaced with a 10 camera (M2 series) motion analysis system (Oxford Metrics Ltd, Oxford, UK) to capture the 3-D position of markers at 120 Hz. Kinematic data were collected at 250 Hz. A Woltring filtering technique was applied to the marker data with a predicted MSE value of 20 according to recommended

Vicon processing protocols (Vicon Peak, Centennial, CO, USA). Ground reaction force data were synchronized with the Vicon system for simultaneous collection. The ground reaction forces were collected at 1000 Hz frequency and filtered using a low-pass, anti-aliasing filter with a cutoff frequency of 30 Hz. Points of initial contact and toe-off were visually identified using the ground reaction force and all data were normalized to 101 data points for the stance phase. The ground reaction force data was downsampled prior to being combined with the marker data and processed using Plug-in Gait to determine hip and knee joint moments. Moments were normalized to a product of mass and height and reported in Newton-meters per kilogram·meter (Nm/kgm). Joint moment calculations were based on the following parameters: 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.

Statistical analysis

Comparisons between groups were made at pre-test, post-test and on change scores following the intervention. Group means and associated 95% confidence intervals (CI) were calculated for each percent of the stance phase. Curve analysis was used to determine points during stance phase of landing where significant differences were present between groups. An alpha level of P <0.05 was performed across the stance phase to identify time periods where the CI bands for the two groups did not cross[26]. Confidence interval comparison allows for group comparisons to be made throughout the duration of the stance phase rather than comparing peak points as these tend to represent only a discrete minimum or maximum value of the stance phase. The kinematic dependent variables were mean joint angles for trunk lateral flexion (the position of the trunk relative to the pelvis), hip flexion, internal rotation and adduction, knee flexion, valgus and internal rotation. The kinetic dependent variables were mean external moments for hip flexion, hip internal rotation and adduction as well as knee flexion, abduction and internal rotation throughout the stance phase of the SSC. Effect sizes were calculated for joint moments on the point where the mean difference between pre- and post-test scores were the largest and where the CI bands did not cross. Cohen's d was calculated by taking the mean difference (from pre and post-tests in this case) and dividing by the standard deviation of the control group. An effect size of > 0.8 with a confidence interval that does not cross 0 is considered a strong effect that can be interpreted as clinically meaningful. Furthermore descriptive statistics for age, height and mass and sessions completed were compared between groups using separate ANOVA models with Tukey post-hoc comparisons.

RESULTS

There were no differences between groups at pre-test for age, mass or height ($P > 0.05$); however, there was a significant main effect between groups for mass at post-test ($F_{2,20}= 3.25$, $P = 0.049$). Tukey post-hoc test revealed the core stability group had a significantly greater mass than the control group (see Table 7). All subjects enrolled in the plyometric group completed 100% of the intervention sessions and all subjects in the core stability group completed at least 9 out of 12 (9.5 $\pm$ 0.5 sessions). Significant findings for within group comparisons between pre- and post-test where intervals during the stance phase the CI bands did not overlap are reported in Table 8.

Table 7. Group demographic means and standard deviations (SD) at pre- and post-test.

	Control	Plyometric	Core Stability
Pre-test			
Age (yr)	14.8 (0.4)	15.1 (1.1)	14.5 (0.8)

Height (cm)	168.6 (4.5)	172.1 (8.0)	169.2 (7.3)
Mass (kg)	52.1 (6.1)	62.6 (8.8)	56.8 (7.9)
Post-test			
Age (yr)	14.8 (0.4)	15.3 (1.04)	14.5 (0.8)
Height (cm)	168.9 (4.4)	172.5 (8.4)	169.3 (7.4)
Mass (kg)	52.0 (5.7)*	64.0 (9.1)	57.4 (7.8)*

* Indicates a statically significant difference between groups at post-test, $F_{2,20} = 3.25$, $P = 0.49$.

Table 8. Significant differences for SSC kinematic and kinetic change scores for all groups. Angles were reported in degrees and moments in Nm/kgm. Cohen's d effect size was calculated from the point in the stance phase where the CI bands did not cross and the mean difference was the largest. Effect sizes were only calculated for the kinetic variable to enhance the clinical interpretation of the data.

Group	**Variable**	**% Stance Phase**	**Mean Difference (SD)**	**Effect Size: d (CI)**
Control	Hip flexion angle	1-19	-21.5 (0.5)	
Plyometric	Hip flexion angle	1-12	-13.5 (0.3)	
Core stability	Hip flexion angle	1-15	-16.5 (0.3)	
Control	Knee flexion angle	25-35	-9.7 (0.2)	
		85-101	16.1 (2.9)	
Plyometric	Knee flexion angle	84-101	18.8 (3.1)	
Core stability	Knee flexion angle	13-49	-8.9 (1.0)	
		88-101	12.9 (1.9)	
Core stability	Hip flexion moment	19-21	-0.54 (0.05)	-1.54 (-2.56, -0.36)*

* A strong effect size where the CI did not cross 0

All 3 groups had a significant decrease in hip flexion angle ($P < 0.05$). The control group showed a decrease from 1-19% of stance phase where the mean difference for this period of time was -21.5 $\pm$ 0.5 degrees (see Figure 17). Similarly, the plyometric group had a decrease from 1-12% of stance and the mean difference from pre- to post-test was -13.5 $\pm$ 0.3 degrees (see Figure 18). Finally, the control group demonstrated a mean difference of -16.5 $\pm$ 0.3 degrees between 1-15% of the stance phase (see Figure 19).

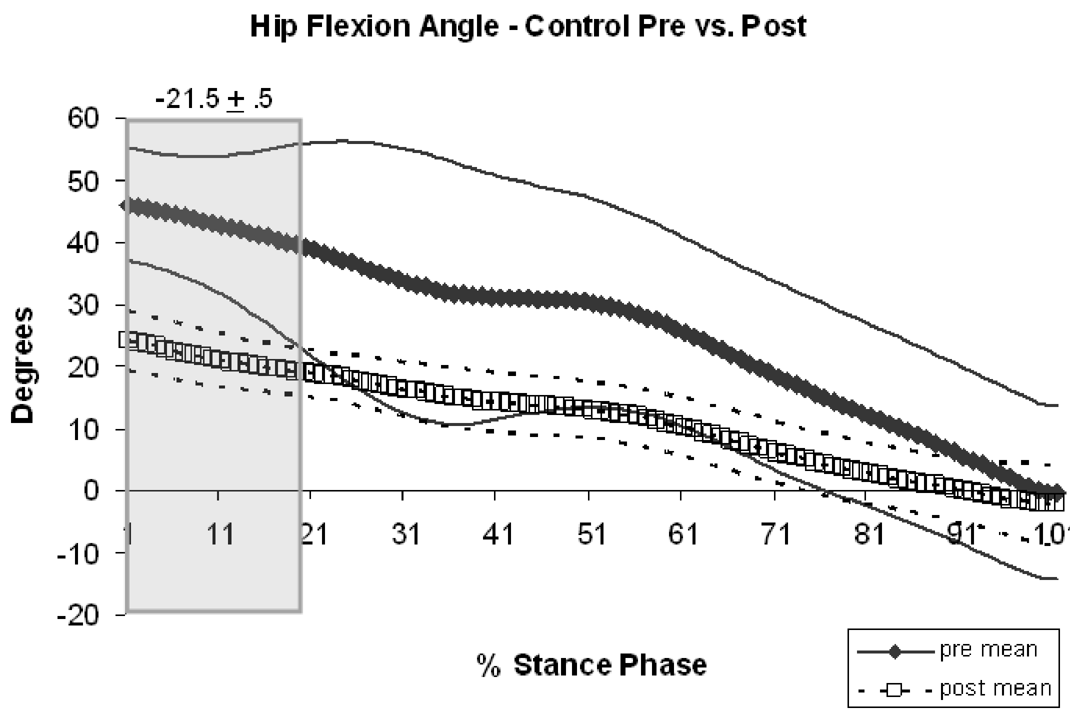

Figure 17. Control Group Change Scores for SSC Hip Flexion Angle
Control group change score from pre-test to post-test for hip flexion angle. The lines surrounding the mean scores represent the 95% confidence intervals. The post-test mean was significantly lower from 1-19% of the stance phase. The mean difference for this window was -21.5 $\pm$ 0.5 degrees, P <0.05.

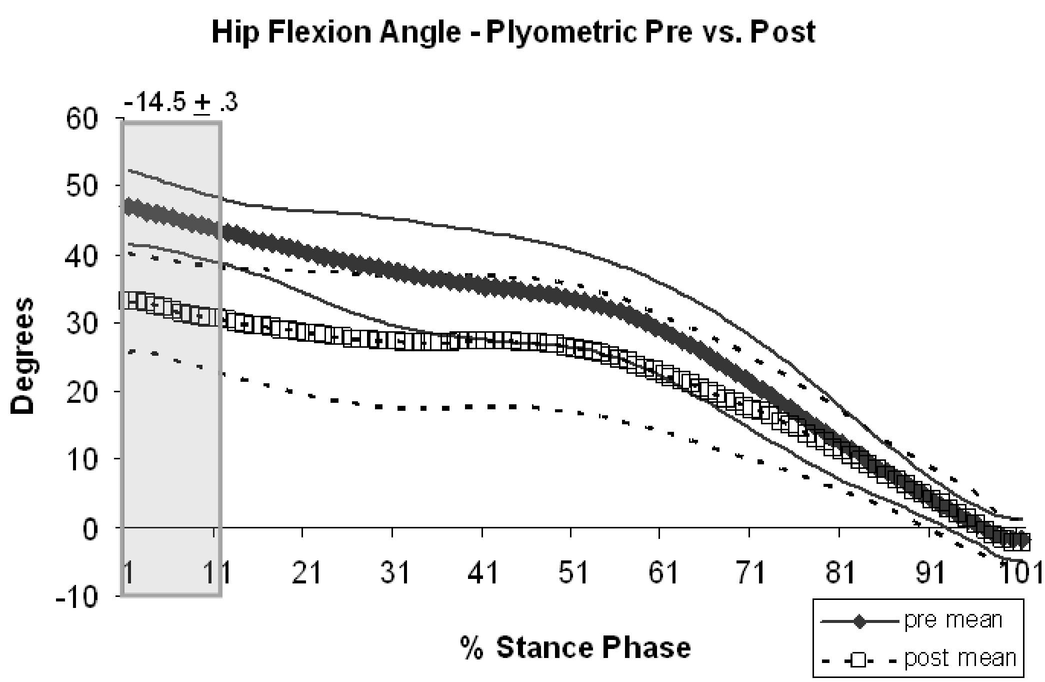

Figure 18. Plyometric Group Change Scores for SSC Hip Flexion Angle

Plyometric group change score from pre-test to post-test for hip flexion angle. The lines surrounding the mean scores represent the 95% confidence intervals. The post-test mean was significantly lower from 1-12% of the stance phase. The mean difference for this window was -13.5 ± 0.3 degrees, *P* <0.05.

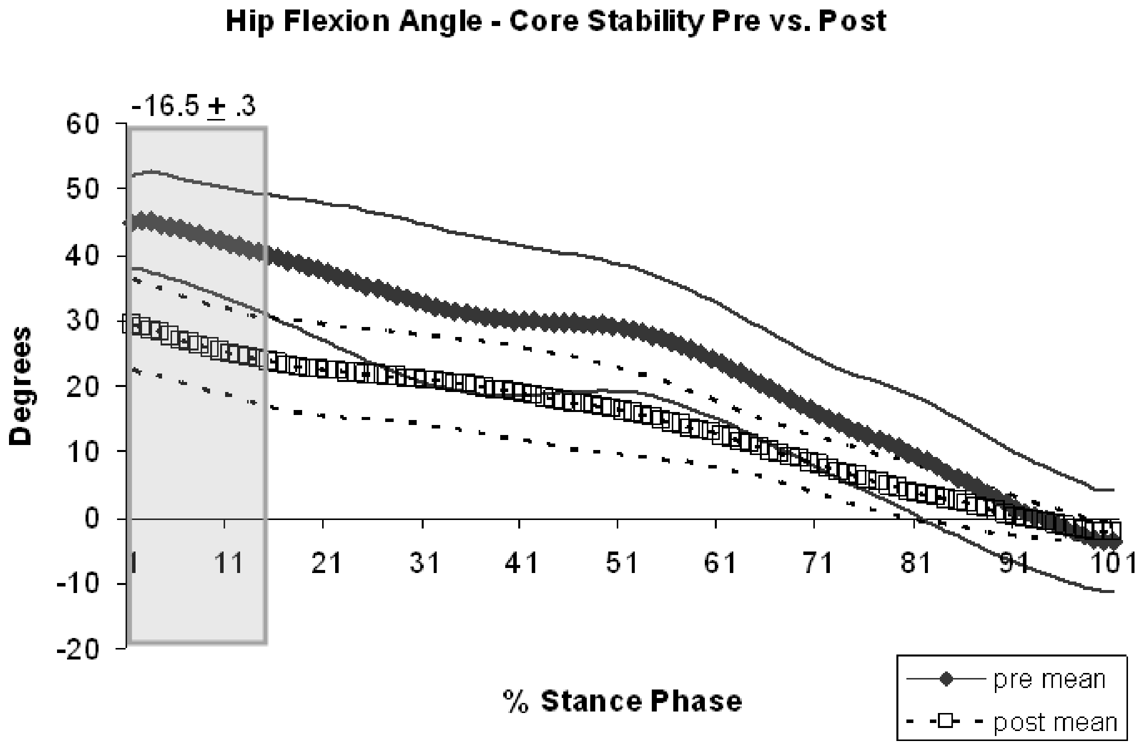

Figure 19. Core Stability Group Change Scores for SSC Hip Flexion Angle
Core stability group change score from pre-test to post-test for hip flexion angle. The lines surrounding the mean scores represent the 95% confidence intervals. The post-test mean was significantly lower from 1-15% of the stance phase. The mean difference for this window was -16.5 ± 0.3 degrees, *P* <0.05.

A significant change in the knee flexion patterns was also shown for all 3 groups (*P* < 0.05). The control group demonstrated a decrease in knee flexion from 25-35% of the stance phase and then an increase in knee flexion angle during the final stage of cutting from 85-101% (see Figure 20). The mean difference for these 2 intervals were -9.7 ± 0.2 and 16.1 ± 2.9 degrees respectively. The plyometric group only had a significant increase from the 84-101% window during the propulsion phase of the task where the mean difference was 18.8 ± 3.1 degrees (see Figure 21). The core stability group followed the same pattern as the control group consisting of a decrease in knee flexion from 13-49% of stance and then an increase from 88-101%. The mean difference for these 2 windows were -8.9 ± 1.0 and 12.9 ± 1.9 degrees respectively (see Figure 22).

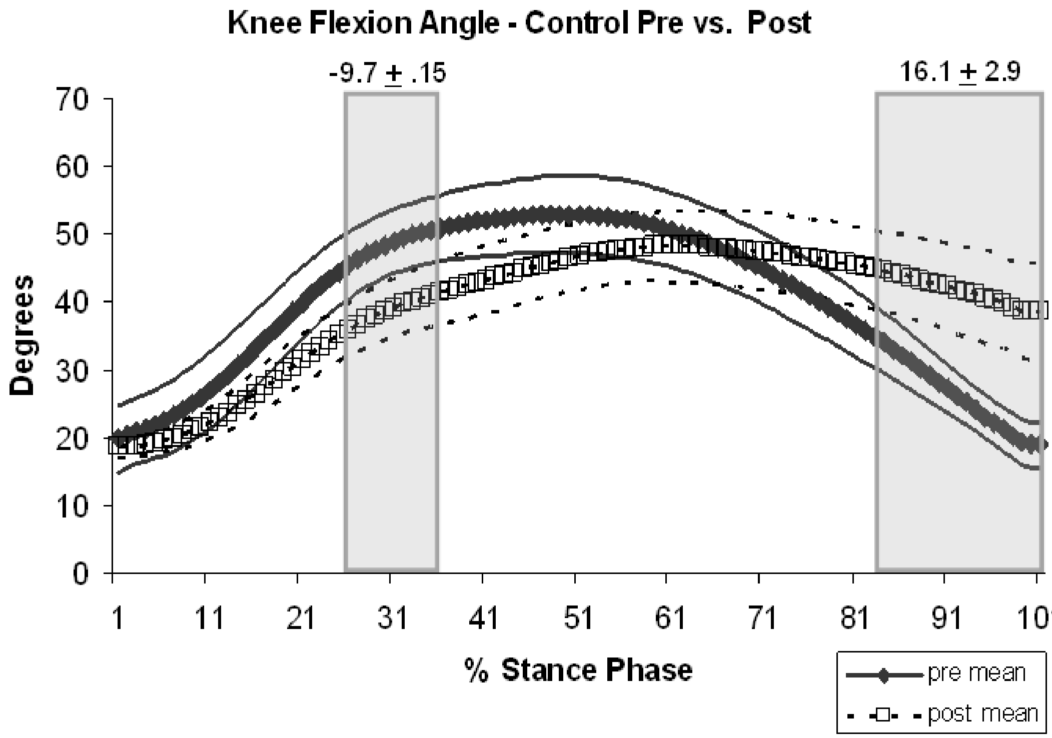

Figure 20. Control Group Change Scores for SSC Knee Flexion Angle
Control group change score from pre-test to post-test for knee flexion angle. The lines surrounding the mean scores represent the 95% confidence intervals. The post-test mean was significantly lower from 25-35% of the stance phase and then higher from 85-101%. The mean difference for the window was -9.7 ± 0.2 and 16.1 ± 2.9 degrees respectively, *P* <0.05.

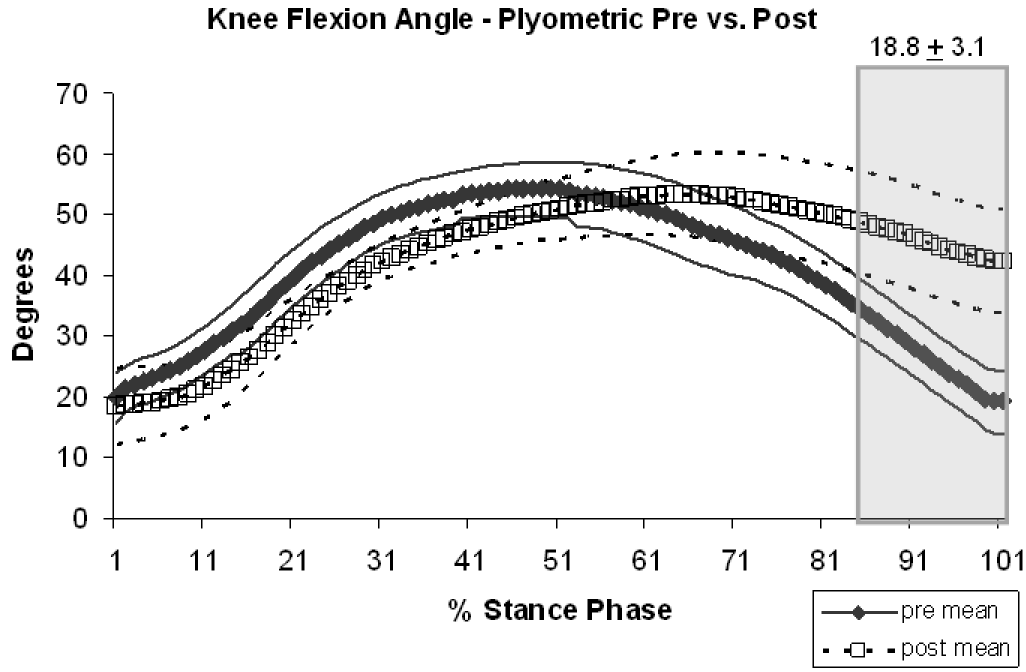

Figure 21. Plyometric Group Change Scores for SSC Knee Flexion Angle
Plyometric group change score from pre-test to post-test for knee flexion angle. The lines surrounding the mean scores represent the 95% confidence intervals. The post-test mean was significantly higher from 84-101% of the stance phase. The mean difference for the window was 18.8 $\pm$ 3.1, P <0.05.

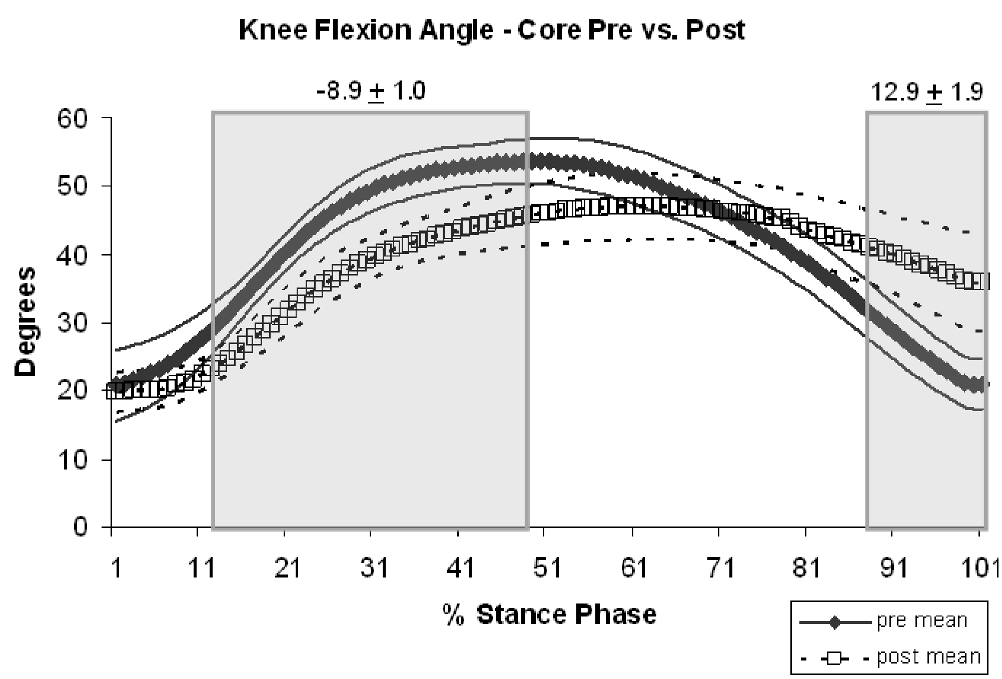

Figure 22. Core Stability Group Change Scores for SSC Knee Flexion Angle
Core stability group change score from pre-test to post-test for knee flexion angle. The lines surrounding the mean scores represent the 95% confidence intervals. The post-test

mean was significantly lower from 13-49% of the stance phase and then higher from 88-101%. The mean difference for the window was -8.9 ± 1.0 and 12.9 ± 1.9 degrees respectively, P <0.05.

The only finding for all the within group comparisons using the kinetic variables was a significant decrease in the hip flexion moment for the core stability group. This significant difference took place between 19-21% of the stance phase where a mean difference of -0.54 ± 0.05 Nm/kgm was shown (see Figure 23). In additional this mean difference translated as strong effect size, d = -1.54 (-2.56, -0.36).

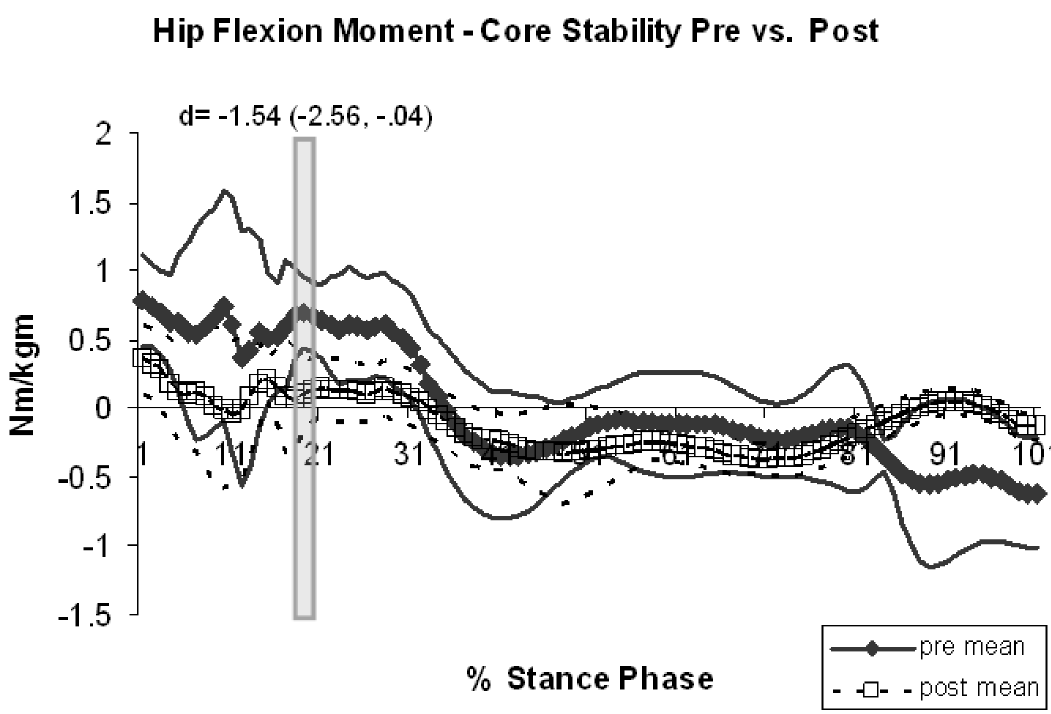

Figure 23. Core Stability Group Change Scores for SSC Hip Flexion Moment
The core stability group change score from pre-test to post-test for hip flexion moment. The lines surrounding the mean scores represent the 95% confidence intervals. The post-test mean was significantly lower from 19-21% of the stance phase The first window had a mean difference of -0.54 ± 0.05 Nm/kgm, P <0.05. There was a strong effect size that did not cross 0 as represented by a Cohen's d = -1.54 (-2.56, -0.36).

DISCUSSION

The results of this study did not support our hypotheses. The primary finding suggests that the intervention programs did not influence SSC kinematics in the sagittal plane in a way that differed from the control group as a result of 4 weeks of practice. Specifically, the change in hip flexion pattern was extremely similar for all subjects regardless of plyometric or core stability exercises. All groups were significantly less flexed at initial contact through the early part of weight acceptance and deceleration; however, they maintained the same amount of hip extension at push off. Furthermore, the shape of the knee flexion curve changed from pre-test to post-test in all 3 groups in the final stage of the stance phase indicating the subjects all remained in a more knee flexed position during push off at post-test (see Figures 20-22). Because there are no other studies that graphically represent knee flexion values during a SSC, there are no data to compare the results of this study to determine whether the knee flexion values are within a normal range. The control and core stability groups both experienced a decrease in flexion during the weight acceptance phase in contrast to the plyometric group as they maintained a similar amount of knee flexion during this window. It is plausible that the emphasis placed on knee flexion during plyometric training is related to the sustained amount of knee flexion between testing sessions during the weight acceptance phase of the SSC.

The results of the sagittal plane kinematics suggest a learning curve associated with performing the SSC. An effort was made to minimize this phenomenon by providing all subjects with oral instruction as well a demonstration on how to perform the SSC. Furthermore, prior to testing the subjects underwent practice trials until they notified the test administrator they felt comfortable with the task. McLean et al.[51] found a strong linear relationship for adult female athletes between years of sport experience and inter-trial variability during a SSC. This relationship suggested that the fewer years a subject had in athletic participation the higher her inter-trial variability. This finding may help to explain the changes seen over time where as the subjects continued to participate in soccer and lacrosse (both sports that incorporate the SSC), their individual variability may have decreased.

The core stability group had a significant decrease in the external hip flexion moment from 19-21% of the stance phase. This finding has been previously shown in the jump landing literature[13] and has been attributed to an increased efficiency of the gluteal muscles to eccentrically control the collapse into hip flexion following neuromuscular training.[52] Pollard et al.[52] compared male and female athletes during a SSC and found that females had significantly greater internal hip extensor moments (the equivalent to an external hip flexor moment) compared to males. Therefore, it may be that following core stability training the females in our study began to adopt a sagittal plane kinetic profile similar to that of male athletes. Future research may include the comparison of a male control group as well to provide more insight into this area.

Overall, this study had fewer significant findings than hypothesized. There is little previous research to compare as there are no other studies examining the effects of a neuromuscular intervention on trunk kinematics and 3-dimensional hip and knee biomechanics. One study[53] examined hip and knee sagittal plane kinematics in addition to electromyography variables during a SSC in adult elite female athletes before and after a season long comprehensive training program. There were no significant kinematic differences in this study which is contrary to our findings. However, the subjects served as their own controls during the previous season and subject kinematics were measured using electrogoniometers. Furthermore, the subjects were adult, elite female athletes and therefore it is realistic to assume they also had many more years experience in athletics suggesting a less pliable motor pattern.

Plyometric exercises are considered a staple in comprehensive neuromuscular training programs. In this study there were no significant changes demonstrated by the plyometric group independent from the control and core stability group. This data set is part of a larger scale study that included drop landing testing at the same time and found significant differences in both kinematic and kinetic variables at the knee joint. Therefore, the argument can be made that the neuromuscular gains acquired from the included plyometric training exercises do not necessarily translate to SSC movement patterns.

Movements that involve deceleration and a sudden change of direction such as during the SSC are hypothesized to cause noncontact ACL injuries. However, no known studies to date have reported biomechanical risk factors of a SSC established via a prospective research design as is the case in the jump landing literature.[9] This may be related to the controlled manner in which the SSC is performed, thereby not challenging the neuromuscular system to the same extent the drop jump landing task does. For our study, subjects performed the SSC between 4.0-5.0 m/s which for most subjects anecdotally equated to about 75% of a full sprint. This is in comparison to a drop jump landing where once the subject steps off the platform they have no control over how fast they land. Therefore a drop jump landing could potentially lead to greater external loads that must be resisted by the static and dynamic stabilizers to successfully accomplish the task. We propose that the nature of joint loading during a SSC would not necessitate a subject to utilize newly acquired neuromuscular coordination.

The results of this study are the first to try and demonstrate adaptations in trunk and 3-dimensional lower extremity biomechanics during sidestep cutting as a result of neuromuscular control-based interventions. In summary, the plyometric group demonstrated little change apart from the control group suggesting that the task may not challenge the neuromuscular system. The core stability group did show a decrease in the external hip flexor moment indicating an adaptation in sagittal plane loading at the hip potentially due to increased efficiency in hip extensor muscle function. However, this change did occur over a very short window of the stance phase. Overall, there were no considerable findings that occurred during the SSC that relate to clinically meaningful changes as a result of plyometric or core stability training.

MANUSCRIPT 3

THE RELATIONSHIP BETWEEN THE LATERAL STEPDOWN TEST AND LOWER EXTREMITY KINETICS AND KINEMATICS DURING A SPORT SPECIFIC TASK

ABSTRACT

Context: Anterior cruciate ligament (ACL) injuries are more common in adolescent and adult female athletes than males and are believed to be related to poor neuromuscular control. Research using motion analysis testing has identified trunk and lower extremity kinematic and kinetic variables associated with increased risk for anterior cruciate ligament injuries. Motion analysis testing is time consuming and requires expensive equipment. There is a need for a simple screening tool that can be utilized on a wide scale basis to identify those at risk for injury. The lateral stepdown test (LST) is a clinical tool used to assess lower extremity and trunk quality of movement. **Objective:** To determine the relationship between changes in the lateral stepdown test and lower extremity biomechanical measures after a 4 week neuromuscular control intervention. **Design:** Cohort study. **Setting:** High school athletic field and motion analysis laboratory. **Patients or Other Participants:** 24 healthy junior varsity female lacrosse and soccer players. **Intervention(s):** Independent variables were group (core stability, plyometric, control) and task (drop vertical jump and sidestep cut). Subjects performed 5 trials each of drop vertical jump (DVJ), sidestep cut (SSC) and LST before and after participating in a four week core stability or plyometric program. Trunk, hip and knee kinetics and kinematics were extracted and averaged for each group. The subjects' LST was scored from 0-6 points post-collection by a single examiner using videotape footage and a group mean was calculated. The LST classified trunk, pelvis plane and knee movement as well as single-leg balance where a higher score represented poorer movement quality. **Main**

Outcome Measures: Dependent variables were change scores for mean peak trunk and lower extremity kinetic and kinematic variables during the DVJ and SSC and overall score of the LST. A Pearson Product Moment correlation was run to determine the relationship between kinetics and kinematics with LST score for each group. Additionallly, a Spearman for all nonparametric values was also run. **Results:** No significant correlations were found between the LST and peak kinematic and kinetic variables during a DVJ and SSC, $P > 0.05$. No significant differences were shown within groups on the LST score following the intervention training. **Conclusions:** The LST may not be a good clinical measure for predicting function during a DVJ or SSC. Further research is needed with a larger, more diverse subject population.

INTRODUCTION

A recent meta-analysis investigating noncontact anterior cruciate ligament (ACL) injury rates reported that females are three times more likely to suffer an ACL injury compared to males.[54] Links between neuromuscular dysfunction of the proximal stabilizers and lower extremity injury has been identified in the literature. Prospective laboratory studies identified trunk neuromuscular control deficits[11] and biomechanical factors[9] associated with increased risk for ACL injury in females. Females who performed a drop vertical jump (DVJ) with greater knee abduction torque and knee valgus angles comprised of both knee and hip coronal plane movement were at greater risk for a noncontact ACL injury.[9] Cadaver models have shown that when compared to neutral loads, forces applied lateral to the sagittal plane (valgus) increase the strain on the ACL upwards of 30%.[8] Additionally, a study performed on collegiate athletes demonstrated that lateral angular trunk displacement was the greatest predictor of knee ligament injury. This finding may be due to lateral trunk lean placing increased loads on the knee joint in the coronal plane, ultimately resulting in valgus collapse.[11]

Laboratory based research is central to understanding underlying mechanisms, identifying risk factors, and establishing differences between specific populations in regards to ACL injury. However, it is also time consuming and requires expensive, highly technical equipment thus limiting the feasibility of using these tools to identify individuals at risk for injury. There is a need for a clinical tool that can be used to screen athletes and identify those who may benefit from participation in a neuromuscular control program. Hewett et al[18] proposed the use of a portable force plate as a means for identifying athletes who demonstrate greater vertical ground reaction forces during a DVJ. While the use of dynamic force plate testing is possible, it requires relatively expensive equipment and the knowledge to collect and interpret the data that may not be accessible to clinicians at all levels.

The lateral stepdown test (LST) was designed to evaluate quality of movement in regards to lower extremity neuromuscular control.[55] It assesses unilateral neuromuscular control measures associated with ACL injury mechanisms including balance, trunk lean, pelvis movement, and knee valgus collapse during a controlled dynamic movement. Moreover, the LST can be implemented into a clinical setting with the possibility of screening for injury risk during pre-participation physical exams as well as quantifying improvement in lower extremity and trunk neuromuscular control.

We propose that the neuromuscular patterns used to control the trunk, hip, and knee joint during the LST are similar to the patterns utilized during dynamic tasks such as a DVJ or sidestep cut (SSC). Theoretically, if an individual demonstrates poor eccentric control of the hip and thigh musculature during the LST then they may also exhibit neuromuscular control patterns associated with increased ACL risk during high speed and high force generating task. Lawrence et al.[34] grouped healthy females with decreased hip external rotation strength and found they also landed with an increased external knee valgus moment and a decreased knee flexion moment. These findings suggest that diminished strength of the hip musculature places females at greater risk for ACL injury due to a higher quadriceps muscle moment and a decreased ability to control frontal plane loading.[9, 34]

Injury prevention programs stem from the identification of neuromuscular control deficits demonstrated by at risk populations.[21] These programs often include a combination of flexibility, strength, balance, agility and plyometric exercises in an attempt at improving lower extremity and trunk dynamic movement patterns. While the shotgun approach of these prevention programs has demonstrated positive results in decreasing injury risk[20, 40-42, 56] and improving biomechanical patterns[13, 15, 17, 30], it is unknown which component is responsible for the noted changes. Zazulak et al[57] identified the need for specific trunk stability training programs used in conjunction with repeated neuromuscular testing in order to determine the relationship between trunk stability and ACL injury risk. The LST may serve as a test that can be easily repeated where improvement in quality of movement and may help clinicians determine whether an individual has progressed following training.

Therefore the purpose of this study was two-fold: first, to identify a relationship between lower extremity and trunk joint mechanics (forces and range of motion) during a sport specific task and the score of the LST; and secondly, to determine whether a four week training program focused either on plyometric or core-stability exercises would improve performance of the LST. We hypothesized that there would be a significant correlation between the LST score and the hip internal rotation, knee internal rotation, and knee valgus angles as well as the external rotation and adduction moments at the hip and internal rotation and valgus moments at the knee during the DVJ. Secondly, we expected to see no significant correlations between the LST score and trunk, hip, and knee kinematics as well as kinetics during the SSC. Finally, we hypothesized there would be significant decreases in the LST group means following the 4 week intervention for both the plyometric and core stability groups.

METHODS

This study utilized a cohort design where the independent variables tested were group (core stability, plyometric and control) and task (DVJ and SSC). The dependent variables were lower extremity kinematic and kinetic variables as well as overall score on the LST. The kinematic variables assessed were lateral spine angle, hip flexion, internal rotation and adduction as well as knee flexion, internal rotation and valgus. External joint moments for hip flexion, internal rotation and adduction, knee flexion, internal rotation and valgus were also collected.

Subjects

Twenty four females volunteered for this study from three local area high schools. Subjects (14.8 $\pm$ 0.8 yrs, 1.7 $\pm$ .07 m, 57.7 $\pm$ 8.5 kg) were actively participating on a junior varsity lacrosse or soccer team had no history of trunk or lower extremity surgery and no previous injury within the past six weeks that limited participation in athletics or physical activity. Furthermore subjects had no neurological disorders that may affect balance and had not participated in a formal core stability or plyometric training program as determined by parent and subject self-report. All subject's parent or guardian signed an informed consent form and the subject read and signed an informed assent form for this study which was approved by the University of Virginia Institutional Review Board for Health Sciences Research (IRB-HSR #14039).

Instrumentation

Kinematic data was obtained using a 10 camera Vicon 624 motion analysis system (Vicon Peak, Lake Forest, CA, USA). Synchronized kinetic data was captured using a conventional in-ground AMTI force plate (AMTI, Watertown, MA, USA). Kinematic and data were captured at 250 Hz and kinetic data were captured at 1000 Hz. Digital video during the LST was captured using a Canon PowerShot *SD1100 IS* Digital Elph (Canon USA, Inc., Lake Success, NY, USA) The LST was used as an indicator of lower extremity and trunk neuromuscular control.[55] Subjects were scored on 5 criteria from digital video captured of them performing the test.

Testing Procedures

Subjects reported to the motion analysis laboratory for pre-testing. Anthropometric measurements including height, mass, leg length, knee and ankle width were taken and recorded. Subjects were fitted with Brooks running shoes (Brooks® Sports, Inc., Bothell, Washington, USA) model Radius 06 running shoes and had retroreflective markers placed bilaterally on the following anatomic landmarks to represent lower extremity segments: 2nd metatarsal head, calcaneus, lateral malleolus, lateral midshank, lateral femoral condyle and lateral midthigh in accordance with the Vicon Clinical Manager (Vicon, Oxford Metrics, London, UK) protocol. A four marker cluster was secured around the hips over the sacrum using elastic tape. To capture trunk motion markers were also placed on the sternum, xiphoid process, C7 and T10 spinous processes and bilateral acromion processes.

The order of task for the DVJ, SSC and LST was counterbalanced using a Latin Square where five consecutive trials of each were collected. Subjects were instructed on how to perform each task and a demonstration was given to ensure comprehension.

Subjects were allowed to practice each of the three tasks until they felt comfortable. For the DVJ, subjects were directed to stand on a 25 cm box and leading with their right leg step off the box landing equally on both feet. Both feet contacted separate embedded force plates and immediately upon contacting the ground the subject performed a maximal vertical jump off both legs. The height of the box was chosen because it is the average maximum vertical jump height achieved by adolescent females when performing a DVJ.[18] Kinetic and kinematic data were collected for all subjects and the mean values were used for analyses.

Subjects performed the SSC by running at 4.0-5.0 m/s pace down a 10 meter runway and contacting their right foot on an embedded force plate and changing direction to the left. Tape was placed on the ground between 35-55 degrees creating an alley for subjects to run through. Approach speed was calculated by measuring the velocity of the sacral cluster marker as a representation of center of mass velocity. Subjects performed five acceptable trials requiring a clean strike of the foot on the force plate, visualization of all markers and an approach speed at the pre-determined velocity. Kinetic and kinematic data were collected for all subjects and the mean values were used for analyses.

Lastly the LST was explained and demonstrated for the subject. The subject was instructed to begin standing on a 20 cm box on her right leg and hands placed on her hips. The subject was told to bend her right knee until the sole of her left shoe lightly touched the ground and then straighten her knee, returning to the start position. This movement was repeated five consecutive times. Subjects were recorded using a digital camera (Canon, PowerShot *SD1100 IS* Digital Elph) and kinematic data were collected. The LST was scored by a single assessor who was blinded to the intervention group assignment. The assessor graded the subjects using a rubric where 0-1 points was considered good, 2-3 points was medium and 4-6 points was poor movement quality. Subjects' performance was viewed and scored based on the following criteria: 1 point for use of an arm strategy to maintain or recover balance, 1 point for side trunk lean, 1 point for the pelvis rotating or elevating with respect to the other side 1 point for failure to maintain steady unilateral stance and 1 or 2 points for the tibial tuberosity deviating medial to a vertical line cross the 2nd toe and medial border of the foot respectively. The subject either received 1 or 2 points for positioning of the knee (see Table 9) .[55]

Table 9. The criteria used to score the LST. Subjects received either a 0 or 1 for all of the variables except for knee position where they could be given a score of 0, 1 or 2 depending on the position of the tibial tuberosity in reference to the foot.

Step Down Test (20 cm/8 in box)	**Possible Points**
Arm Strategy: If subject used an arm strategy in an attempt to recover balance	1 point
Trunk Movement: Trunk lean to side	1 point
Pelvis Plane: If pelvis rotated or elevated one side compared with the other	1 point
Knee position: Knee deviates medially and tibial tuberosity crossed an imaginary vertical line over	
The 2nd toe	1 point
Medial border of the foot	2 points
Maintain Steady Unilateral Stance: Stepped down on the non-tested side, or if the test limb became unsteady (ie. wavered from side to side on the tested side)	1 point

	TOTAL

Each subject repeated the testing following a four week intervention. All subjects completed testing within a 10 day period following the final session of intervention exercises. Subjects were re-instructed on how to perform the DVJ, SSC and LST and allowed to re-acquaint themselves with the tasks. Following the completion of the post-testing session subjects were dismissed from the study (see Figure 24).

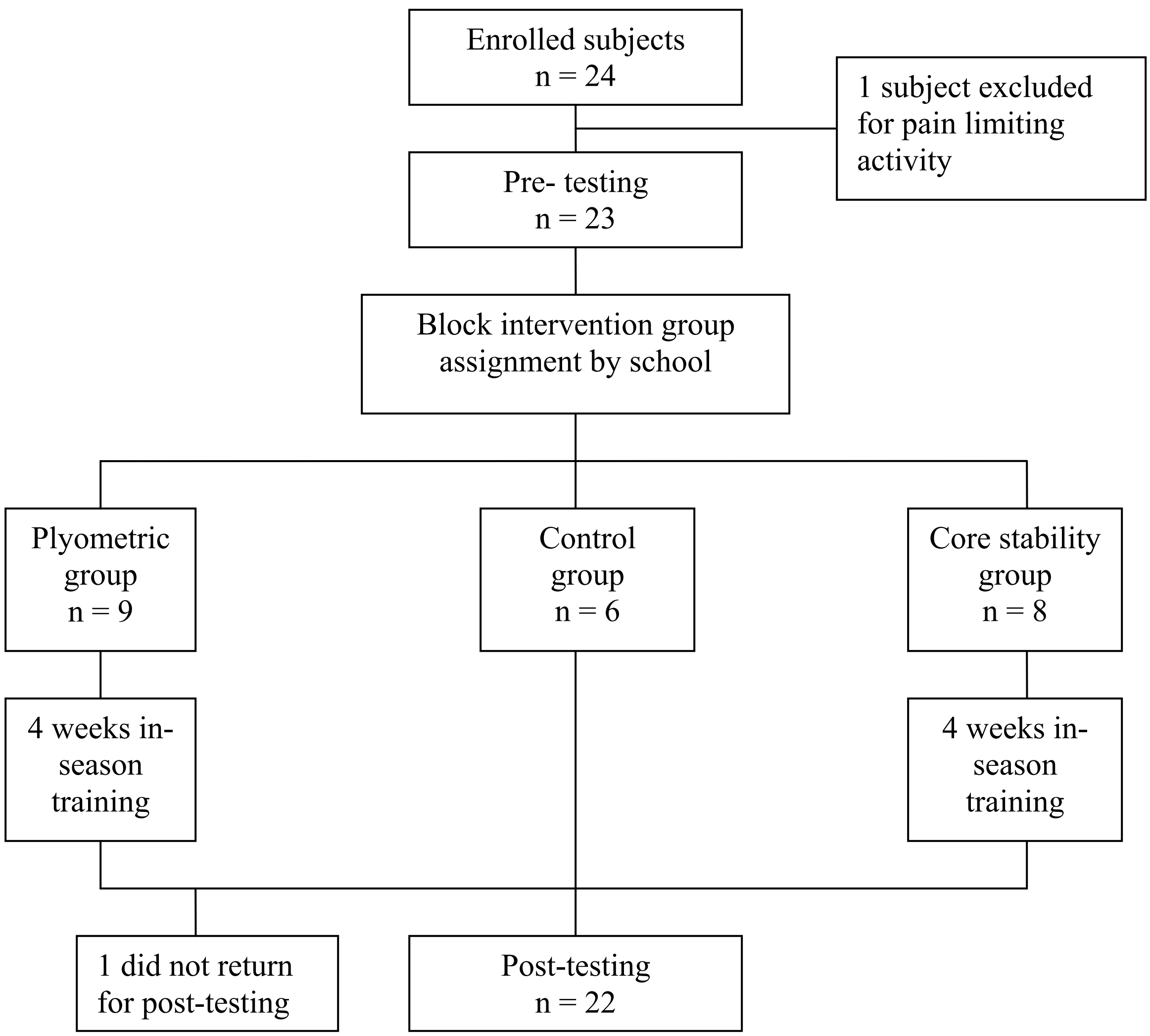

Figure 24. CONSORT flowchart outlining the progression of testing order and subject dropout.

Intervention programs

Teams were allocated to one of three intervention groups (control, plyometric or core stability) and subjects participated as an entire team three times a week for four weeks.[19] The coaches were given an attendance log to monitor compliance of the athletes enrolled in the study. They were also provided an exercise protocol to follow which included directions to give the athletes on how to perform the exercises as well as pictures and visual keys to look for while they supervised the sessions. Additionally, a certified athletic trainer from each school observed one session a week and filled out an assessment form to subjectively determine how the coaches and athletes responded to the intervention program. The plyometric and core stability programs were designed to be completed in no more than 20 minutes and with no additional exercise or rehabilitation equipment required.

The plyometric program (see Table 10.) consisted of a series of double and single limb jumps as well as skipping exercises focused on quality takeoff and landing form. The exercises included were adapted from various ACL prevention and neuromuscular training programs where the emphasis was placed on soft, balanced, controlled landing.[12, 13, 20-22] The plyometric program was divided into two phases with a progression occurring after the sixth session where the difficulty level increased by incorporating more single-leg landings and multi-planar movements. The program relied upon peer critique to reinforce subjects were performing the exercises with correct form. Exercises for the core stability group (see Table 11.) were targeted at improving strength of the abdominal and lumbar stabilizers, hip extensors, external rotators and abductors.[23-25] After completion of six sessions subjects progressed to a second phase of exercises that incorporated more challenging positions and combining maneuvers from phase one that focused on increasing trunk stability with more traditional strength gain exercises.

Table 10. Plyometric Group Exercise Progression

Phase 1 (Weeks 1 & 2)	Sets / Reps
Forward / backward single-leg line jumps	30 forward / backward
Side to side single-leg line jumps	30 side / side
High skips	Field length
Distance skips	Field length
Broad jumps*	2 x 10
Tuck jumps*	2 x 10
Alternating single-leg lateral jumps	2 x 10
Phase 2 (Weeks 3 & 4)	
Squat jumps*	2 x 10
Forward single-leg hop, hop & stick*	2 x 10
Single-leg max vertical jump*	10
Single-leg jump for distance*	10
Broad jump, jump, jump, vertical jump*	5
180 jumps*	10
R/L only single-leg lateral jumps*	2 x 10

** Denotes partner watching

Table 11. Core Stability Group Exercise Progression

Phase 1 (Weeks 1 & 2)	Sets / Reps
Side plank knee bent	3 x 20 seconds
Abdominal draw-in	4 x 10 seconds
Side lying hip abduction	4 x 10 seconds
Side lying hip external rotation (clam shells)	4 x 10
Crunches	4 x 15
Lumbar extension hands on head	4 x 10
Walking lunges hands on hips	Field length
Phase 2 (Weeks 3 & 4)	
Side plank legs extended with abdominal draw-in	3 x 20 seconds
Hamstring bridge with abdominal draw-in	4 x 10
Quadruped hip extension/external rotation/abduction	4 x 10
Crunches opposite elbow to knee	4 x 15
Lumbar extension arms straight	4 x 10
Squats with ball toss*	4 x 10
Lunges with ball toss*	4 x 10

Data analysis

A force platform (AMTI OR 6-7, Watertown, MA, USA) was used to collect raw ground reaction forces at 1000 Hz and interfaced with a 10 camera (M2 series) motion analysis system (Oxford Metrics Ltd, Oxford, UK) to capture the 3-D position of markers at 120 Hz. Kinematic data were collected at 250 Hz. A Woltring filtering technique was applied to the marker data with a predicted MSE value of 20 according to recommended Vicon processing protocols (Vicon Peak, Centennial, CO, USA). Ground reaction force data were synchronized with the Vicon system for simultaneous collection. The ground reaction forces were collected at 1000 Hz frequency and filtered using a low-pass, anti-aliasing filter with a cutoff frequency of 30 Hz. Points of initial contact and toe-off were visually identified using the ground reaction force and all data were normalized to 101 data points for the stance phase. The ground reaction force data was downsampled prior to being combined with the marker data and processed using Plug-in Gait to determine hip and knee joint moments. Moments were normalized to a product of mass and height and reported in Newton-meters per kilogram·meter (Nm/kgm). Joint moment calculations were based on the following parameters: 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.

Statistical analysis

Pre-test data means and standard deviations were calculated for kinetic and kinematic variables for each subject. Data was tested for normality and identified as skewed and/or kurtotic. One Pearson Product Moment correlation matrix was used to determine the relationship between kinematic, kinetic and LST scores during a DVJ.

Similarly, a separate Pearson Product Moment correlation matrix was used to determine the relationship between kinematic, kinetic and LST scores during a SSC. Significant correlations from the Pearson Product Moments were squared to represent the percent variance in the kinetic and kinematics explained by the variance in the LST score. Separate Spearman Rho Correlations were calculated for the variables that were identified as non-parametric for the DVJ and SSC. The *a priori* level for all correlations was set at $P \leq 0.05$ (see Table 12). Dependent t-tests were run to determine whether within group differences were present for the LST scores following the intervention. Finally Cohen's d effect sizes were calculated to determine clinical relevance for the LST scores. Data were analyzed using the Statistical Package for Social Sciences (SPSS version 16.0; SPSS Inc., Chicago, IL, USA) for Microsoft Windows XP.

RESULTS

Seven total variables were identified as non-parametric with a skewness or kurtosis value of >1.0 (see Table 12). No significant correlations were found between the LST score and any of the kinematic or kinetic variables during either the DVJ or SSC, $P > 0.05$. Finally no significant differences were shown within groups for the LST score, $P > 0.05$ and Cohen's d effect sizes were also non-significant indicating none of the groups showed improvement following the intervention program.

Table 12. Correlation coefficients and significance between the LST score and peak trunk, hip and knee kinematic and kinetic variables during a DVJ and SSC for all subjects.

	DVJ correlations	**Sig.**	**SSC correlations**	**Sig.**
Kinematic & kinetic variables	**LST score**		**LST score**	
Lateral spine flexion angle	-0.09	.72	0.003	0.99
Hip flexion angle	-0.252	0.3	0.019*	0.36
Hip adduction angle	0.145*	0.52	0.063	0.78
Hip internal rotation angle	0.109	0.67	-0.244	0.26

Knee flexion angle	-0.346	.15	-0.21	0.34
Knee valgus angle	-0.174*	0.48	-.209	0.34
Knee internal rotation angle	-0.011	0.96	0.361	0.09
Hip flexion moment	-0.236	0.33	-0.230	0.30
Hip adduction moment	0.144	0.56	0.21*	0.35
Hip internal rotation moment	-0.421*	0.07	-0.11	0.63
Knee flexion moment	0.048*	0.85	-0.18	0.42
Knee valgus moment	0.037	0.88	0.054	0.81
Knee internal rotation moment	-0.016	0.95	0.331*	0.13

* Indicates a non-parametric correlation coefficient.

Table 13. Descriptive statistics for the variables included in the DVJ correlation. Note a skewness or kurtosis value >1.0 is indicative of not normally distributed data. A coefficient of variation > 0.25 represents a relatively well distributed data set.

Variable	Range	Min	Max	Mean	Std. Deviation	Skewness	Kurtosis	Coefficient of variation
LSTOverall	4.00	1.00	5.00	3.05	1.13	-0.11	-0.17	0.37
LatSpineFlexAng	6.76	3.80	10.55	6.62	1.84	0.21	-0.31	0.28
HipFlexAng	57.59	24.75	82.33	62.43	16.17	-0.79	-0.08	0.26
HipAddAng	24.74	-12.21	12.54	-1.27	5.73	0.72	1.38	-4.51
HipIRAng	45.55	-8.29	37.27	9.32	11.46	0.49	0.72	1.23
KneeFlexAng	58.58	56.57	115.15	85.40	15.03	-0.27	-0.01	0.18
KneeValgusAng	51.64	-46.93	4.71	-9.57	13.51	-1.45	1.81	-1.41
KneeIRAng	43.84	9.59	53.43	36.13	12.05	-0.46	-0.14	0.33
HipFlexMom	1.07	0.61	1.68	1.11	0.30	0.53	-0.20	0.27
HipAddMom	0.82	0.03	0.85	0.39	0.23	0.49	-0.76	0.60
HipIRMom	0.45	0.10	0.54	0.24	0.12	1.24	1.36	0.52
KneeFlexMom	0.69	0.50	1.19	0.90	0.15	-0.85	2.17	0.17
KneeValgusMom	0.22	-0.30	-0.08	-0.21	0.06	0.58	-0.35	-0.30
KneeIRMom	0.08	0.00	0.08	0.04	0.02	0.37	-0.36	0.60

DISCUSSION

The LST score has been proposed to quantify quality of movement. However, based on the results from this study there does not appear to be a relationship between performance on the LST and peak lower extremity kinematic and kinetic variables associated with increased risk for ACL injury during both a DVJ and SSC.

The LST is not a truly functional test in that athletes are rarely, if ever required to lower their center of mass 20cm while maintaining single leg stance. Rather, the LST attempts to challenge the neuromuscular system by controlling the position of the femur through eccentric control of the hip and thigh muscles. It may be that the LST that limits the potential for the subjects to use a compensatory strategy because of the constrained instructions given to them prior to testing. Furthermore, the participants were not informed of the grading criteria which may have resulted in "sloppier" movement patterns not relating to how they organized their movement during a higher velocity task such as DVJ or SSC.

The subjects included in this study were all healthy, physically active females with no previous ACL injuries. There was a normal distribution of LST scores within the small sample size; however, many of the kinematic and kinetic variables were not normally distributed indicating a clustering of peak values. This occurred despite a relatively respectable distribution of scores as indicated by a coefficient of variation greater than 25% for all but 2 of the variables included in the correlation model for the DVJ (see Table 13). Future studies could include more subjects from a more diverse population base (injured and healthy) to see whether distribution values normalized potentially leading to a significant linear relationship.

Our final hypothesis was that we would see a significant decrease in the group score from pre-test to post-test for both the plyometric and core stability groups. Again, we found no significant differences within groups following a 4 week intervention program. These findings may be due to the small sample size and specifically limited number of participants who were categorized into the "poor" quality of movement category. Literature focused on neuromuscular control has suggested that individuals who are considered "high risk" respond the most to training.[15, 30, 33] Therefore, we may have seen a ceiling a effect with the subjects who demonstrated “good” to “medium” quality of movement. Based on our results, the LST may not be a good predictor of function; however, more research is needed before a definitive conclusion can be reached. Future investigations could look at subjects individually and categorize them based on the baseline LST prior to participating in a neuromuscular control intervention to better understand the idea of responders and non-responders.

With the lack of significant findings, an initial response may be to say the LST is not a good tool for identifying individuals at risk for ACL injury. However, it may be that the relationship simply needs to be looked at from a different perspective or at a time point in time such as during the peak vertical ground reaction force. Further research is needed to gain a better understanding of what information the LST is offering. A potential future study may involve performing a principle component analysis to determine whether any of the kinematic or kinetic variables cluster and can be entered into a regression model. Another potential study could involve grouping individuals based their LST score and performing a curve analysis with confidence interval bands for the same biomechanical variables to determine if the groups demonstrate different movement patterns over the course of the stance phase during a DVJ and SSC.

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APPENDICES

APPENDIX A

The Problem

Research question

Manuscript #1

This study was designed to answer the following questions:

1) Will there be a difference in hip, knee and trunk kinematics for female high school athletes during a drop vertical jump following a four week core stability intervention?
2) Will there be a difference in hip, knee and trunk kinematics for female high school athletes during a drop vertical jump following a four week plyometric training intervention?
3) Which group will show greater changes in hip, knee and trunk kinematics during a drop vertical jump following the four week intervention programs?
4) Will there be a difference in hip and knee kinetics for female high school athletes during a drop vertical jump following a four week core stability intervention?
5) Will there be a difference in hip and knee kinetics for female high school athletes during a drop vertical jump following a four week plyometric training intervention?
6) Which group will show greater changes in hip and knee kinetics during a drop vertical jump following the four week intervention programs?

Manuscript #2

This study was designed to answer the following questions:

1) Will there be a difference in hip, knee and trunk kinematics for female high school athletes during a left sidestep cut following a four week core stability intervention?
2) Will there be a difference in hip, knee and trunk kinematics for female high school athletes during a left sidestep cut following a four week plyometric training intervention?
3) Which group will show greater changes in hip, knee and trunk kinematics during a left sidestep cut following the four week intervention programs?
4) Will there be a difference in hip and knee kinetics for female high school athletes during a sidestep cut following a four week core stability intervention?
5) Will there be a difference in hip and knee kinetics for female high school athletes during a sidestep cut following a four week plyometric training intervention?
6) Which group will show greater changes in hip and knee kinetics during a sidestep cut following the four week intervention programs?

<u>Manuscript #3</u>

This study was designed to answer the following questions:

1) Is there a relationship between the lateral stepdown test score and hip, knee and trunk kinematics during a drop vertical jump in female high school athletes?
2) Is there a relationship between the lateral stepdown test score and hip, knee and trunk kinematics during a sidestep cut in female high school athletes?
3) Is there a relationship between the lateral stepdown test score and hip and knee kinetics during a drop vertical jump in female high school athletes?

4) Is there a relationship between the lateral stepdown test score and hip and knee kinetics during a sidestep cut in female high school athletes?
5) Would 4 weeks of either a plyometric or core stability intervention program positively influence the outcome of the lateral stepdown test?

Experimental hypotheses

Manuscript #1

1) Following a core stability program there will be a decrease in lateral trunk flexion, hip internal rotation and adduction during a drop vertical jump.
2) There will be significant difference following a plyometric training program in hip flexion, internal rotation and adduction as well as lateral trunk flexion, knee flexion, internal rotation and valgus during a drop vertical jump.
3) The plyometric group will demonstrate greater changes in their kinematic pattern during a drop vertical jump compared to the core stability group after four weeks of training.
4) After four weeks of training the core stability group will demonstrate decreases in hip internal rotation and adduction moments during a drop vertical jump.
5) Following four weeks of training the plyometric group will have decreased hip flexion, adduction and internal rotation moments. Similarly, they will show decreased knee flexion, valgus and internal rotation moments.
6) The plyometric group will demonstrate greater changes in their kinetic pattern during a drop vertical jump compared to the core stability group after four weeks of training.

Manuscript #2

1) There will be a decrease in lateral trunk lean, hip adduction and internal rotation during a sidestep cut following a four week core stability program.
2) There will be a decrease in lateral trunk lean, hip adduction and internal rotation and knee valgus and internal rotation angles. Additionally there will be an increase in hip and knee flexion angles during a left sidestep cut following a four week plyometric training program.
3) There will be no significant differences between plyometric and core stability groups in their kinematic patterns during a left sidestep cut following a four week training program.
4) There will be a decrease in hip flexion, adduction and internal rotation moments during a sidestep cut following a four week core stability training program.
5) There will be a difference in hip flexion, adduction and internal rotation as well as knee flexion, valgus and internal rotation moments during a sidestep cut following a four week plyometric training program.
6) There will be no significant differences between plyometric and core stability group in hip and knee kinetic patterns during a sidestep cut following a four week intervention program.

Manuscript #3

1) There will be a significant correlation between the lateral stepdown test score and hip and knee kinematics during a drop vertical jump. Specifically for the hip internal rotation, knee internal rotation and knee valgus angles.
2) There will be no significant correlation between the lateral stepdown test score and hip and knee kinematics during a sidestep cut.

3) There will be a significant correlation between the lateral stepdown test score and hip and knee kinetics during a drop vertical jump. Specifically for the hip internal rotation and adduction moment as well as knee internal rotation and knee valgus moments.
4) There will be no significant correlations between the lateral stepdown test score and hip and knee kinetics during a sidestep cut.
5) There would be a significant improvement in the lateral stepdown test score for the plyometric and core stability groups.

Operational Definitions

Core Stability – A foundation of trunk dynamic control that allows production, transfer and control of force and motion to distal segments of the kinetic chain.[58]

Core Stability Program – A program emphasizing neuromuscular coordination of the abdominal, low back and hip muscles. Subjects will participate in 15 minutes of training, three times a week for four weeks under the guided supervision of coaches and peers.

Drop Vertical Jump (DVJ) - Dropping from the height of 25 cm and landing on both feet where upon contact with the ground initiating an immediate maximal vertical jump.

Dynamic Knee Valgus Angle – A valgus angle upon visualization that may also be comprised of femoral adduction, femoral internal rotation in relation to the hip and tibial external rotation in relation to the femur with or without foot pronation.[31]

Healthy – No history of lower extremity or back surgery and no lower extremity injury within the past six weeks that limited participation in physical activity. Hip and Knee Joint Moments - The resultant force times the perpendicular distance from the joint (hip and knee) axis of rotation.

Kinematics – The study of the variables that describe movement and independent of the forces that cause the movement.[59]

Kinetics – The study of the forces that produce movement and the resultant energetics.[59]

Lateral Stepdown Test (LST) – A clinical test used to determine neuromuscular control by observing quality of movement. Subjects are scored using a 6 point scale where a score of 0-1 is good, 2-3 is fair and 4-6 is poor. The subjects' score is based on trunk lean, pelvic and knee position as well as maintenance of unilateral stance.[55]

Leg Dominance - The imbalance between muscular strength and joint kinematics in contralateral lower extremity measures.[31]

Ligament Dominance - When knee ligaments, rather than lower extremity musculature are relied upon to absorb a significant portion of the ground reaction force during sports maneuvers.[31]

Neuromuscular Control – The unconscious response to an afferent signal concerning dynamic knee joint stability.[41]

Neuromuscular Imbalances - Muscle strength or activation patterns that lead to increased joint load.

Neuromuscular Training – A program designed to better develop joint-stabilization patterns that employ feed-forward mechanisms (muscular preactivation patterns) may preset muscular contraction to increase knee stability.[31]

Plyometric Program – A neuromuscular control program incorporating various jumping exercises focused on proper landing form. Subjects will participate in 15 minutes of training, three times a week for four weeks under the guided supervision of coaches and peers.

Quadriceps Dominance - An increase in external knee flexor moments over knee extensor moments when performing sport movements that generate high lower extremity joint torques.[31]

Sidestep Cut (SSC) – An approach run of 10 meters between 4.5-5.5 m/s followed by planting the right foot and changing direction to the left between an angle of 35 and 55 degrees.

Assumptions

1) All subjects were truthful when filling out the general and lower extremity health history forms.
2) Subjects gave their best effort when performing the drop vertical jump, sidestep cut and lateral stepdown test.
3) All subjects in the core stability and plyometric groups gave their best effort during the training sessions.
4) Subjects in the control group did not engage in any additional training outside of the team practices that included exercises similar to those of the plyometric or core stability group programs.

Delimitations

1) Females currently participating on a junior varsity lacrosse or soccer team
2) No injury in the past 6 weeks that limited participation in athletics or physical activity
3) Subjects with no prior history of lower extremity or back surgery.
4) No previous participation in a formal core stability or plyometric training program

Limitations

1) Small sample size.

2) Disproportionate representation of lacrosse and soccer athletes in all group. The control and core stability groups had equal number of both while the plyometric group was comprised solely of lacrosse players.

Significance of the study

<u>Manuscript #1:</u>

Females who participate in sports that involve jumping and pivoting are at a higher risk for suffering an ACL injury than males in the same sport. Prospective research studies have identified biomechanical factors associated with increased risk for ACL injury. Larger valgus knee angles and greater external knee abduction moments while landing from a jump were found to highly relate to ACL injury risk. Furthermore, the link between core stability and knee injury was prospectively established when females with decreased neuromuscular control of the core went on to suffer an ACL injury. Prevention programs targeted at correcting poor biomechanics through improved neuromuscular control have been shown to result in decreased ACL injury. Although beneficial, it is unknown which of the components are most effective in altering biomechanical patterns. It is important to identify how specific components such as plyometric or core stability training may affect kinematic and kinetic patterns during sport specific tasks. By identifying exercises that may decrease risk factors, prevention programs can be streamlined allowing for better implementation on a wide scale basis.

<u>Manuscript #2:</u>

Noncontact ACL injuries commonly occur when decelerating and rapidly changing direction. Research studies have examined biomechanical patterns of sidestep cutting in an attempt to understand to the underlying mechanism of an ACL injury. While no prospective research has been done to link sidestep biomechanics and ACL injury risk, there are commonalities in kinematic and kinetic patterns between the mechanics of sidestep cutting and those shown to increase injury risk during a jump landing. Programs designed to prevent ACL injuries are multifactorial in that they encompass a wide variety of skills and exercises. However, little research has been done to identify which of the components included in these programs are effective in altering biomechanical patterns believed to be associated with increased injury risk. Therefore, it is important to examine how exercises targeted at improving one aspect of ACL injury risk can alter biomechanical patterns during sidestep cutting.

Manuscript #3:

Research studies examining biomechanical patterns during sport specific movements such as jump landing and sidestep cutting are time consuming and require expensive equipment. While these studies have been valuable in identifying ACL injury risk factors there is a need for an easily accessible screening tool that may be used on a more widespread basis. The lateral stepdown test is a tool that can be used clinically to identify individuals with poor core and lower extremity neuromuscular control. In order to determine whether a clinical tool such as this can be used to identify those at risk for injury a relationship must be established against known variables associated with ACL injury risk. Furthermore, a clinical test needs to be sensitive enough to demonstrate improvement in neuromuscular control following a training intervention. By establishing a clinical tool that is capable in identifying individuals at risk for ACL injury it may be possible to incorporate wide scale screening at many levels.

APPENDIX B

Literature Review

The purpose of this paper is to 1) describe the anatomy of the lower extremity, 2) discuss the incidence of anterior cruciate ligament (ACL) injuries in female athletes, 3) outline the literature regarding ACL injury mechanism including a review of both intrinsic and extrinsic risk factors, 4) compare gender differences in lower extremity biomechanics during jump landings and cutting tasks and 5) outline intervention programs utilized to decrease ACL injury risk and alter biomechanical patterns.

Lower Extremity Anatomy

The lower extremity consists of three major joints: the hip, knee and ankle that serve as the base of support for the body as weight is transferred during locomotion.[60] The hip is classified as a ball and socket joint and serves to connect the trunk to the lower extremity. The joint is formed by the articulation of the head of the femur in the acetabulum of the pelvis (the fusion of the ilium, ischium and pubic bones with skeletal maturation). The hip articulation is considered to be the most stable joint due to the cartilaginous and ligamentous support surrounding the acetabulum.[61] These static stabilizers consist of the fibrocartilaginous ring known as the acetabular labrum that assists in deepening the fossa, the joint capsule, and the iliofemoral, pubofemoral and ischiofemoral ligaments that act to reinforce and strengthen the hip joint.[62]

The hip joint is surrounded by large muscle groups that function as dynamic stabilizers to generate and dissipate forces in the proximal segment of leg. The anterior muscles primarily work to flex the hip and consist of the iliacus, psoas muscles, the rectus femoris and sartorious muscle. The posterior musculature is comprised of the gluteus maximus and hamstring muscle group that act to extend the hip as well as the gemellus inferior and superior, obturator externus and internus, piriformis and quadratus femoris that all function to externally rotate the hip. The gluteus medius and gluteus minimus concentrically contract to internally rotate the hip and abduct the femur as well as maintain a level pelvis when the body is in a position of single leg support. Medially the adductor group made up of the adductor longus, brevis and magnus along with the pectineus and gracilis adduct and internally rotate the thigh.[60-62]

The knee articulation is made up of the tibiofemoral and patellofemoral joints which provide limited bony structure and support which requiring the joint to rely heavily on the surrounding ligamentous and muscular structures for stability and force transmission. The knee is typically considered a modified hinge joint because its primary movements are flexion and extension; however, the knee is capable of internal and external rotation as well as accessory motions of valgus and varus bending and anterior and posterior gliding. The primary functions of the knee are to create a stable base during weight bearing and a mobile environment for locomotion. However, this dichotomous relationship places the knee at risk for injury due to it's role as a means for dynamic function as well as force absorption.[61, 62]

The bones that make up the knee joint are the femur, tibia, fibula and patella. The fibula does not articulate with the femur but serves as a location for muscle attachments within the lower extremity. The patella sits on the anterior aspect of the knee within the femoral intercondylar fossa. The patella serves to improve the mechanical advantage of the quadriceps tendon by increasing the lever arm and thereby reducing the amount of force required to perform a knee extension.[62] Two fibrocartilage discs called the menisci sit atop the tibial plateau and help to deepen and stabilize the articular surface. The menisci also attenuate forces by increasing the amount of joint surface in contact and providing shock absorption within the knee. Finally, the menisci serve to enhance movement in the tibiofemoral joint by improving lubrication between the two surfaces.[62]

The ligamentous structures of the knee assist in static stabilization where the minimal amount of bony support is lacking. The anterior and posterior cruciate ligaments provide an extensive portion of intraarticular stability as they pass diagonally in opposite directions from the tibial surface to the femoral condyles. The posterior cruciate ligament (PCL) is commonly considered the primary static stabilizer of the knee because of its strength and ability to resist posterior displacement of the tibia on the femur.[62] In contrast, the anterior cruciate ligament (ACL) primarily resists anterior translation of the tibia on the femur with secondary resistance to tibial internal rotation in respect to the femur. Despite the contribution to intraarticular stability, the cruciate ligaments are not located within the synovial capsule and therefore are considered extrasynovial structures.[61] The collateral ligaments of the knee run medial and lateral to the joint line and function to resist valgus and varus forces respectively. The joint capsule is a fibrous structure that envelops the joint and contributes to stabilization in the anteromedial, anterolateral, posteromedial and posterolateral directions. Furthermore, the capsule is lined with a synovium that helps to nourish and lubricate the joint.[60]

Muscles crossing the knee joint act as the dynamic stabilizers and primary movers to cause flexion, extension and internal and external rotation. The anterior aspect of the thigh is dominated by the quadriceps group made up of the rectus femoris, vastus lateralis, vastus medialis, vastus intermedius all acting to extend the knee. The sartorious muscle also assists in knee flexion as well as tibial internal rotation. Posteriorly, the biceps femoris, semimembranosus and semitendinosus form the hamstring group that functions to flex the knee and assist the ACL in reducing anterior tibial movement on the femur. Moreover, the biceps femoris externally rotates while the semimembranosus and semitendinosus internally rotate the knee.[60-62]

The ankle or talocrural joint is formed by the distal portions of the tibia and fibula with the articulation of the superior portion of the talus. The talocrural joint is a hinge joint allowing plantar and dorsiflexion of the foot. Support is provided laterally by the anterior talofibular, posterior talofibular and calcaneofibular ligaments. The deltoid ligament complex on the medial side of the ankle consists of four separate ligaments: the anterior tibiotalar, posterior tibiotalar, tibiocalcaneal and tibionavicular ligament. The subtalar joint is made up of the inferior portion of the talus with the superior part of the calcaneus and provides inversion and eversion movement in combination with midtarsal joints.[60-62]

The muscles of the lower leg and ankle are separated into four compartments each divided by a strong fascia binding. The anterior compartment consists of the tibialis anterior, extensor hallucis longus, extensor digitorum longus and peroneus tertius which all act to dorsiflex the foot and ankle. The muscles of the lateral compartment are the evertors of the foot and ankle, the peroneus longus and brevis. The superficial posterior compartment contains the gastrocnemius, soleus and plantaris muscles that together form the triceps surae muscle group and serve in plantarflexion. The deep posterior compartment contains the tibialis posterior, flexor digitorum longus and flexor hallucis longus muscles that assist in inversion and plantar flexion as well as toe flexion and forefoot adduction.[60-62]

ACL Injury Incidence

Research demonstrates a "gender bias" in the disproportionate rate of ACL injury within the female population compared to their male counterparts. It is estimated that 1 in 3,000 people in the United States will suffer an ACL injury, totaling 100,000 ACL injuries annually.[58] While epidemiological studies report females to be 4 to 6 times more likely to suffer an ACL injury, it remains unclear which characteristics play a role as predisposing factors.[58, 63] A statement published by the International Olympic Committee suggests that as females mature and the level of athletic play improves the gender gap in ACL injuries decrease. This can be seen by a drop in female to male ratios from 4.5 at the high school level to 3.63 and .95 at the collegiate and professional levels respectively.[64] Furthermore, the long term repercussions associated with injury and reconstructive surgery include a re-injury risk of at least double when compared to a group of healthy adults[65] as well as early onset osteoarthritis within ten years following injury.[66] Therefore, reducing the risk of ACL injury remains a topic of interest within the medical community.

ACL Injury Mechanism

As outlined by Bahr and Krosshaug,[67] identifying the causative mechanism and related risk factors are key steps in the process of preventing sports related injuries. The challenge with understanding specific mechanism lies within the multifactorial nature of an ACL injury. Studies inconclusively link intrinsic factors such as fluctuating hormone levels,[68-70] ACL size and width of the femoral intercondylar notch,[71, 72] and the quadriceps angle[73] to the gender bias. Moreover, extrinsic factors including lower extremity biomechanics,[2] strength and conditioning of muscles,[20, 74] neuromuscular coordination,[74] and level of participation in athletics and coaching skills[75] are common topics in the current research surrounding ACL injuries in females. An estimated 70% of ACL injuries are due to a non-contact mechanism associated with deceleration and commonly occur when landing from a jump or performing a cutting maneuver.[2, 44, 76] Therefore, it is necessary to examine these dynamic movement patterns in research by developing controlled situations that make an attempt at recreating functional scenarios.

A noncontact mechanism is typically associated with the knee nearing full extension, suggesting that increased quadriceps shear force may be one of the factors placing high strain loads on the ACL.[2] Ireland[77] termed "the position of no return" as a kinetic chain posture where the hip appears adducted and internally rotated in conjunction with knee valgus and tibial external rotation on a pronated and externally rotated foot. She believes that this precarious positioning begins at the hip and pelvis structure and that muscle deficiency or a lack of mechanical advantage result in an unbalanced posture during dynamic maneuvers.[77] It is also believed that non-sagittal plane movements such as valgus and internal rotation forces contribute to increased ligament loading but laboratory based testing has documented sub-injury level loads during dynamic movements.[47]

Risk Factors

Research related to identifying risk factors continues to explore various possibilities in an effort to unveil the complicated nature of ACL injuries and ultimately the optimal method for minimizing risk. The term extrinsic risk factors refers to those related to outside the body while intrinsic indicates those from within the body.[3] Risk factors can also be divided into more specific subcategories as will be the case for this paper.

Anatomical

Variables such as quadriceps angle (Q-angle), excessive foot pronation, body mass index (BMI), femoral notch width and geometry of the ACL and general joint laxity are grouped under the term anatomical risk factors. Q-angle has been proposed as a contributing factor to ACL injury risk and is linked with increased femoral anteversion as well as tibial rotation.[73] While research has shown that females tend to have larger Q-angles than their male counterparts,[78, 79] there have been no conclusive studies linking a larger Q-angle with increased risk for ACL injury.

The subtalar joint is a main contributor for attenuating force at the foot and ankle complex and therefore acts to modify the amount of force transmitted up the kinetic chain to proximal joint soft tissue structures. Excessive or prolonged pronation through the stance phase contributes to increased tibial internal rotation. Because the ACL is placed in tension with tibial internal rotation[80] it is therefore thought that pronation may play a role in increasing ACL injury risk.[73] However, only retrospective data has established a relationship between increased navicular drop and ACL injury[81] and it is not clear whether pronation can be marked as a significant predictor of injury.

Increased BMI has been shown to be a sensitive and specific predictor of ACL injury in female athletes. Furthermore, it was reported as the only modifiable risk factor when compared to other non-modifiable anatomical structures.[82] It is unclear what the relationship between increased BMI and ACL incidence. However, there is speculation that it relates to poor neuromuscular control patterns potentially due to less time spent participating in physical activity,[82] or an ability of the trunk and core to maintain proper posturing during dynamic activity resulting in greater loading of the hip and knee.[11]

Femoral notch and ACL geometry are anatomical factors that cannot be controlled or modified. Research in this area is difficult to interpret based on the varying methods for measuring intercondylar notch width and ligament size and shape. However, researchers have agreed on general concepts relating to ACL geometry. It is intuitive that stress placed on a smaller ACL would register as a higher load and that failure would come at a lower load.[3] Furthermore, an association has been made between notch width and ACL injury. Previous studies have shown that notch width is smaller in those with bilateral ACL injury than those with unilateral tears. Secondly, individuals with bilateral and unilateral ACL injury have smaller notch widths compared to healthy controls.[3, 64] Prospective studies demonstrated that intercondylar notch stenosis is linked with increased risk for ACL injury, however, it is unknown whether this is related to a smaller ligament or just the bony structure.[82, 83]

Dynamic stability of the knee joint is comprised by both active (neuromuscular) and passive (ligamentous) joint structures. A proposed risk factor for ACL injury is the presence of general joint laxity. As passive stability is decreased due to an inherent laxity of the ligaments, dynamic stability of the knee joint during sport related movements may also be jeopardized. Generalized joint laxity or hypermobility is defined as increased joint range of motion relative to a normal population.[84] Myer et al[85] prospectively identified knee joint hyperextension and side-to-side differences in anterior-posterior tibial translation as factors that increased risk for ACL injury in adolescent females. Similarly, Uhorchak et al[82] identified generalized joint laxity as a risk factor for noncontact ACL injury in adult males. It appears that hypermobility plays a role in contributing to noncontact ACL injury and can be used as a clinical screening tool to identify individuals who are at increased risk.

Hormonal

Since the discovery of hormone receptors on the human ACL (osetrogen, testosterone and relaxin) research has considered the effect sex hormones may play on ligament composition, structure and metabolism.[86, 87] Studies done on the influence of increased levels of estrogen and progesterone have demonstrated that acute increases in hormone concentration throughout the menstrual cycle potentially influence collagen synthesis and ACL metabolism in a dose-dependent and time-dependent way.[88] Researchers are coming to a consensus that the risk for ACL injury seems to be greater during the preovulatory rather than the postovulatory phase.[64]

Fluctuating levels of sex hormones are also implicated to contribute to increased anterior knee joint laxity however few studies have documented this relationship.[3] Shultz et al[89] demonstrated that increases in anterior knee laxity occur with varying levels of hormones and that this change takes place at the knee joint after time delay of about 3-4 days after hormone peak fluctuations. It is difficult to draw conclusions across studies in this area of investigation due to methodology and variability of menstrual cycle phases amongst subjects.[90] Uhorchak et al[82] identified knee arthrometer measures as a predictor of noncontact ACL injury in females only as compared to their male subjects. This may in part be due to the consistent finding that females have greater anterior knee laxity as compared to males.[91, 92]

Maturation

A recent peak of interest in the ACL research community is the influence of maturation on ACL injury risk. Adolescence is marked by a period of physical change, particularly rapid growth in height, body mass and the appearance of secondary sex characteristics. On average, growth is seen two years earlier in females than males with females growing at a rate of three inches a year at peak height velocity (PHV) from ages 10-12 and boys topping at four inches a year from 12-16 years. Beunen et al[93] reported strength increasing linearly through age fifteen in girls with no indication of a strength spurt while boys also increase linearly through age fourteen followed by an obvious acceleration in strength through the remainder of the teenage years and into the early mid-twenties.

Quatman et al[94] found that over a two year period of adolescence males increased vertical jump height while females showed no improvement. Furthermore, males demonstrated significantly lower landing forces during both years of maturation as compared to their female counterparts. These discrepancies between sexes are due to the neuromuscular changes that occur as a result of changes in height, muscle and fat mass as well as hormonal influences. Previous literature indicates that changes in neuromuscular control are seen following PHV.[95] An increase in length of the long bones translates to a higher center of mass as well as longer lever arms and the potential for an increase in joint torque.[94] Furthermore, the size and strength of an adolescent's muscles have not dramatically increased therefore causing an imbalance between muscle size and strength affecting coordination.[93, 96] Hewett et al[95] reported a decrease in neuromuscular control at the knee for girls from early to late puberty whereas boys showed better neuromuscular control during the later stages of puberty than they demonstrated in early stages. Similarly, Branta et al[97] argue that males demonstrate continued improvement in motor skills throughout adolescence where females peak in motor skills during early teenage years typically followed by a plateau or even decline into the later teenage years. It is believed that the decline or early peak in neuromuscular control seen by females is linked to the divergence in ACL injury rates with the onset of puberty.[18, 94, 95]

Biomechanical and Neuromuscular

Cadaveric biomechanical studies have established consistent results showing that the primary force affecting ACL stability is anterior shear force.[28] This force may result from either an internal mechanism such as a dominating quadriceps muscle contraction near full knee extension or an external cause as seen with an anterior directed force from the posterior aspect of the lower leg.[98] In addition to anterior shear force, in vitro studies have indicated that varus, valgus and internal rotational torques also increase the loading on the ACL.[99] However, motion analysis research hypothesizes that motion occurring in the coronal plane at the knee is the result of a combination of femoral rotation and adduction as well as tibial rotation and foot and ankle eversion.[9]

Dynamic joint loading consists of forces that change with time and joint angle that are either absorbed or transmitted to surrounding joints. Neuromuscular factors associated with dynamic joint loading consist of reaction time, motor unit recruitment and neuromuscular coordination. Moreover, specific muscle performance characteristics such as endurance or fatigue, strength and activation patterns are all involved in maintaining normal dynamic loading.[3] These neuromuscular characteristics can be altered by physical development[100-102] as well as training programs.[16, 24, 36]

There are many factors that have both negative and positive effects on dynamic joint loading and neuromuscular control. Fatigue,[103] unanticipated movements,[104] and an erect posture during landing or cutting maneuvers all negatively affect dynamic muscle control. Neuromuscular imbalances such as ligament dominance, quadriceps dominance and leg dominance have also all been proposed to be linked with increased lower extremity joint loading.[31] On the contrary muscular co-contraction,[105] preparatory planning for cutting and landing,[104] agility and plyometric training as well as adequate muscle activation[106] are all considered factors resulting in a positive impact on dynamic joint loading.[3]

The mechanics associated with ACL injury are thought to be caused by an inability to control postural adjustments, resulting in irregular dynamic loading patterns at the knee joint. A study examining unanticipated events such as reactive cutting and demonstrated increased joint torques in the frontal and transverse planes when compared to preplanned cutting.[104] Furthermore, a deficiency in muscle activation may lead to increased joint forces due to the limited or delayed ability of the muscle to absorb external loads. Besier et al[106] demonstrated that unanticipated movements result in activation patterns targeted at generalized co-contraction of both the hamstring and quadriceps muscles. In contrast, a preplanned dynamic task instituted selective activation patterns geared towards utilizing muscles with a mechanical advantage best capable of countering the external loads applied to the joint.

Fatigue is another factor related to the inability to control postural adjustments during dynamic movements. When fatigued, muscle fibers demonstrate a diminished capacity for absorbing energy, thus minimizing the role of the surrounding joint musculature as a dynamic stabilizer.[107] Furthermore, fatigue resulted in delayed onset of quadriceps and hamstring muscle activation decreasing shock absorption.[108] Chappell et al[107] found increased peak anterior tibial shear force, decreased knee flexion angle and increased valgus knee moment as a result of lower extremity fatigue in females during a stop jump task. Finally, a study[109] looking at the effect of a 60 shuttle run protocol in collegiate female soccer players showed a significant increase in the knee internal rotation at initial contact and peak angle. Therefore it appears that fatigue does have a negative impact on knee biomechanics and neuromuscular control while performing dynamic movements.

Neuromuscular imbalance is defined as muscle strength or activation patterns that lead to increased joint load.[31] Three specific imbalances associated with ACL injury risk are ligament, quadriceps and leg dominance.[110] Ligament dominance is exhibited when the ligament rather than the surrounding joint musculature is used to absorb a ground reaction force.[32] This classification can be visualized by increased medial knee motion and increased valgus knee moments and ground reaction forces.[4]

An individual with quadriceps dominance has an increase in internal knee extensor moments over internal knee flexor moments potentially leading to long term strength imbalances and muscle activation coordination.[31] Huston et al[91] showed that during isokinetic testing elite female athletes took significantly longer to produce maximum hamstring torque when compared to male athletes. Furthermore the females relied upon quadriceps activation in response to anterior tibial translation rather than the hamstring musculature. An over-reliance on quadriceps musculature can mean individuals are placing added anterior shear stress to the ACL during dynamic activities placing them at greater risk for noncontact injury.

Finally leg dominance is considered in relation to side-to-side strength, flexibility and kinematic imbalances.[31] In a model used to predict ACL injury, half of the factors included were kinematic or kinetic side-to-side differences between limbs.[9] Individuals with side-to-side differences are at risk for injury in both the dominant and non-dominant leg. Frequent reliance upon the dominant leg places increased stress and repeated loading on the knee. On the other hand, irregular use of the non-dominant leg results in musculature that is incapable of absorbing forces generated during dynamic tasks by the stronger leg.[31]

Performing tasks with an upright posture is believed to increase the risk of ACL injury. It is believed that landing with decreased hip, knee or ankle flexion places greater stress on the ACL and surrounding joint structures in order to absorb the ground reaction force.[111] Secondly, a quadriceps contraction with the knee near full extension increases the amount of anterior tibial shear placed on the ACL.[98] Blackburn et al[111] proposed that by emphasizing trunk flexion an individual concomitantly increased hip and knee flexion in due to the mechanics of the kinematic chain. Overall, it has been shown that by increasing flexion within the kinematic chain a dampening effect occurs resulting in absorption of ground reaction forces while decreasing anterior shear stress.

As mentioned earlier the dynamic knee valgus angle is comprised of femoral rotation and adduction as well as tibial rotation and foot and ankle eversion. This kinematic variable along with an external knee abduction moment have been statistically shown to predict ACL injury. Hewett et al[9] showed that female athletes that suffered ACL injuries prospectively had a larger knee abduction angles and an average of 2.5 time greater knee abduction moment than females who did not injure their ACL. Therefore it is believed that individuals who display these variables during dynamic movements are at greater risk for injury due to the increased loading and stress placed on the ligament.

A new interest in ACL risk factor research is examining the core musculature in relation to controlling the position of the trunk and lower extremity during landing and cutting activities. Zazulak et al[11] demonstrated that individuals with decreased trunk neuromuscular control were at greater risk for ACL injury. Researchers speculate that decreased control of the core may play a role in increased dynamic valgus positioning.[11, 35, 112] Of particular interest is the role of the hip musculature in eccentrically controlling femoral adduction and internal rotation. In a single leg standing position the vertical ground reaction force travels medial to the hip joint center of rotation, resulting in an external hip abduction moment. In order to avoid movement of the femur into excessive adduction, the external abduction moment must be countered by an internal muscle moment of equal magnitude and direction. Furthermore, using a double pendulum model Houck et al[113] proposed that lateral positioning of the trunk center of mass relative to the knee joint center of rotation shifts knee moments towards adduction which has been linked with increased risk for ACL injury. Because of these findings there is a push towards incorporating trunk neuromuscular control training in ACL prevention programs.

Gender Comparison of Lower Extremity Biomechanics

As mentioned above there are several different viewpoints citing various factors for why females are at greater risk for ACL injury. Despite the multifactorial approach to ACL risk research, the biomechanics and neuromuscular control risk factors continue to be the only modifiable factors. Researchers continue to develop an understanding of the differences between sexes at an adult level in various athletic simulated tasks. However, because sample groups and methodology differ in each study it is still not entirely clear which biomechanical factors are conclusively different between men and women.

Jump Landings

Researchers propose that kinematic differences such as landing with increased hip and knee extension as well as hip adduction and knee abduction place adult females at greater risk for ACL injury. Decker et al[114] found that recreationally active females had decreased knee flexion at instant contact compared to males. Similarly, Salci et al[7] found a significant decrease in knee and hip flexion angle in collegiate female volleyball players. However, other authors have reported no significant differences between males and females in hip and knee flexion angles when landing from a jump.[115, 116] In addition, studies by Ford[5] and Kernozak[115] showed that adolescent and adult female athletes had greater knee valgus angles at instant contact and maximum angles. Furthermore, Jacobs et al[117] found that females had a larger valgus peak joint displacement angle than males during a forward jump. Overall, it appears that one of the most consistent findings demonstrates that females have greater knee valgus angles compared to males during jump landing tasks.

A consensus on kinetic data during jump landing tasks is muddled due to the lack of consistent results amongst various studies. Decker et al[114] showed no differences in peak moments at the hip, knee or ankle between matched adult male and female athletes when performing a 60 cm landing. However, Chappell et al[107, 118] demonstrated on two separate occasions that females had greater knee extension moments during the point of peak tibial anterior shear force as compared to males during several different stop jump tasks. Furthermore these same studies showed that on average females had a valgus knee moment during the landing portion of the jump while males had a varus knee moment. Kernozak et al[115] found that adult females had a decreased peak varus moment compared to males. More often than not adult females have increased moments in the coronal plane compared to males, which researchers believe is linked to the increased incidence of ACL injury within this population.

Sidestep Cutting

Sidestep cutting is a functional maneuver that is performed in most sports. Unlike studies examining landing tasks in relation to ACL injury, research investigating the kinematic patterns of adult males and females during a sidestep cut is rather consistent. Malinzak et al[44] found decreased knee flexion and increased knee valgus angles during preplanned sidestep cutting in adult female recreational athletes. This study showed that females had eight fewer degrees of knee flexion and 11 more degrees of knee valgus throughout the entire phase of cutting. McLean et al[51] reproduced similar results using a group of high performance athletes. In this study females had more knee abduction (valgus) while performing a sidestep cut maneuver. Furthermore, in a later study McLean et al[45] showed that females also had decreased hip and knee flexion during sidestep cutting, indicating a more erect posture throughout the task. The similar nature of these findings may be a result of the similarities found in the methods and design for the research studies.

However when examining the kinetic patterns associated with sidestep cutting there seem to be fewer consistencies reported in the literature. In one study [46] there were no differences between male and female collegiate soccer players in hip, knee or ankle joint moments during an unanticipated sidestep cut while a different study[45] showed adult recreational female athletes had larger knee valgus moments and more variability within this measure than males during cutting. Furthermore, another paper examining collegiate athletes showed females had greater knee valgus moments than males and that the knee valgus moment correlated to decreased neuromuscular control at the hip.[47] Along the same line of relating forces at the knee to more proximal control Pollard et al[52] found that female collegiate soccer players had larger adductor moments and smaller hip extensor moments compared to their male counterparts. Therefore, it appears that there is a relationship between hip and knee neuromuscular control and these findings indicate that there is a need for a focus on hip mechanics during neuromuscular control interventions.

ACL Prevention and Neuromuscular Control Intervention Programs

Researchers continue to unlock the underlying causes of noncontact ACL injuries through prospective biomechanical studies. Moreover, neuromuscular control programs aimed at altering potential risk factors are growing in popularity. However, many important details are still not well understood, potentially resulting in less effective programs. In the literature there are two primary ways of measuring an intervention's effectiveness. One common method is to track ACL injury rates to get a representation of injury incidence in the intervention group versus the control group. A second way of identifying whether an intervention program was successful is to pre- and post-test the biomechanical patterns of the intervention and control groups. Although this method does not truly represent effectiveness in preventing ACL injuries, it is beneficial in demonstrating whether some of the variables associated with injury risk can be modified. This section will serve to highlight both ACL prevention programs and neuromuscular control intervention programs.

ACL Prevention Programs

Currently, many ACL prevention programs take a multifactorial approach including various components such as warm up, stretching, strengthening, plyometric and sport-specific agility drills. Studies that have been successful in reducing injury risk attribute these results to improving dynamic knee joint stability.[20, 119]

A meta-analysis examined individual interventions and suggested that to in order to reduce ACL injury rates a program needed to incorporate a plyometric component in combination with technique training or an emphasis on correct biomechanics.[119] Programs that utilized plyometric exercises decreased ACL injury risk[20, 38, 41, 120] where as those that did not incorporate plyometrics were less successful in reducing risk.[40, 121] Theoretically, plyometric exercises target the muscles as well as connective tissue and the nervous system by working the stretch-shortening cycle. Furthermore, stressing proper landing mechanics and body positioning is important in decreasing potentially injurious positioning and force absorption patterns.[119]

Technique training can be done by providing the athlete feedback through the use of health care providers, coaches, teammates or with visuals such as video footage or mirrors. Education of risk factors is a way of making athletes more aware of dangerous positioning and neuromuscular patterns. However, research has shown that studies that used activities to re-enforce learning were more successful in minimizing injury risk.[20, 41, 120]

The optimal frequency, duration and season for incorporating an injury prevention program are unknown. Contrary to what type of exercises to include, research studies are more varied when it comes to the timing of prevention programs. Hewett et al[20] were able to significantly reduce the rate of ACL injuries with a preseason training program that lasted for 60-90 minutes, three times a week. Although highly effective in reducing injury and improving performance outcomes most teams do not have the resources and time to invest in such lengthy training sessions. In contrast a study using female collegiate soccer players significantly reduced the rate of ACL injuries during practice by implementing an in-season modified warm-up program three times a week.[122] Myklebust et al[56] designed a prevention program that lasted 15 minutes, three times a week during pre-season and then had a maintenance session once a week while the athletes were in-season. All of these programs were successful in reducing injury risk but used different methods of achieving their goal. It is clear that more research is needed to determine the frequency and duration needed for fewer ACL injuries.

Neuromuscular Control Training Interventions

Neuromuscular control deficits manifesting as poor biomechanical patterns are known risk factors for noncontact ACL injuries.[9] Research studies examining the ability of neuromuscular control programs to alter biomechanical patterns are becoming more prevalent in the literature surrounding ACL injury prevention. Although these types of studies do not directly translate to demonstrating decreased injury risk, they help to hypothesize how ACL prevention programs achieve minimized risk. By incorporating training programs similar to those used to reduce injury risk, we can identify what risk factors are modifiable and further target which key exercises are necessary in making these changes.

Data regarding success of neuromuscular control training interventions are harder to interpret. The tasks analyzed and the variables reported do not always match up which makes comparisons between studies challenging to make. Following a six week training program that included both plyometric training and core strengthening, female collegiate athletes showed an increase in knee flexion angle. More importantly they also showed a decrease in the knee valgus moment suggesting a decreased risk for non-contact injury risk.[12] Significant decreases in varus and valgus knee joint moments were also found following intensive neuromuscular training that included plyometric, core strength, movement, balance, resistance and interval speed training.[16] The increase in knee flexion is in accordance with a study done by Myer et al.[36] Comparing plyometric training and balance training it was found that while both programs decreased hip adduction angles during a DVJ and knee valgus angles during a medial drop landing the plyometric training was more effective in altering sagittal plane kinematics during a DVJ.

Studies have also been less successful in demonstrating changes in biomechanical patterns following intervention programs. Herman et al[24] found no significant changes in knee or hip kinematics or kinetics following a nine week strength training program. Although improvements in strength were shown, these gains did not translate to movement patterns suggesting that single-plane strengthening may not be an effective way of decreasing ACL injury alone. A study examining the effect of a commonly used injury prevention program in high school female athletes found a decrease in hip adduction and internal rotation angles. However, no significant improvements were made in decreasing the knee valgus angle or increasing hip or knee flexion during a DVJ.[15] More research is needed to increase the number of studies examining the effect of neuromuscular control intervention programs on alter lower extremity biomechanics during various dynamic movements.

The same challenges and unknowns that exist for ACL injury prevention programs are true for neuromuscular control training programs. Researchers have yet to identify the optimal exercises, duration and frequency and dose for implementing these programs in order to see maximal results. One aspect of injury prevention that has not yet been addressed with formal research is whether developmental level or age of the athlete affects the amount of change seen following an intervention. Some have hypothesized that by targeting an earlier age group it may be possible to more significantly modify movement patterns. Younger athletes have had less time to establish motor control strategies and thereby their movement patterns may be more adept to change than those of an older, more mature and experienced athlete.[12] Therefore, it is important to include populations of varying age and skill in order to determine what group is most easily modifiable.

Conclusion

Research on ACL injury risk factors and prevention continues to demand attention due to the added finding of long term disability related to osteoarthritis and ACL injury. Deficits in neuromuscular control have been shown to be moldable through the use of multifaceted intervention programs. Wide-scale intervention programs will be benefited by recognizing what specific components are needed to optimize changes in biomechanical patterns. Furthermore, there is a need for the development of a clinical screening tool that can be used to help identify athletes at greater risk for ACL injury. Improving injury screening and prevention by making them feasible will allow clinicians to better care for an athletic population.

APPENDIX C

Additional methods

Table C1. IRB Informed Consent Form

Parents' or Guardians' Permission for Your Child to Be in a Research Study

Agreement of a Child under Age 18 to Be in a Research Study

In this form "you" means the child in the study *and* the parent or guardian.

- ✓ If you are the parent or guardian, you are being asked to give permission for your child to be in this study.
- ✓ If you are the child, you are being asked if you agree to be in this study.

In this form "we" means the researchers and staff involved in running this study at the University of Virginia.

In this form "you" means the person (your child) who is being asked to be in this study. As the parent or guardian, you are being asked to give permission for your child to be in this study.

1. Participant's Name______________________________

What is the Purpose of this Form?

This form will help you decide if you want to be in the research study. You need to be informed about the study, before you can decide if you want to be in it. You do not have to be in the study if you do not want to. You should have all your questions answered before you give your permission or consent to be in the study.

Please read this form carefully. If you want to be in the study, you will need to sign this form. You will get a copy of this signed form.

Why is this research being done?

The purpose of this study is to determine how doing four weeks of exercise can affect movement patterns during sport specific tasks. The anterior cruciate ligament (ACL) helps to stabilize the knee joint during sport activities. Adolescent and adult females injure their ACL more that males when playing sports. Researchers believe that lower extremity movement patterns are a reason for the increase in injury rates for females. Exercise training programs are believed to improve poor mechanics and improve speed and agility. However, it is unknown what type of exercise is most beneficial in improving these movement patterns.

You are being asked to be in this study, because we want to see how your movement patterns, running speed and jump height and balance are changed after four weeks of specific exercises.

Up to 75 girls from different local high schools will be in this study at UVA.

How long will this study take?

Your participation in this study will require 2 study visits over a 6 week period of time. Each visit will last about 1 hour and 30 minutes. You will also be asked to spend 15 minutes during practice 3 times a week for 4 weeks doing an exercise program with other teammates.

What will happen if you are in the study?

Screening: 15 minutes

- If you agree to participate you will sign this consent form
- You will be asked to fill out a general health history and lower extremity history questionnaire to determine whether you are eligible for this study.

First Testing Session: 1 hour and 30 minutes

- You will come to the motion analysis lab in Fontaine Research Park
- We will review your health history forms together

- *Biomechanical analysis*: You will have a set of reflective stickers placed on the center of your chest, low back, knees, shins and feet that can be seen by the 10 special motion analysis cameras around the room. The cameras are connected to a computer which will create a 3-dimensional stick figure of you running and jumping. You will be asked to do a running task that involves planting your right foot and turning left. This task is similar to sports movements. You will also be asked to do a jump landing test where you will stand on a box, step off the edge and land on the ground and then immediately jump straight up into the air as high as you can. You will also perform a balance test where you will stand on a small box on one leg and slowly lower your body until your other foot touches the ground. The reflective stickers will be taken off.

- *Speed & agility testing:* You will perform a few tests including a:

- 60 meter shuttle run where you will sprint back and forth between 2 lines on the ground.
- Maximum vertical jump test where you will be asked to jump as high as you can off 2 legs.
- Single-leg hop test where you will hop repeatedly on one-leg for 10 meters as fast as you can.
- T-agility test that includes running forwards, backwards and shuffling right and left between cones.

Study Treatment: 15 minutes, 3 times a week for 4 weeks

- Your school will be randomly assigned (like the flip of a coin) to 1 of 3 study groups. You have an equal chance of being assigned to any one of the groups. You cannot choose which group you are assigned.
- Depending on which group you may or may not be asked to do exercises for 15 minutes during practice, 3 days a week for 4 straight weeks.
- The 3 groups are: 1) control group – no extra exercises other than practice, 2) core strength – exercises focusing on strengthening the hips, abdomen and back 3) jump training – exercises focusing on good form and mechanics during jumping and landing

Follow-up Session: 1 hour and 30 minutes

- This session will follow the same order as the first testing session. Both biomechanical analysis and speed and agility testing will be done. This session will take place within 2 weeks following the final day of performing the exercises or within 8 weeks following the initial testing session for the control group.

Study Schedule table

	Visit 1 (screening)	Visit 2 (1st testing)	Visit 3 (follow-up)
Study week		0	6-8 weeks
Informed consent	x		
Review study eligibility	x	x	
Health history	x	x	
Biomechanical analysis		x	x
Speed & agility testing		x	x

If you want to know about the results before the study is done:
We will not be able to tell you any information until the results have been studied. You may contact the researcher afterwards if interested in finding out more.

What are the risks of being in this study?
Both the core strengthening and jump landing interventions (exercise programs) used in this study are considered experimental and the subject will be randomized between the standard practice group and the exercise group.

Risks and side effects related to the exercise sessions include:

Likely

- Muscle soreness – may result in pain during daily activities

Less Likely

- Muscle or tendon strain – may result in pain and loss of function for a short period of time.
- Joint injury

Risks of Videotaping:

You will be videotaped as part of this study during the balancing test. This is so your performance can be scored at a later time. During the balance test your entire body will be videotaped including your face. However, there will be no close up images of you during this test. Your video will be saved using a subject identification number and the access to this footage will only be view by the researchers. Your footage will be held in a locked filing cabinet to protect your privacy. The tapes will be destroyed following the closure of this research study.

Other unexpected risks:
You may have side effects that we do not expect or know to watch for now. Call the study leader if you have any symptoms or problems you think may be related to participating in this study.

Could you be helped by being in this study?

We cannot promise that you will be helped by being in this study.
You may benefit from being in this study. Possible benefits include: increased strength and ability to control movement patterns. These benefits may translate to improved performance in athletic events and decreased risk for injury. In addition, information researchers get from this study may help others in the future.

What are your other choices if you do not join this study?

The only choice is not to be in this study.

Will you be paid for being in this study?

You will not get any money for being in this study.

Will being in this study cost you any money?

It will not cost you any money to be in this study.

What if you are hurt in this study?

There is a small chance you could get hurt by this study in a way we did not expect. If you are hurt as a result of being in this study, we have no plans to pay you for lost wages, disability, or discomfort. If you are hurt in the study in a way that is unexpected (meaning *in a way that is not listed in the risks part of this form)*, ***the sponsor or*** your insurance company may pay for your treatment. If they do not pay, the University of Virginia will treat you free of charge. If you have questions about what will be covered if you are hurt in the study, talk to the study leader. You do not give up any legal rights by signing this form.

What happens if you leave the study early?

You can change your mind about being in the study any time. You can agree to be in the study now and change your mind later. If you decide to stop, please tell us right away. You do not have to be in this study to get services you can normally get at the University of Virginia.

If you decide to stop being in the study, we will ask you to inform the study leader that you are no longer interested in participating.

How will your personal information be shared?

The UVa researchers are asking for your permission to gather, use and share information about you for this study. If you decide not to give your permission, you cannot be in this study, but you can continue to receive regular medical care at UVA.

If you sign this form, we may collect any or all of the following information about you:

- Personal information such as name, address, date of birth, social security number
- Your medical records and test results from before, during and after the study from any of your doctors or health care providers (including mental health care and substance abuse records, and HIV/AIDS records)
- Information needed to bill others for your care

Who will see your private information?

- The researchers to make sure they observe the effects of the study and understand its results
- People or committees that oversee the study to make sure it is conducted correctly
- People who evaluate study results, which can include sponsors that make the drug or device being studied, researchers at other sites conducting the same study, and government agencies that provide oversight such as the Food and Drug Administration (FDA)

The information collected from you might be published in a medical journal. This would be done in a way that protects your privacy. No one will be able to find out from the article that you were in the study.

What if you sign the form but then decide you don't want your private information shared? You can change your mind at any time. Your permission does not end unless you cancel it. To cancel it, please send a letter to the researchers listed on this form. Then you will no longer be in the study. The researchers will still use information about you that was collected before you ended your participation. UVa researchers will do everything possible to protect your privacy.

Please contact the researchers listed below to:

- Obtain more information about the study
- Ask a question about the study procedures or treatments
- Report an illness, injury, or other problem (you may also need to tell your regular doctors)
- Leave the study before it is finished
- Express a concern about the study

Study Leader: Kate Jackson
Human Services, Curry School of Education
210 Emmet St. South
PO Box 400407
Charlottesville, VA 22904
Telephone: (434) 924-6184 – work
(434) 284-1838 - cell

Principal Investigator: Christopher Ingersoll
Human Services, Curry School of Education
210 Emmet St. South
PO Box 400407
Charlottesville, VA 22904
Telephone: (434) 924-6187

What if you have a concern about a study?

You may also report a concern about a study or ask questions about your rights as a research subject by contacting the Institutional Review Board listed below.

University of Virginia Institutional Review Board for Health Sciences Research
PO Box 800483
Charlottesville, Virginia 22908
Telephone: 434-924-2620
Fax: 434-924-2932

When you call or write about a concern, please give as much information as you can. Include the name of the study leader, the IRB-HSR Number (at the top of this form), and details about the problem. This will help officials look into your concern. When reporting a concern, you do not have to give your name.

Conclusion

Please check one of the following:

______ You agree to be contacted after this study is done for follow up information.

_____ You do not agree to be contacted after this study is done for follow up information.

What does your signature mean?

Before you sign this form, please ask questions about any part of this study that is not clear to you. Your signature below means that you understand the information given to you about the study and in this form. If you sign the form it means that you agree to join the study.

PARENTAL/GUARDIAN PERMISSION AND ASSENT FROM MINOR

PARTICIPANT (SIGNATURE)	PARTICIPANT (PRINT)	DATE

To be completed for any minor age 15 or above.

If a translator is involved in the consent process because the potential subject does not speak English well or at all, the participant should NOT sign on this line-leave this line blank. Instead, the participant should sign the Short Form written in the language they can understand.

By signing below you confirm you have the legal authority to sign for this minor.

PARENT/GUARDIAN (SIGNATURE)	PARENT/GUARDIAN (PRINT)	DATE

By signing below you confirm that you have fully explained this study to the potential subject, allowed them time to read the consent or have the consent read to them, and have answered all their questions.

PERSON OBTAINING CONSENT (SIGNATURE)	PERSON OBTAINING CONSENT (PRINT)	DATE

TRANSLATOR (SIGNATURE)	TRANSLATOR (PRINT)	DATE

If a translator was used to explain this study to a potential subject, the translator must sign and date this line.

Table C2. IRB Informed Assent Form

Participant's Name_________________________ Medical Record # ____________

ASSENT FORM TO PARTICIPATE IN A RESEARCH STUDY

Researchers at the University of Virginia are trying to learn more about whether doing four weeks of exercise can change movement patterns during running and jumping. This is called a research study. Adult and teenage females hurt their knees more often than males when playing a sport. A reason for this is that females run and jump differently than males do when playing sports.

You are asked to be in this research study because we want to see how your movement patterns during running, jumping and balancing are changed after four weeks of exercises.

The people in charge of this study are Kate Jackson and Chris Ingersoll.

This study will take place at the Gait and Motion Analysis Lab in Fontaine Research Park.

This is what will happen during this study. For the first session you will help your parent/guardian answer some questions about whether you've had an injury recently. This will take about 10 minutes. On the second session you will have reflective stickers put on different areas of your hips, legs and feet so that special motion analysis cameras can follow you and create a stick figure model of you on the computer screen. You will be asked to do a few tests that show us how well you can jump, run and balance. These will all be explained and demonstrated for you before you begin. The second session will take about 1 hour and 30 minutes.

You will be assigned to a group within this project where you will either be asked to do some extra exercises for 15 minutes during practice or just nothing else besides a normal practice day. You will be randomly put in this group, like flipping a coin. The exercises will take place 3 days a week for 4 weeks.

After the 4 weeks of exercises are over you will be asked to come back to the motion analysis lab for another hour and 30 minute session and we will have you go through the jumping, running and balance activities again.

Sometimes things happen to people in research studies that may hurt them or make them feel bad. These are called risks. The risks of this study are that you may have some muscle soreness from doing the exercises. Another risk is that you may hurt a muscle or joint while participating in the testing sessions or during the exercise program. This risk is not very likely.

People also may have good things happen to them because they are in research studies. These are called benefits. The benefits to you of being in this study may be that you get stronger and have better movement patterns during running, jumping and balancing. Being in this study will also help the researchers answer some questions about girls who play sports.

You do not have to be in this study if you do not want to be.

You may stop being in the study at any time. If you decide to stop, no one will be angry or upset with you. If you would like to stop at any time please let the researcher know.

You will not receive any money for being in this research study.

Please ask as many questions as you need to make sure you understand the study before you sign this form.

__________________________ ____________________________ ________

MINOR'S NAME (SIGNATURE) (If age 7 up to 15) | MINOR'S NAME (PRINT) | DATE

If the minor is not able to read English, the minor should not sign this form. There should be written documentation in the study file noting that study was explained to the child, all questions were answered and the child verbally agreed to participate in the study.

__________________________ ____________________________ ________

PARENT OR GUARDIAN (SIGNATURE) | PARENT OR GUARDIAN (PRINT) | DATE

If parent/guardian is unable to read English they should not sign this form. They should instead sign the short form in a language they are able to read.

If you are unable to obtain a signature from both parents explain why here:

__________________________ ____________________________ ________

TRANSLATOR (SIGNATURE) | TRANSLATOR (PRINT) | DATE

If a translator was used to explain this study to a potential subject, the translator must sign and date this line.

__________________________ ____________________________ ________

PERSON OBTAINING ASSENT (SIGNATURE) | PERSON OBTAINING ASSENT (PRINT) | DATE

Table C3. General Medical Health History Form

Exercise and Sport Injury Lab

Medical Questionnaire: General

Subject ID:_______________**IRB#** ______________

HEIGHT	WEIGHT	SEX	AGE	DATE OF BIRTH
				/ /

What is your dominant hand? Right ☐ Left ☐

Which leg would you use to kick a ball? Right ☐ Left ☐

Which leg would you use to jump from? Right ☐ Left ☐

Please check below if you have or have had any of the following:

General Medical

☐ Allergies (latex, heat, cold, electricity, medications, etc)
☐ Cancer
☐ Biomedical Devices (implants, pacemaker)
☐ Currently pregnant or nursing
☐ Recent illness (upper respiratory infection, cold, infections)
☐ Diabetes
☐ Asthma
☐ Surgery
☐ Other: ______________________

Please explain any checked items: ____

____

Please provide date of last physical exam: __________________________________

Neurological

☐ Epilepsy/seizures
☐ Anxiety disorders
☐ ADHD
☐ Diabetic Neuropathy
☐ Concussion OR Traumatic Brain Injury
☐ Cerebral Palsy
☐ Balance Disorder
☐ Vertigo
☐ Parkinson's Disease
☐ Multiple Sclerosis
☐ Other ________________

Please explain any checked items: ____

____

Cardiovascular

☐ Stroke
☐ High Blood Pressure
☐ Heart Attack
☐ Shortness of Breath
☐ Sickle Cell Trait
☐ Heart Murmur
☐ Heart Disease (Coronary Heart Disease, Arteriosclerosis)
☐ Thrombosis or Embolism
☐ Marfan's Syndrome
☐ Cardiac Arrythmia (Irregular Heart Beat)
☐ Other: _______________

Exercise and Sport Injury Lab

Medical Questionnaire: General

Please explain any checked items: ____

General Orthopedic

☐ Rheumatoid Arthritis
☐ Osteoarthritis
☐ Osteoporosis/Osteopenia
☐ Previous Fracture
☐ Surgery
☐ Gout
☐ Assistive Devices (crutches, braces)
☐ Other: ________________

Please explain any checked items: ____

____

Other

Have you taken any prescription or over the counter medications within the last 24 hours?

Yes ☐ ***No*** ☐

If yes, please list: ____

____

Have you consumed any of the following stimulants or depressants in the last 12 hours?

☐ Caffeine
☐ Tobacco
☐ Alcohol
☐ Other__________________

If yes, please explain:

____

____

Do you exercise regularly? ***Yes*** ☐ ***No*** ☐

If yes, how often, what type and for how long? ________________________________

____

Are you currently on an athletic team? ***Yes*** ☐ ***No*** ☐

If yes, at what level? ____

If yes, for what sport? ____

Table C4. Lower Extremity Health History Form

Exercise and Sport Injury Lab
Medical Questionnaire: Lower Extremity

Subject ID:_______________ **IRB#** ________________

Activities of Daily Living
Please check below if you have difficulty with any of the following:

- ☐ Sitting
- ☐ Standing
- ☐ Walking
- ☐ Walking up stairs
- ☐ Walking down stairs
- ☐ Running
- ☐ Sprinting
- ☐ Other: _______________

Please explain any checked items:

____

____

Orthopedic
Regarding your lower extremity (hips, thighs, knees, shins, ankles, feet) please answer the following questions:

Do you have a history of any broken bones?

Please explain the extent of the injury including the date and severity:

____

____

Do you have a history of any torn or sprained ligaments?

Please explain the extent of the injury including the date and severity:

____

____

Do you have a history of any dislocations?

Please explain the extent of the injury including the date and severity:

____

____

Do you have a history of any muscle or tendon strains or tears?

Please explain the extent of the injury including the date and severity:

____

____

Exercise and Sport Injury Lab

Pain
Please check below any boxes which describe your pain:

- ☐ Burning
- ☐ Stinging
- ☐ Aching
- ☐ Tingling/Numbness
- ☐ Tightness
- ☐ Pinching
- ☐ Other: _______________

Please explain any checked items:

____

____

Please rate the frequency of your pain:

- ☐ Every day
- ☐ Few times per week
- ☐ Few times per month
- ☐ Few times per year

Please explain any checked items:

____

____

How do you reduce your pain level? ____

____

What activities or motions reproduce your pain? ________________________________

____

How long does your pain last?

- ☐ All day
- ☐ Half a day
- ☐ Few hours
- ☐ One hour
- ☐ Several minutes
- ☐ Less than one minute
- ☐ Other___________

Please explain any checked items:

____

____

Please rate your current pain by marking the line below:

No pain ____ *Worst Imaginable*

Exercise and Sport Injury Lab

Pain

Please circle any areas in which you experience pain.

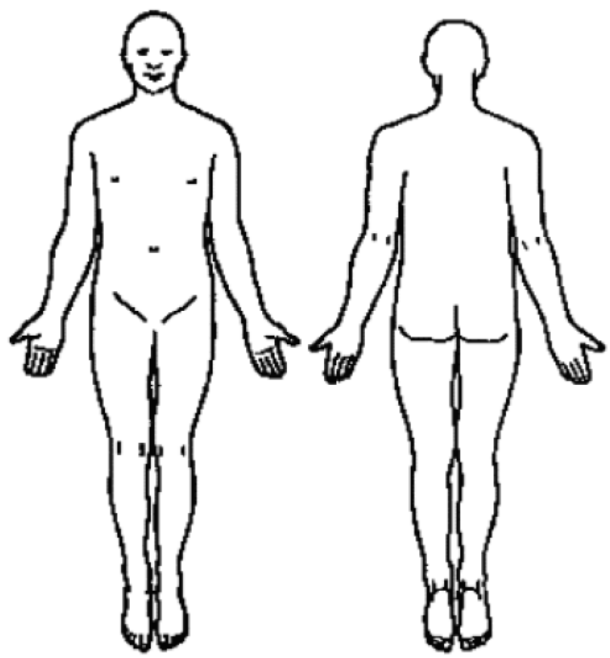


Table C5. Plyometric Exercise Program Handout

PLYOMETRIC TRAINING PROGRAM

<u>Overall objectives:</u>

- Perform exercises with concentration on using good lower extremity joint alignment/form
- Perform exercises a quick as possible rebounding off the ground and exploding into next jump while maintaining good form
- Perform exercises in equal amounts and with equal effort for both legs

Phase I: Sessions 1-6, spread out over a 2 week period

1) FORWARD SINGLE-LEG LINE JUMPS: PHASE I

Directions to athletes:

- Find a straight line on the field
- Place your hands on your hips and standing on your right foot jump forward and backward over the line at a comfortable height
- Concentrate on landing in a balanced position with your hip and knee slightly bent and your trunk in line over your legs and feet
- Do this as fast as possible but *make sure you are under control*
- Perform 30 jumps, forward and back = 1
- Switch to left leg and follow same steps
-

What to look for	How to Correct
Falling off balance	**Slow down and focus on good form**
Trunk leaning forward	**Bend at the hips and knees to keep a low base**
Front of knee collapsing inward	**Keep knees and hips over toes**

BAD:
-Weight forward
-Shoulders, hips and knee too far past toes

BAD LANDING

GOOD LANDING

GOOD:
-Weight balanced
-Shoulders and hips in line
- Knee bent over toes

2) SIDE TO SIDE SINGLE-LEG LINE JUMPS: PHASE I

Directions to athletes:

- Find a straight line on the field
- Place your hands on your hips and standing on your right foot jump side to side over the line at a comfortable height
- Concentrate on landing in a balanced position with your hip and knee slightly bent and your trunk in line over your legs and feet
- Do this as fast as possible but *make sure you are under control*
- Perform 30 jumps, side to side = 1
- Switch to left leg and follow same steps

What to look for	How to Correct
Falling off balance	**Slow down and focus on good form**
Trunk leaning to the side	**Bend at the hips and knees to keep a low base**
Front of knee collapsing inward	**Keep knees and hips over toes**

BAD:
- Trunk leaning
- Foot and knee not in line under the hip
- Knee not flexed enough

BAD EXAMPLE

GOOD EXAMPLE

GOOD:
- Flexed knee
- Straight vertical line from shoulder through hip, knee and foot

3) HIGH SKIPS: PHASE I

Directions to athletes:

- Beginning on end line of field
- Skip as *high* as you can using big arm swings to propel your body upwards
- Skip down the field moving in a straight line, minimizing sideways movement
- Concentrate on bending your hips and knees, landing softly on the ground
- Power up with the opposite leg as soon as you land on one
- Skip for the length of field

What to Look For	How to Correct
Landing stiff and straight	**Bend more at the hips and knee**
Leaning to the side to generate power	**Keep trunk in line with hips**
Not using arms to propel body upward	**Emphasize arm swing**
Not skipping in a straight line	**Limit side to side excursion**

GOOD JUMPING POSITION

GOOD:
- Vertical body alignment
- Big arm swing
-Powering up

GOOD LANDING POSITION

GOOD:
- No trunk lean
- Foot in line with knee, hip and shoulders
- Knee bending to absorb force for quiet landing

4) DISTANCE SKIPS: PHASE I

Directions to athletes:

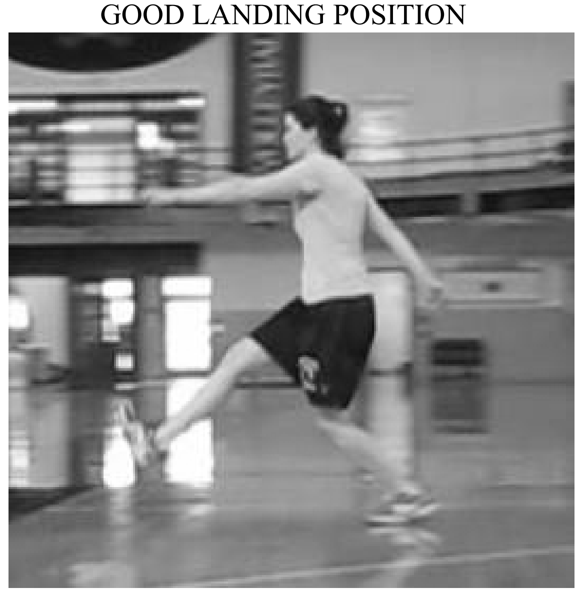
- Beginning on end line of field
- Skip as *far* as you can using big arm swings to propel your body forwards
- Skip down the field moving in a straight line, minimizing sideways movement
- Concentrate on bending your hips and knees, landing softly on the ground
- Power forward with the opposite leg as soon as you land on one
- Skip for the length of field

What to Look For	How to Correct
Landing stiff and straight	**Bend more at the hips and knee**
Leaning to the side or forward to generate power	**Keep trunk in line with hips**
Not using arms to propel body forward	**Emphasize arm swing**
Not skipping in a straight line	**Limit side to side excursion**

GOOD JUMPING POSITION

GOOD:
- Vertical body alignment
- Big arm swing
-Powering forward

GOOD LANDING POSITION



GOOD:
- No trunk lean
- Knee, hip & trunk in line
- Knee bent to absorb force for quiet landing

5) STANDING BROAD JUMP: PHASE I

Directions to athletes:

- *Find a partner* to watch as you perform this exercise
- Beginning with feet shoulder width apart bend hips and knees and swing arms to perform maximum forward jump taking off and landing equally on both feet
- Concentrate on bending your hips and knees in order to land softly on the ground with your weight evenly distributed and sticking the landing
- You should be in a balanced position, not leaning too far forward or backwards or to one side
- Each partner should perform 2 sets of 10 jumps

What to Look For	How to Correct
Landing stiff and straight	**Bend more at the hips and knees – quiet landing**
Landing with trunk leaning forward or back	**Keep shoulders over hips**
Landing with knee bent inward	**Knees over toes and shoulder width apart**
Not using arms to propel body forward	**Emphasize arm swing**

BAD & GOOD LANDING POSITION

BAD:
- Center of knee not over center of shoe but inward

GOOD:
- Vertical trunk – well balanced
- Bent hips and knees
- Front of knee over center of shoe

6) Tuck Jumps: Phase I

Directions to athletes:

- *Find a partner* to watch as you perform this exercise
- Beginning with feet shoulder width apart
- Bend hips and knees and swing arms to perform maximum vertical jump taking off and landing equally on both feet
- In the air tuck both of your knees up to your chest
- Land softly with bent hips and knees with your weight evenly distributed between legs
- You should be in a balanced position, not leaning too far forward or backwards or to one side
- Immediately upon landing perform another jump for maximal height
- Each partner should perform 2 sets of 10 jumps as fast as possible with controlled movement

What to Look For	How to Correct
Landing stiff and straight	**Bend more at the hips and knees – quiet landing**
Landing with the trunk leaning forward or back	**Keep shoulders over hips**
Landing with the knee bent inward	**Keep knees over toes and feet shoulder width apart**
Not bringing both knees up to chest at equal height	**Equal push off for both legs**
Not using arms to help power the body upward	**Emphasize arm swings**

BAD LANDING POSITION

GOOD JUMPING POSITION

BAD:
- Center of knee not over center of shoe or under hips
- Not bent enough at hips

GOOD:
- Knees at even height up to chest
- Trunk vertical & not leaning to one side

7) ALTERNATING SINGLE-LEG LATERAL BOUNDING: PHASE I

Directions to athletes:

- Beginning with feet shoulder width apart
- Bend hips and knees and jump to the side pushing off one leg and landing on the opposite leg
- Land softly with bent hips and knees with your weight evenly distributed and your trunk balanced over your hips
- You should be in a balanced position, sticking the landing and regaining control before jumping back towards the starting position
- Perform this as quickly as possible while keeping good form and balance
- Each person should perform 2 sets of 10 jumps where right and left jump = 1

What to Look For	How to Correct
Landing stiff and straight	**Bend more at the hips and knees – quiet landing**
Landing with trunk leaning to one side	**Keep shoulders over hips**
Landing with knee bent inward	**Knees over toes and shoulder width apart**
Not being able to maintain balance	**Slow down and focus on form**

BAD LANDING POSITION

BAD:
- Trunk leaning to the side, shoulders not over hips
- Not bent enough at knee

GOOD LANDING POSITION

GOOD:
- Foot in line with knee, hip and shoulder
- Trunk vertical & not leaning to one side

Phase II : Sessions 7-12, spread out over a 2 week period

1) SINGLE-LEG HOP, HOP, HOP & STICK: *PHASE II*

Directions to athletes:

- Beginning on your right leg with your hands on your hips hop forward three times in a row quickly
- Focus on bending the hips and knees during jumping and landing and keeping a balanced trunk where your shoulders are over your hips
- On the third hop "stick" the landing and hold for a count of 5 seconds, you should be in a balanced position with knees bent over toes and hips bent and in line with shoulders
- Each person should perform this combination 10 times on each leg

What to Look For	How to Correct
Landing stiff and straight	**Bend more at the hips and knees – quiet landing**
Landing with trunk leaning to one side	**Keep shoulders over hips**
Landing with knee bent inward	**Knees toes forward with knees and hip over toes**
Not being able to maintain balance	**Slow down and focus on form**

BAD LANDING POSITION

GOOD LANDING POSITION

BAD:
- Trunk leaning to the side

- Not bent enough at hip & knee

GOOD:
- Foot in line with knee, hip and shoulder
- Trunk vertical & not leaning to one side
- Knee and hip flexed

2) SQUAT JUMPS: *PHASE II*

Directions to athletes:

- Find a partner to watch you and give feedback on form
- Starting with feet shoulder width apart bend at the hips and knees into a squat position, keeping your back straight and not letting your chest go farther forward than your knees
- From this position jump up as high as you can using your arms and reaching for the ceiling
- Land softly by flexing the hips and knees and keeping the center of your knee over your toes
- Immediately upon landing continue into the next jump by squatting to the ground again
- Perform 2 sets of 10 jumps for max height and speed while keeping good form, alternate sets with your partner so you have time to rest

What to Look For	How to Correct
Landing stiff and straight	**Bend more at the hips and knees – quiet landing**
Landing with the trunk leaning forward or back	**Keep shoulders over hips**
Landing with the knee bent inward	**Keep toes forward & knees and hips over toes**
Not being able to maintain balance	**Slow down and focus on form**
Not using arms to help power the body upward	**Emphasize arm swings to increase explosiveness**

BAD STARTING/LANDING POSITION

BAD:
- Trunk leaning to the side
- Knees bent inward, not in line over toes

GOOD STARTING/LANDING POSITION

GOOD:
- Foot in line with knee, hip and shoulder
- Trunk vertical & not leaning to one side
- Knee and hip flexed

3) SINGLE-LEG MAXIMAL VERTICAL JUMP: *PHASE II*

Directions to athletes:

- Find a partner to watch you and give feedback on form
- Standing on your right leg bend your hip and knee to explode upward as high as you can using your arms to generate momentum
- Land softly on the same leg by flexing the hips and knees and keeping the center of your knee over your toes
- Hold this landing for a count of 3 using your arms for balance if necessary
- Perform 10 jumps on each leg for max height
- Alternate sets with your partner so you have time to rest

What to Look For	How to Correct
Landing stiff and straight	**Bend more at the hips and knees – quie**
Landing with the trunk leaning to side, forward or back	**Keep shoulders over hips**
Landing with the knee bent inward	**Keep toes forward & knees and hips ov**
Not being able to maintain balance	**Slow down and focus on form**
Not using arms to help power the body upward	**Emphasize arm swings to increase expl**

BAD:
- Trunk leaning to the side
- Foot and knee not in line under hip
- Knee not bent enough

BAD LANDING FORM

GOOD TAKEOFF FORM

GOOD:
- Trunk vertical & not leaning to one side
- Hip & knee bent

4) SINGLE-LEG JUMP FOR DISTANCE: *PHASE II*

Directions to athletes:

- Find a partner to watch you and give feedback on form
- Standing on your right leg bend your hip and knee to explode forward as far as you can using your arms to generate momentum
- Land softly on the same leg by flexing the hips and knees and keeping the center of your knee over your toes
- Hold this landing for a count of 3 using your arms for balance if necessary
- Perform 10 jumps on each leg for max distance
- Alternate sets with your partner so you have time to rest

What to Look For	How to Correct
Landing stiff and straight	**Bend more at the hips and knees – quiet landing**
Landing with the trunk leaning to side, forward or back	**Keep shoulders over hips**
Landing with the knee bent inward	**Keep toes forward & knees and hips over toes**
Not being able to maintain balance	**Slow down and focus on form**
Not using arms to help power the body upward	**Emphasize arm swings to increase explosiveness**

BAD LANDING POSITION

BAD:
- Trunk leaning too far forward
- Hip not bent enough
- Unbalanced position

GOOD LANDING POSITION

GOOD:
- Trunk vertical
- Hip & knee bent

5) BROAD JUMP, JUMP, JUMP, VERTICAL JUMP: *PHASE II*

Directions to athletes:

- Find a partner to watch you and give feedback on form
- Beginning with feet shoulder width apart bend your hips and knees and swing arms to perform maximum forward jump taking off and landing equally on both feet
- Concentrate on bending your hips and knees in order to land softly on the ground with your weight evenly distributed and sticking the landing
- You should be in a balanced position, not leaning too far forward or backwards or to one side
- Perform 3 consecutive broad jumps
- At the end of the 3^{rd} broad jump perform a maximal vertical jump off of both feet trying to land in the same spot you jumped from
- Perform 5 repetitions of this combination of jumps (3 broad jumps and 1 vertical jump = 1)

What to Look For	How to Correct
Landing stiff and straight	**Bend more at the hips and knees – quiet landing**
Landing with the trunk leaning forward	**Keep shoulders over hips**
Landing with the knee bent inward	**Keep toes forward & knees and hips over toes**
Unequal weight distribution	**Maintain a balanced position**
Not using arms to help power the body upward	**Emphasize arm swings to increase explosiveness**

BAD JUMPING POSITION

BAD:
- Trunk leaning to the side
- Feet unevenly leaving the ground → not jumping with equal force

BAD LANDING POSITION

BAD:
- Trunk leaning too far forward
- Knees bent inward

6) 180 JUMPS: *PHASE II*

Directions to athletes:

- Find a partner to watch you and give feedback on form
- Beginning with feet shoulder width apart bend hips and knees and jump off both feet rotating 180 degrees so that you are facing in the opposite direction you started from
- Concentrate on bending your hips and knees in order to land softly on the ground with your weight evenly distributed and sticking the landing
- You should be in a balanced position with shoulders over hips over knees over toes
- Upon landing, immediately jump and turn 180 degrees in the opposite direction you just came from
- Perform 10 jumps where 2 180 degree jumps = 1

NOTE: Should not be turning in a complete circle rather one jump clockwise, the next counterclockwise

What to Look For	How to Correct
Landing stiff and straight	**Bend more at the hips and knees – quiet landing**
Landing with the trunk rotated or leaning	**Keep shoulders over hips**
Landing with the knee bent inward	**Keep toes forward & knees and hips over toes**
Unequal weight distribution	**Maintain a balanced position**
Not using arms	**Emphasize arm swings to help rotate the body**

BAD LANDING POSITION

BAD:
- Weight on the heels → hips not over feet

GOOD LANDING POSITION

GOOD:
- Hips in line over feet

- Hips & knees bent

7) SINGLE-LEG LATERAL BOUNDING: *PHASE II*

Directions to athletes:

- Find a partner to watch you and give feedback on form
- Begin by standing on your right leg with your hands on your hips jump sideways to the left landing on the same leg you jumped from
- Concentrate on bending your hips and knees in order to land softly on the ground with your weight evenly distributed and sticking the landing
- You should be in a balanced position with shoulders over hips over knees over toes
- Upon landing regain your correct form and jump back to your original starting position of that same leg
- Perform on both right and left legs 10 jumps where side to side = 1 jump
- Alternate with your partner for rest

What to Look For	How to Correct
Landing stiff and straight	**Bend more at the hips and knees – quiet landing**
Landing with trunk leaning to one side	**Keep shoulders over hips**
Landing with knee bent inward	**Knees toes forward with knees and hip over toes**
Not being able to maintain balance	**Stick the landing - slow down and focus on form**

BAD:
- Side trunk lean
- Foot and knee not in line with hip

BAD LANDING POSITION

GOOD LANDING POSITION

GOOD:
- Trunk in vertical position
- Foot and knee in line

Table C6. Core Stability Exercise Handout

CORE STABILITY TRAINING PROGRAM

Overall objectives:

- Perform exercises with concentration on using good lower extremity joint alignment/form
- Perform exercises in a slow and controlled manner to maximize neuromuscular gains
- Perform exercises in equal amounts and with equal effort on both sides

Phase I: Sessions 1-6, spread out over a 2 week period

1) ABDOMINAL DRAW-IN: PHASE I

Directions to athletes:

- Lay on your back with your hips and knees bent, feet on the floor and arms resting comfortably on the ground at your side
- Using your stomach muscles try to pull your belly button down towards your spine, this is a very subtle movement
- Do not crunch up or use your abdominal muscles, do not suck your stomach in but focus on using your inside stomach muscles by tightening your core (back and stomach)
- Continue to breathe normally while you hold this contraction
- Perform this exercise 10 times holding each contraction for 5 seconds

What to look for	How to Correct
Crunching or sitting up	**Keep back against the floor**
Sucking in your stomach	**Concentrate on only using deep core muscles**
Holding your breath	**Try to breathe normally**

GOOD:
- Knees bent and feet on floor
- Arms relaxed at side
- Breathing normally

BAD:
- Feet not on floor
- Arms and neck not relaxed
- Crunching up

2) SIDE PLANK WITH KNEES BENT: PHASE I

Directions to athletes:

- Lay on your side with your knees bent
- Push up so that you are supporting yourself on your forearm with your elbow bent to 90 degrees
- Your elbow should be under the shoulder joint
- Bring your hips up off the ground and hold your trunk in a straight line from your chest to your knees like a plank
- Rest your non-supporting arm against your side
- Perform this exercise 2 times on your right and left side holding for 20 seconds each time

What to look for	How to Correct
Using both arms to support	**Relax the non-support arm against the trunk**
Sagging or over arching with the hips	**Focus on holding a straight line from chest to knees**

GOOD:
- Hips in straight line with chest and knees
- Knees bent
- Non-support arm relaxed at side

BAD:
- Both arms used for support
- Hips sagging
- Leaning forward

3) JANE FONDA: PHASE I

Directions to athletes:

- Lay on your side with your legs straight and your arm closest to the ground supporting your head
- With the top leg, point your toe straight forward
- Slowly raise your top leg towards the sky, opening up your hip to about 30-45 degrees (about a distance of 2 feet between your shoes) Raising your leg should take about 2 seconds
- Slowly lower your leg back down over a count of 4 seconds
- Perform 3 sets of 10 exercises on both right and left sides

What to look for	How to Correct
Toe pointing up	**Point toe forward**
Bringing leg forward	**Open hips by bringing leg straight up**
Raising and lowering too quickly	**Slow down – 2 seconds up, 4 seconds down**

GOOD:
- Toe pointing forward
- Leg opening straight up
- Between 30-45 degree angle at top point of exercise (about 2 feet)

BAD:
- Toe pointing upwards
- Leg coming forward

4) CLAM SHELLS: PHASE I

Directions to athletes:

- Lay on your side with your knees bent and your arm closest to the ground supporting your head
- Keeping your feet together and your knees bent, open your top leg by bringing your knee up towards the sky, taking about 1 second do perform this part
- Slowly lower your top leg back down to the starting position so that both knees are touching, this should be done over a count of 2 seconds
- Perform 3 sets of 10 exercises on both right and left sides

What to look for	How to Correct
Feet coming apart	**Keep feet together**
Legs straight	**Bend knees**
Raising and lowering too quickly	**Slow down – 1 second up, 2 seconds down**

GOOD:
- Toes together
- Knees bent
- Lying on the side

BAD:
- Feet apart
- Knees not bent

5) CRUNCHES: PHASE I

Directions to athletes:

- Lay on your back with your knees bent, feet on the floor and your arms folded across your chest
- Tighten your abdominal muscles and crunch your trunk until your head and shoulder blades are up off the ground
- In a slow and controlled manner lower your back and head down towards the ground over a count of 2 seconds
- Exhale on the way up and inhale on the way back to the ground
- Perform 4 sets of 15

What to look for	How to Correct
Feet coming up off the ground	**Keep feet down on the ground**
Arms behind the head	**Arms across the chest only using abdominals to lift**
Shoulder blades not coming up off ground	**Continue to crunch until upper back is lifted**
Raising and lowering too quickly	**Slow down – 1 second up, 2 seconds down**

GOOD:
- Feet on the ground
- Knees bent
- Arms across the chest
- Shoulder blades up off the ground

BAD:
- Arms behind head assisting movement

6) SUPERMAN HANDS ON HEAD: PHASE I

Directions to athletes:

- Lay on your stomach with your legs straight and shoulder width apart and your hands overlapped behind your head
- In a slow and controlled manner lift your chest and legs up off the ground at least 6 inches keeping your knees straight, this should take about 2 seconds
- In a slow and controlled manner lower your chest and legs back down towards the ground over a count of 2 seconds
- Perform 4 sets of 10

What to look for	How to Correct
Overarching the back	**Go to a comfortable point, head about 6" off ground**
Legs lifting unevenly	**Lift to same height about 6" off ground**
Raising and lowering too quickly	**Slow down – 1 second up, 2 seconds down**

GOOD:
- Hands on back of head
- Legs straight lifting evenly
- Chest and legs about 6" off the ground

BAD:
- Arms used to push up

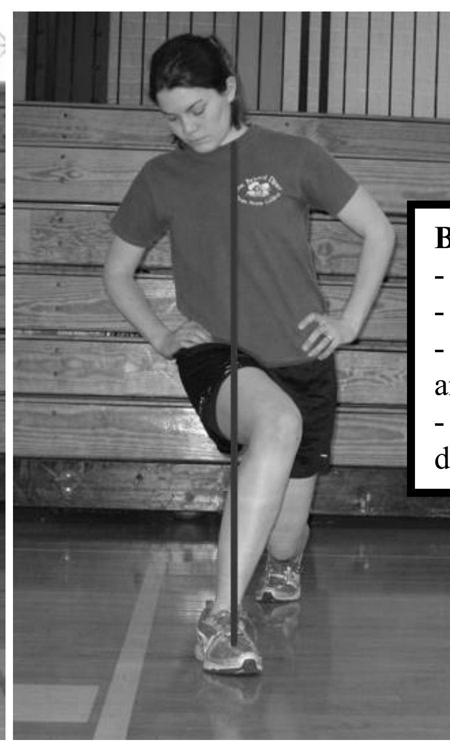
7) Walking lunges hands on hips: phase I

Directions to athletes:

- Find a partner to watch you during this exercise and give you feedback on your form
- Place your hands on your hips and lunge forward with your right leg bending at the hips and knees
- Focus on keeping your trunk straight and the center of your knee over the center of your shoe
- Your forward knee should not move past your ankle joint and your back knee should be hovering just above the ground
- Return to a standing position by straightening at the hips and knees
- Take a step with the opposite leg and following the same guidelines
- This exercise should be done in a slow, controlled manner focusing on form and keeping your balance
- Go across and back the width of the field while doing this exercise

What to look for	How to Correct
Trunk leaning to one side	**Maintain vertical position, eyes looking forward**
Knee moving inward past toes	**Keep center of knee in line with 2nd toe**
Knee moving forward in front of ankle	**Stop in line with ankle and lunge down, not forward**
Hands flailing to keep balance	**Keep hands on hips and SLOW DOWN**

GOOD:
- Hands on hips
- Knee over toes
- Trunk straight
- Eyes forward



BAD:
- Trunk lean
- Knee inward
- Knee past ankle
- Eyes looking down

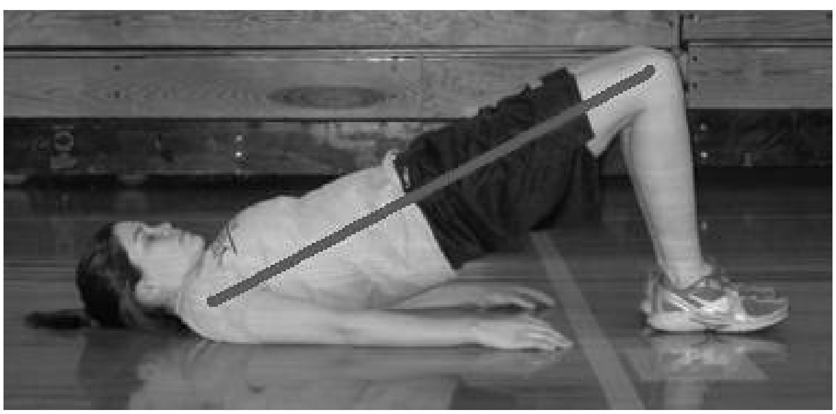
Phase II: Sessions 7-12, spread out over a 2 week period

1) BRIDGE WITH ABDOMINAL DRAW-IN: PHASE II

Directions to athletes:

- Lay on your back with your hips and knees bent and feet flat on the floor
- Perform the abdominal contraction by tightening your core and focusing on bringing your belly button down towards your spine
- While holding this abdominal contraction bridge up by lifting your hips and butt up off the ground
- You should form a straight diagonal line from your knees to your chest
- Keep your arms in a relaxed position at your side
- Hold the bridge for a count of 1, maintain the core contraction and slowly lower yourself back to the ground
- Pause giving yourself a chance to breathe and repeat for 3 sets of 10 repetitions

What to look for	How to Correct
Overarching or sagging the trunk	**Want a straight line from knees to shoulders**
Arms being used to push up	**Arms relaxed on the ground at the side**
Raising and lowering too quickly	**Slow down – 1 second up, 2 seconds down**



GOOD:
- Arms relaxed on floor
- Straight line from knees to shoulders
- Feet flat on the floor

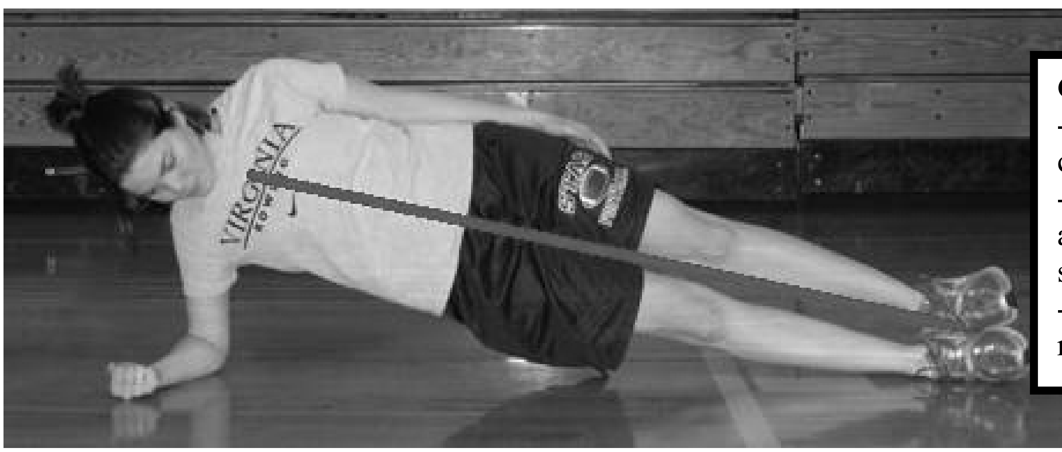
BAD:
- Arms behind head
- Overarching the trunk

2) SIDE PLANK WITH LEGS STRAIGHT: PHASE II

Directions to athletes:

- Lay on your side with your knees straight
- Push up so that you are supporting yourself on your forearm with your elbow bent to 90 degrees
- You can either spread your feet or put them together one on top of the other
- Bring your hips up off the ground and hold your trunk in a straight line from your chest to your feet like a plank, the only contact points with the ground should be your forearm and feet
- Rest your non-supporting arm against your side
- Perform this exercise 2 times on your right and left side holding for 20 seconds each time.

What to look for	How to Correct
Using both arms to support	**Relax the non-support arm against the trunk**
Sagging or over arching with the hips	**Focus on holding a straight line from chest to knees**



GOOD:
- Straight line from chest to feet
- Support elbow bent and arm under shoulder
- Non-support arm relaxed at side

BAD:
- Both arms used for support
- Hips over-arching
- Leaning forward

3) FIRE HYDRANTS: PHASE II

Directions to athletes:

- Position yourself on the ground on your hands and knees
- With your knee bent, kick your right leg out behind you and then lift and open the same leg out to the side (like you are a dog peeing on a fire hydrant)
- Slowly return the leg to an all-fours position
- Try to keep your back flat and not let it sink down in the middle or let the hip of the leg that is on the ground shift out to the side
- Alternate to the left side, keeping your knee bent, kicking straight back and lifting out to the side
- Slowly return the left leg to an all-fours position
- Perform 3 sets of 10, where 1 repetition is movement on both right and left sides

What to look for	How to Correct
Sagging the back	**Keep the back flat and support hip even with moving hip**
Elbows bent	**Elbows straight and positioned under the shoulder**
Raising and lowering too quickly	**Slow down – 1 second up, 2 seconds down**

GOOD:
- Keeping the back flat
- Hands and knee under the shoulder and hip
- Knee bent and lifted out to the side

BAD:
- Back sagging
- Elbows bent
- Knee not maximally rotated out to the side

4) CRUNCHES WITH A TWIST: PHASE II

Directions to athletes:

- Lay on your back with your knees bent, feet on the floor and your arms folded across your chest
- Tighten your abdominal muscles and crunch your trunk until your head and shoulder blades are up off the ground
- Rotate your trunk so that you are directing your left shoulder towards your right thigh
- In a slow and controlled manner lower your back and head down towards the ground over a count of 2 seconds
- Alternate sides, this time crunch up and then rotate your right shoulder towards your left thigh
- Exhale on the way up and inhale on the way back to the ground
- Perform 4 sets of 15 where each crunch counts as 1 repetition

What to look for	How to Correct
Feet coming up off the ground	**Keep feet down on the ground**
Arms behind the head	**Arms across the chest only using abdominals to lift**
Shoulder blades not coming up off ground	**Continue to crunch until upper back is lifted**
Touching elbow to knee	**Bring elbow to opposite thigh**
Raising and lowering too quickly	**Slow down – 1 second up, 2 seconds down**

GOOD:
- Feet flat on the ground
- Arms across the chest
- Shoulder blades up off the ground
- Rotating left shoulder to right thigh

BAD:
- Legs in the air
- Arms behind the head
- Shoulder blades still on the ground
- Rotating at the neck instead of the trunk

5) SUPERMAN ARMS OUT FRONT: PHASE II

Directions to athletes:

- Lay on your stomach with your legs straight and shoulder width apart and your arms outstretched in front of you
- In a slow and controlled manner lift your arms and chest up off the ground while at the same time lifting your legs up off the ground at least 6 inches keeping your knees straight, this should take about 2 seconds
- In a slow and controlled manner lower your arms/chest and legs back down towards the ground over a count of 2 seconds
- Perform 4 sets of 10

What to look for	How to Correct
Overarching the back	**Go to a comfortable point, head about 6" off ground**
Legs lifting unevenly or bending at the knee	**Straight knee and lift to same height about 6" off ground**
Arms and chest not lifting evenly	**Lift until the chest is off the ground keeping arms out**
Raising and lowering too quickly	**Slow down – 1 second up, 2 seconds down**

GOOD:
- Arms and legs lifting evenly off the ground
- Arms and legs straight out

BAD:
- Knees bent
- Chest not off the ground

6) SQUATS WITH LACROSSE STICK OR SOCCER BALL OVERHEAD: PHASE II

Directions to athletes:

- Find a partner to help give you feedback on using good form
- Stand with your feet a little wider than shoulder width apart and hold a lacrosse stick or soccer ball over your head
- Squat down by bending your hips and knees like you are sitting back in a chair, your weight should be on your heels and distributed evenly between right and left legs
- Do not let your knee move inwards instead focus on keeping the front of your knees over your toes
- Squat down until your knees are bent to 90 degrees or until your thighs are parallel with the ground
- Keep your back straight and do not bend forward at the waist

What to look for	How to Correct
Feet too close together	**Stand just wider than shoulder width apart**
Knees collapsing inwards	**Keep knees pointed forward and over toes**
Trunk bending forward at the waist	**Keep back flat and sit back when squatting**
Trunk leaning to the side	**Keep equal weight over both legs**

GOOD:
- Trunk straight
- Wide stance
- Knees over toes

BAD:
- Trunk leaning forward
- Feet narrow
- Knees collapsing in

7) LUNGES WITH PARTNER BALL TOSS: PHASE II

Directions to athletes:

- Find a partner to throw with and help watch you for good form
- Holding your lacrosse stick or soccer ball lunge forward with your right leg bending at the hips and knees
- Focus on keeping your trunk straight and the center of your knee over the center of your shoe
- Your forward knee should not move past your ankle joint and your back knee should be hovering just above the ground
- In this down position give a good pass to your partner
- Return to a standing position by straightening at the hips and knees
- Allow your partner to pass the ball back to you in the same manner
- Repeat the lunge and pass alternating the forward leg
- This exercise should be done in a slow, controlled manner focusing on form and keeping your balance
- Perform 4 sets of 10 lunges, where each lunge counts as 1

What to look for	How to Correct
Trunk leaning or rotating to one side	**Maintain vertical position, eyes looking forward**
Knee moving inward past toes	**Keep center of knee in line with 2nd toe**
Knee moving forward in front of ankle	**Stop in line with ankle and lunge down, not forward**
Falling over, losing balance	**Slow down and concentrate on balance**

GOOD:
- Trunk straight
- Knee over toes
- Knee in line over ankle

BAD:
- Trunk rotating and leaning
- Knee inside of toes
- Knee too far forward of ankle

Table C7. High School Athletic Trainer Observation Sheet

School ________________________________
Team _________________________________
Session # ______________________________
ATC __________________________________

Respond to the following statements by circling the word you feel best matches your observations.

	Always	Most of the time	Some of the time	Rarely	Never
1) In general, the coach is instructing the athletes how to correctly perform the exercises.					
2) In general, the coach is emphasizing key mistakes to look for.					
3) In general, the coach is giving constructive feedback during the exercises.					
4) In general, the athletes are listening and following the directions given.					
5) In general, the athletes are working hard to perform the exercises correctly.					
6) In general, the athletes seem challenged by the exercises they are asked to perform.					

7) Any additional comments regarding an observation you had that did not fit elsewhere on this questionnaire.

Table C8. Vicon Camera Calibration

1. Open Workstation version 4.6
2. Click ‘systems’, live monitors
3. View ‘calibration marker pairs’
4. Adjust camera sensitivity for each camera
5. Click ‘systems’, calibrate cameras
6. Under calibration select ‘all new data’
7. Click ‘calibrate’
8. For static calibration select ‘start’
9. Select ‘start’ for dynamic calibration while wanding the capture area
10. Examine ‘static reproducibility’ and ‘wand visibility’, accept calibration if static reproducibility is under 2% and wand visibility is over 80%

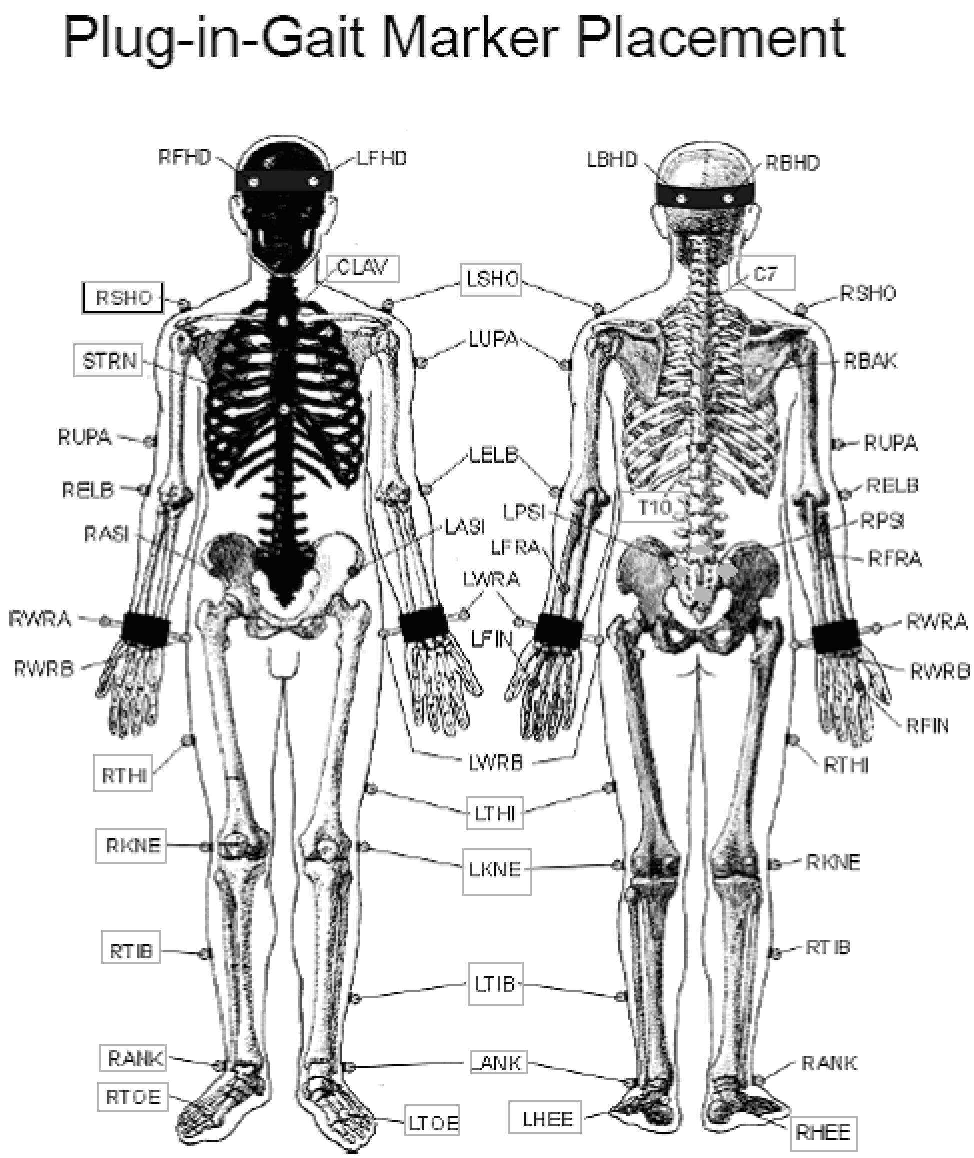
Table C9. Subject Setup

1. Collect anthropometric data (mass, height, leg length, knee width, ankle width)
2. Fit with standardized footwear
3. Palpate and apply markers to anatomical landmarks (lateral malleoli, 2^{nd} metatarsal head, center of calcaneus, lateral femoral condyle, lateral shank, lateral thigh, acromion process, T10 process, C7 process, manubrium and xiphoid process)
4. Position cluster over sacrum and secure with elastic wrap
5. In Workstation: Click ‘file’, open database
6. Select appropriate database and click ‘open’
7. Click on the ellipse button
8. Highlight ‘patient classification’ and select ‘new patient’
9. Click ‘new session’
10. Click ‘new trial’
11. Label trial ‘static’
12. Apply individual marker labels
13. Select ‘trial’, ‘autolabel calibration’, save
14. Identify right and left ASIS and PSIS landmarks using pointing wand and label respectively (RASI, LASI, RPSI, LPSI)
15. Label proximal and distal markers for each pointing trial
16. Save
17. Add and label dynamic trials as needed

Table C10. Vicon Data Processing Directions

1. Open Workstation v4.6
2. Highlight pointing trials (RASI, LASI, RPSI, LPSI)
3. In ‘pipeline’ choose ‘perform dynamic bodylanguage model’, under option select ‘pelvis calibration’ and ‘save trial’, choose ‘process now’
4. Highlight static trial
5. In ‘pipeline’ choose ‘perform dynamic bodylanguage model’, under option select ‘pelcalrec’, ‘ run static gait model’ and ‘save trial’, choose ‘process now’
6. Open dynamic trial, identify event for initial contact of force plate and toe off of force plate using diamond symbol
7. In ‘pipeline’ chose: ‘fill gaps (restricted to 30 samples)’, ‘apply woltring filtering routine (predicted MSE 20)’, ‘perform dynamic bodylanguage modeling (pelvis calrec)’, ‘generate gait cycle parameters’, ‘run dynamic gait model’ and ‘save trial’, choose ‘process now’
8. In notepad create a .txt file
9. Identify subject name TAB name of trial TAB mass of subject (kg) TAB height of subject (m)
10. Repeat for all desired trials and subjects and save .txt files
11. In Labview 7.1 click open Vicon Parameter Extractor
12. Open .txt file
13. In ‘process file namefield’ browse folder for .txt file that was just created
14. In ‘common path’ identify common folder where all Vicon files are stored
15. In ‘processing settings’ choose from .c3d event files and ‘define parameters’
16. Under ‘output parameters’ choose appropriate units for extraction (Nm/kg*m) and generate files (.crv, .ac, .ap, trc)
17. Run ‘select curves’ to identify the kinetic or kinematic variable that are desired, where 0=x (sagittal), 1=y (frontal), 2=z (transverse)

Figure C1. Vicon Plug-In-Gait Marker Placement



APPENDIX D

Additional Results

Tables of additional results from manuscripts 1 and 2 can be accessed on a cd stored in the University of Virginia Exercise and Sport Injury Laboratory.

Table D1. Group pre-test demographics

Descriptives

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
age	control	6	14.8333	.40825	.16667	14.4049	15.2618	14.00	15.00
	plyometric	9	15.1111	1.05409	.35136	14.3009	15.9214	14.00	17.00
	core stability	8	14.5000	.75593	.26726	13.8680	15.1320	13.00	15.00
	Total	23	14.8261	.83406	.17391	14.4654	15.1868	13.00	17.00
pre_height	control	6	168.6167	4.54067	1.85372	163.8515	173.3818	161.80	174.00
	plyometric	9	172.1222	8.00215	2.66738	165.9712	178.2732	162.00	185.00
	core stability	8	167.9000	8.67311	3.06641	160.6491	175.1509	156.00	182.00
	Total	23	169.7391	7.47011	1.55762	166.5088	172.9694	156.00	185.00
pre_mass	control	6	52.1167	6.12484	2.50046	45.6890	58.5443	40.10	56.40
	plyometric	9	62.5778	8.83371	2.94457	55.7876	69.3680	49.60	73.40
	core stability	8	56.8000	7.93257	2.80459	50.1682	63.4318	50.40	74.20
	Total	23	57.8391	8.68524	1.81100	54.0834	61.5949	40.10	74.20

Table D2. Pre-test group demographic statistical comparison.

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
age	Between Groups	1.582	2	.791	1.153	.336
	Within Groups	13.722	20	.686		
	Total	15.304	22			
pre_height	Between Groups	85.731	2	42.865	.751	.485
	Within Groups	1141.924	20	57.096		
	Total	1227.655	22			
pre_mass	Between Groups	407.211	2	203.605	3.252	.060
	Within Groups	1252.324	20	62.616		
	Total	1659.535	22			

Table D3. Group post-test demographics

Descriptives

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
age	control	6	14.8333	.40825	.16667	14.4049	15.2618	14.00	15.00
	plyometric	9	15.1111	1.05409	.35136	14.3009	15.9214	14.00	17.00
	core stability	8	14.5000	.75593	.26726	13.8680	15.1320	13.00	15.00
	Total	23	14.8261	.83406	.17391	14.4654	15.1868	13.00	17.00
post_height	control	6	168.91667	4.426925	1.807285	164.27089	173.56244	162.500	174.000
	plyometric	9	172.47778	7.826362	2.608787	166.46190	178.49365	164.000	185.000
	core stability	8	169.31250	7.358656	2.601678	163.16051	175.46449	156.500	182.300
	Total	23	170.44783	6.837455	1.425708	167.49109	173.40456	156.500	185.000
post_mass	control	6	52.03333	5.708123	2.330331	46.04303	58.02364	40.600	55.600
	plyometric	9	62.95556	9.046976	3.015659	56.00143	69.90968	51.600	74.600
	core stability	8	57.42500	7.776476	2.749399	50.92370	63.92630	50.600	74.000
	Total	23	58.18261	8.732159	1.820781	54.40654	61.95868	40.600	74.600

Table D4. Group post-test demographics statistical comparison

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
age	Between Groups	1.582	2	.791	1.153	.336
	Within Groups	13.722	20	.686		
	Total	15.304	22			
post_height	Between Groups	61.465	2	30.732	.636	.540
	Within Groups	967.053	20	48.353		
	Total	1028.517	22			
post_mass	Between Groups	436.502	2	218.251	3.517	.049
	Within Groups	1241.011	20	62.051		
	Total	1677.513	22			

Table D5. Group post-test demographics post-hoc analysis

Multiple Comparisons

Tukey HSD

Dependent Variable	(I) group	(J) group	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
age	control	plyometric	-.27778	.43656	.802	-1.3823	.8267
		core stability	.33333	.44734	.740	-.7984	1.4651
	plyometric	control	.27778	.43656	.802	-.8267	1.3823
		core stability	.61111	.40249	.304	-.4072	1.6294
	core stability	control	-.33333	.44734	.740	-1.4651	.7984
		plyometric	-.61111	.40249	.304	-1.6294	.4072
post_height	control	plyometric	-3.561111	3.664872	.603	-12.83317	5.71095
		core stability	-.395833	3.755376	.994	-9.89687	9.10520
	plyometric	control	3.561111	3.664872	.603	-5.71095	12.83317
		core stability	3.165278	3.378845	.624	-5.38314	11.71369
	core stability	control	.395833	3.755376	.994	-9.10520	9.89687
		plyometric	-3.165278	3.378845	.624	-11.71369	5.38314
post_mass	control	plyometric	-10.922222*	4.151657	.041	-21.42584	-.41860
		core stability	-5.391667	4.254183	.429	-16.15467	5.37134
	plyometric	control	10.922222*	4.151657	.041	.41860	21.42584
		core stability	5.530556	3.827639	.338	-4.15330	15.21441
	core stability	control	5.391667	4.254183	.429	-5.37134	16.15467
		plyometric	-5.530556	3.827639	.338	-15.21441	4.15330

*. The mean difference is significant at the 0.05 level.

Table D6. DVJ mean peak kinematic and kinetic variables correlated with LST score

Descriptive Statistics

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
LSTOverall	19	4.000	1.000	5.000	3.05263	1.129094	-.113	.524	-.175	1.014
LatSpineFlexAng	18	6.756	3.796	10.552	6.61953	1.839990	.214	.536	-.306	1.038
HipFlexAng	19	57.587	24.746	82.334	62.42538	16.170910	-.795	.524	-.083	1.014
HipAddAng	19	24.742	-12.207	12.535	-1.27031	5.732155	.720	.524	1.379	1.014
HipIRAng	18	45.554	-8.286	37.269	9.31604	11.461901	.490	.536	.723	1.038
KneeFlexAng	19	58.584	56.566	115.150	85.40209	15.034057	-.273	.524	-.014	1.014
KneeValgusAng	19	51.638	-46.925	4.713	-9.56585	13.510018	-1.447	.524	1.810	1.014
KneeIRAng	18	43.842	9.590	53.432	36.12574	12.052092	-.461	.536	-.135	1.038
HipFlexMom	19	1.069	.607	1.676	1.10930	.303047	.531	.524	-.201	1.014
HipAddMom	19	.816	.032	.848	.38633	.233416	.493	.524	-.757	1.014
HipIRMom	19	.447	.098	.544	.23569	.122452	1.236	.524	1.359	1.014
KneeFlexMom	19	.686	.500	1.186	.89718	.151805	-.849	.524	2.172	1.014
KneeValgusMom	19	.217	-.296	-.078	-.20838	.063336	.579	.524	-.346	1.014
KneeIRMom	19	.081	-.003	.078	.03526	.021319	.370	.524	-.356	1.014
Valid N (listwise)	17									

Table D7. Pearson product moment correlations for normally distributed DVJ data

Correlations

		LSTOverall	LatSpineFlexAng	HipFlexAng	HipIRAng	KneeFlexAng	KneeIRAng	HipFlexMom	HipAddMom	KneeValgusMom	KneeIRMom
LSTOverall	Pearson Correlation	1.000	-.090	-.252	.109	-.346	-.011	-.236	.144	.037	-.016
	Sig. (2-tailed)		.724	.297	.666	.147	.964	.330	.557	.880	.950
	N	19.000	18	19	18	19	18	19	19	19	19
LatSpineFlexAng	Pearson Correlation	-.090	1.000	-.135	-.311	.234	.304	-.212	-.132	.067	-.060
	Sig. (2-tailed)	.724		.594	.210	.351	.235	.399	.601	.792	.813
	N	18	18.000	18	18	18	17	18	18	18	18
HipFlexAng	Pearson Correlation	-.252	-.135	1.000	-.221	.677**	.399	.371	.075	-.154	.296
	Sig. (2-tailed)	.297	.594		.379	.001	.101	.118	.761	.528	.219
	N	19	18	19.000	18	19	18	19	19	19	19
HipIRAng	Pearson Correlation	.109	-.311	-.221	1.000	-.073	-.259	.079	.034	-.050	.206
	Sig. (2-tailed)	.666	.210	.379		.773	.316	.755	.894	.843	.411
	N	18	18	18	18.000	18	17	18	18	18	18
KneeFlexAng	Pearson Correlation	-.346	.234	.677**	-.073	1.000	.357	.170	-.134	-.204	.108
	Sig. (2-tailed)	.147	.351	.001	.773		.146	.486	.585	.403	.659
	N	19	18	19	18	19.000	18	19	19	19	19
KneeIRAng	Pearson Correlation	-.011	.304	.399	-.259	.357	1.000	.056	.423	.050	.359
	Sig. (2-tailed)	.964	.235	.101	.316	.146		.827	.080	.845	.143
	N	18	17	18	17	18	18.000	18	18	18	18
HipFlexMom	Pearson Correlation	-.236	-.212	.371	.079	.170	.056	1.000	.229	-.613**	.348
	Sig. (2-tailed)	.330	.399	.118	.755	.486	.827		.345	.005	.145
	N	19	18	19	18	19	18	19.000	19	19	19
HipAddMom	Pearson Correlation	.144	-.132	.075	.034	-.134	.423	.229	1.000	.284	.438
	Sig. (2-tailed)	.557	.601	.761	.894	.585	.080	.345		.239	.061
	N	19	18	19	18	19	18	19	19.000	19	19
KneeValgusMom	Pearson Correlation	.037	.067	-.154	-.050	-.204	.050	-.613**	.284	1.000	-.010
	Sig. (2-tailed)	.880	.792	.528	.843	.403	.845	.005	.239		.968
	N	19	18	19	18	19	18	19	19	19.000	19
KneeIRMom	Pearson Correlation	-.016	-.060	.296	.206	.108	.359	.348	.438	-.010	1.000
	Sig. (2-tailed)	.950	.813	.219	.411	.659	.143	.145	.061	.968	
	N	19	18	19	18	19	18	19	19	19	19.000

**. Correlation is significant at the 0.01 level (2-tailed).

Table D8. Spearman rho correlations for non-parametric DVJ data

Correlations

		LSTOverall	HipAddAng	KneeValgus Ang	HipIRMom	KneeFlexMom
LSTOverall	Pearson Correlation	1.000	.145	-.174	-.421	.048
	Sig. (2-tailed)		.552	.477	.072	.846
	N	19.000	19	19	19	19
HipAddAng	Pearson Correlation	.145	1.000	-.061	-.170	.399
	Sig. (2-tailed)	.552		.805	.488	.090
	N	19	19.000	19	19	19
KneeValgusAng	Pearson Correlation	-.174	-.061	1.000	-.004	-.172
	Sig. (2-tailed)	.477	.805		.987	.481
	N	19	19	19.000	19	19
HipIRMom	Pearson Correlation	-.421	-.170	-.004	1.000	.059
	Sig. (2-tailed)	.072	.488	.987		.812
	N	19	19	19	19.000	19
KneeFlexMom	Pearson Correlation	.048	.399	-.172	.059	1.000
	Sig. (2-tailed)	.846	.090	.481	.812	
	N	19	19	19	19	19.000

Table D9. SSC mean peak kinematic and kinetic variables correlated with LST score

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
LSTOverall	23	1.000	5.000	2.65217	1.152416	-.018	.481	-.690	.935
LatSpineFlexAng	23	8.210	30.519	18.50120	5.278574	.355	.481	.286	.935
HipFlexAng	23	30.663	62.493	46.69085	9.101816	-.081	.481	-1.036	.935
HipAddAng	23	-25.130	7.953	-7.55648	7.400531	-.269	.481	.389	.935
HipIRAng	23	-17.363	26.923	9.61615	11.329988	-.640	.481	.332	.935
KneeFlexAng	23	41.852	64.898	54.51217	5.976863	-.369	.481	-.231	.935
KneeValgusAng	23	-41.407	1.667	-12.59424	11.545045	-.853	.481	.170	.935
KneeIRAng	23	12.738	57.025	34.88477	9.480323	-.127	.481	.989	.935
HipFlexMom	22	1.125	3.566	2.01133	.657130	.579	.491	-.129	.953
HipAddMom	22	.544	2.145	1.01426	.413261	1.053	.491	.899	.953
HipIRMom	22	.095	.612	.26827	.144728	.823	.491	-.076	.953
KneeFlexMom	22	1.000	2.620	1.80066	.443988	.174	.491	-.970	.953
KneeValgusMom	22	-1.401	-.206	-.58939	.308562	-.966	.491	.680	.953
KneeIRMom	22	.074	.407	.17252	.078020	1.397	.491	2.653	.953
Valid N (listwise)	22								

Table D10. Pearson product moment correlations for normally distributed SSC data

Correlations

		LSTOverall	LatSpineFlex Ang	HipAddAng	HipIRAng	KneeFlexAng	KneeValgus Ang	KneeIRAng	HipFlexMom	HipIRMom	KneeFlexMom	KneeValgus Mom
LSTOverall	Pearson Correlation	1.000	.003	.063	-.244	-.210	-.209	.361	-.230	-.107	-.182	.054
	Sig. (2-tailed)		.990	.775	.262	.337	.338	.091	.303	.634	.418	.810
	N	23.000	23	23	23	23	23	23	22	22	22	22
LatSpineFlexAng	Pearson Correlation	.003	1.000	.342	-.019	-.140	.133	-.167	.130	-.205	-.108	.059
	Sig. (2-tailed)	.990		.111	.932	.524	.545	.446	.565	.359	.632	.793
	N	23	23.000	23	23	23	23	23	22	22	22	22
HipAddAng	Pearson Correlation	.063	.342	1.000	.355	-.130	.295	-.263	-.479*	-.524*	-.306	.649**
	Sig. (2-tailed)	.775	.111		.096	.554	.172	.226	.024	.012	.166	.001
	N	23	23	23.000	23	23	23	23	22	22	22	22
HipIRAng	Pearson Correlation	-.244	-.019	.355	1.000	.136	.770**	-.408	-.134	-.555**	-.668**	.641**
	Sig. (2-tailed)	.262	.932	.096		.535	.000	.053	.553	.007	.001	.001
	N	23	23	23	23.000	23	23	23	22	22	22	22
KneeFlexAng	Pearson Correlation	-.210	-.140	-.130	.136	1.000	.164	.163	-.086	.027	.201	-.089
	Sig. (2-tailed)	.337	.524	.554	.535		.455	.459	.704	.906	.370	.695
	N	23	23	23	23	23.000	23	23	22	22	22	22
KneeValgusAng	Pearson Correlation	-.209	.133	.295	.770**	.164	1.000	-.418*	-.152	-.496*	-.566**	.333
	Sig. (2-tailed)	.338	.545	.172	.000	.455		.047	.499	.019	.006	.130
	N	23	23	23	23	23	23.000	23	22	22	22	22
KneeIRAng	Pearson Correlation	.361	-.167	-.263	-.408	.163	-.418*	1.000	-.099	.329	.039	-.342
	Sig. (2-tailed)	.091	.446	.226	.053	.459	.047		.663	.135	.862	.119
	N	23	23	23	23	23	23	23.000	22	22	22	22
HipFlexMom	Pearson Correlation	-.230	.130	-.479*	-.134	-.086	-.152	-.099	1.000	.305	.074	-.315
	Sig. (2-tailed)	.303	.565	.024	.553	.704	.499	.663		.167	.743	.154
	N	22	22	22	22	22	22	22	22.000	22	22	22
HipIRMom	Pearson Correlation	-.107	-.205	-.524*	-.555**	.027	-.496*	.329	.305	1.000	.533*	-.754**
	Sig. (2-tailed)	.634	.359	.012	.007	.906	.019	.135	.167		.011	.000
	N	22	22	22	22	22	22	22	22	22.000	22	22
KneeFlexMom	Pearson Correlation	-.182	-.108	-.306	-.668**	.201	-.566**	.039	.074	.533*	1.000	-.503*
	Sig. (2-tailed)	.418	.632	.166	.001	.370	.006	.862	.743	.011		.017
	N	22	22	22	22	22	22	22	22	22	22.000	22
KneeValgusMom	Pearson Correlation	.054	.059	.649**	.641**	-.089	.333	-.342	-.315	-.754**	-.503*	1.000
	Sig. (2-tailed)	.810	.793	.001	.001	.695	.130	.119	.154	.000	.017	
	N	22	22	22	22	22	22	22	22	22	22	22.000

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Table D11. Spearman rho correlations for non-parametric SSC data

Correlations

		LSTOverall	HipFlexAng	HipAddMom	KneelRMom
LSTOverall	Pearson Correlation	1.000	.199	.210	.331
	Sig. (2-tailed)		.363	.348	.133
	N	23.000	23	22	22
HipFlexAng	Pearson Correlation	.199	1.000	-.294	-.044
	Sig. (2-tailed)	.363		.184	.847
	N	23	23.000	22	22
HipAddMom	Pearson Correlation	.210	-.294	1.000	.503*
	Sig. (2-tailed)	.348	.184		.017
	N	22	22	22.000	22
KneelRMom	Pearson Correlation	.331	-.044	.503*	1.000
	Sig. (2-tailed)	.133	.847	.017	
	N	22	22	22	22.000

*. Correlation is significant at the 0.05 level (2-tailed).

Table D12. Control group within group comparison for LST score

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	pre_LST_score	2.8333	6	1.47196	.60093
	post_LST_score	2.66667	6	.816497	.333333

Table D13. Plyometric group within group comparison for LST score

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	pre_LST_score	3.1250	8	.99103	.35038
	post_LST_score	2.37500	8	1.060660	.375000

Table D14. Core stability group within group comparison for LST score

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	pre_LST_score	2.5000	8	1.19523	.42258
	post_LST_score	3.12500	8	.834523	.295048

APPENDIX E

Recommendations for Future Research

- Analyze kinematic and kinetic variable change scores based on high risk and low risk to determine if the high risk subjects responded more significantly to the intervention as compared the group as a whole.
- Include a male control group to determine whether subjects post-intervention more closely resembled male subjects.
- Perform a similar study with the addition of younger athletes to see if less mature females respond similarly to plyometric and core stability training when compared to high school athletes.
- Group individuals based on LST scores (good, medium, poor) and perform curve analysis with confidence interval bands for hip and knee joint kinematics and kinetics to determine if the groups demonstrate different movement patterns over the course of the stance phase during a DVJ and SSC.
- Run a correlation between the LST score and peak values for all possible kinematic and kinetic variables at the hip.
- Use a principle components analysis to determine the amount of explained variance of the LST score by kinematic and kinetic variables during cutting and landing.
- Categorize subjects based on the baseline LST scores prior to participating in an intervention to better understand who responds to neuromuscular control training.

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