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Muscle Strength in the Lower Extremity Does Not Predict Postinstruction Improvements in the Landing Patterns of Female Athletes

Female athletes who participate in cutting and pivoting sports are at particularly high risk for sustaining an anterior cruciate ligament (ACL) injury.[2] The unusually high rate of ACL tears is of particular concern, in light of increasing female participation in collegiate sports since the passage of Title IX legislation. The majority of ACL injuries in female athletes are noncontact in nature[2] and occur frequently during cutting tasks

• **STUDY DESIGN:** Preinstruction and postinstruction testing in a laboratory setting.

• **OBJECTIVES:** To examine the predictive relationship between lower extremity muscle strength and the immediate postinstruction changes in landing patterns of female athletes. We hypothesized that greater strength would be associated with larger postinstruction improvements in landing patterns.

• **BACKGROUND:** Female athletes in high-demand sports may be predisposed to anterior cruciate ligament injury because of poor landing patterns. Instruction has been shown to improve landing patterns. Lower extremity muscular strength may determine the potential for instruction to alter landing patterns.

• **METHODS AND MEASURES:** Thirty-seven female collegiate athletes in high-demand sports participated. Strength was assessed in the following muscle groups: trunk extensors and flexors, hip abductors and extensors, knee flexors and extensors, and ankle plantar flexors. Strength testing was followed by kinetic and kinematic analysis of a drop vertical jump task. Athletes then received verbal instruction on how to improve their landing technique and were retested. Landing variables of interest were force absorption time, peak vertical ground reaction force (vGRF), peak knee flexion and abduction angle, and peak external knee abduction moment. Preinstruction and postinstruction landing variables data were compared. Linear regression models were created with strength values as independent variables and landing variables as dependent variables.

• **RESULTS:** After instruction, athletes significantly increased their force absorption time and peak knee flexion angle, while decreasing their peak vGRF, peak knee abduction angle, and peak external knee abduction moment ($P<.001$). None of the regression models were statistically significant ($P>.05$).

• **CONCLUSIONS:** A brief instructional session promotes short-term improvements in the landing patterns of collegiate female athletes, but muscular strength was a poor predictor of the improvements.

• **LEVEL OF EVIDENCE:** Prognosis, level 4.
J Orthop Sports Phys Ther 2008;38(6):353-361. doi:10.2519/jospt.2008.2726

• **KEY WORDS:** *ACL, biomechanics, hip, knee, motion analysis*

SUPPLEMENTAL VIDEOS ONLINE

or when landing from a jump.[6] Female athletes have repeatedly demonstrated a landing pattern characterized by decreased knee flexion and increased knee valgus, with greater relative vertical ground reaction force and external knee abduction moment in comparison to their male counterparts.[9,15,17,29] Utilization of such a landing pattern has been identified as a factor increasing the risk of ACL injury in female athletes.[8]

Neuromuscular deficits such as muscle weakness or impaired muscle coordination have been identified as substantial and potentially modifiable risk factors related to the gender bias in ACL injury rate.[4] These neuromuscular risk factors are particularly interesting to rehabilitation specialists, as they represent factors that may be amendable to training intervention. In fact, ACL injury prevention programs have had success in correcting potentially risky landing patterns[10,14,20,26] and also in reducing the rate of injury in female athletes.[7,16,22]

Not all training programs have had significant success in reducing ACL injury rates, and female athletes may not universally experience the same magnitude of landing pattern improvement. For example, Pfeiffer et al[24] recently published the results of a randomized

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controlled trial that found no reduction in ACL injury rate in the female athletes who participated. The training consisted of a 20-minute, 2-times-per-week plyometric-based exercise program focused on mechanics and alignment of the lower extremity when landing from a jump and deceleration with directional changes when running.[24] Myer and colleagues[20] have recently reported that female athletes who are at high risk for ACL tear, as classified by their large external knee abduction moment during landing from a drop vertical jump (DVJ), were able to substantially reduce their knee valgus moment after 6 weeks of training that included plyometrics instruction and training, core strengthening, balance exercises, resistance training, and speed training. Although the female athletes reduced their external knee valgus moment, they still did not reduce their moments to values similar to their low-risk female counterparts.[20] Clearly, there is room to improve outcomes of ACL injury prevention programs for female athletes.

Improving muscle strength through strength training could be a key component to successful ACL injury prevention programs. Training often includes instruction to encourage greater knee flexion with less knee valgus during landing, as well as asking athletes to land on their toes.[9] While this instruction is successful at reducing the ground reaction forces associated with landing,[9,18] this landing style could place greater work demand on the lower extremity musculature to absorb the impact of landing.

Female athletes have repeatedly demonstrated weakness in the lower extremity musculature compared to males,[15,28] and it is conceivable that insufficient muscle strength may limit the capacity of female athletes to adopt a less risky landing strategy. Moreover, it is possible that female athletes with significant muscle weakness could experience a decline in athletic performance concomitant with landing pattern improvements, due to the high muscular efforts required for desirable landing technique. The relationship between lower extremity muscular strength and the ability to alter landing patterns in female athletes merits further investigation.[4] It may be necessary to first implement a dedicated strength-building protocol in weak athletes prior to implementing jump training to improve the efficacy of landing instruction.

It is the primary purpose of this investigation to determine if muscular strength in the lower extremity of female athletes is predictive of the amount of improvement in jump landing that occurs following instruction. We define improvement in landing pattern as a slower loading rate, reduced vertical ground reaction force, an increase in knee flexion angle, decreased knee abduction (valgus) angle, and decreased external knee abduction moment following instruction in female athletes. Data have suggested that a wide range of muscles in the lower extremity may play an important role in influencing landing patterns.[4,15,28] Therefore, we chose to conduct a broad sampling of muscles from the lower extremity including the trunk extensors and flexors, hip abductors and extensors, knee extensors and flexors, and ankle plantar flexors. We hypothesized that postinstruction landing patterns would have a longer landing time, reduced vertical ground reaction force, increased knee flexion angle, decreased knee abduction (valgus) angle, and decreased external knee abduction moment in female athletes. We further posited that greater muscle strength in the lower extremity would be predictive of greater magnitude of landing pattern improvements.

Our secondary objective was to determine if changing the landing pattern would negatively impact athletes' jump performance. The potential impact of solely changing landing patterns on the end result of jump height has not been fully described in previous investigations. As mentioned previously, while landing instruction can successfully reduce landing forces,[18] it may do so at the expense of decreased jump height. Thus, we further hypothesized that brief instruction in landing technique would significantly reduce the athletes' jump height during a DVJ from their preinstruction height. We anticipated that muscle strength would be a positive predictor of change in jump height during the DVJ task.

METHODS

Subjects

THIRTY-SEVEN FEMALE, COLLEGIATE athletes were recruited for this study (average ± SD age, 19.5 ± 1.2 years; body mass, 74.6 ± 7.8 kg; height, 1.73 ± 0.09 m; body mass index, 24.8 ± 1.8 kg/m^2). All athletes were participants in sports that involved cutting and pivoting, such as soccer (10), basketball (11), tennis (9), and volleyball (7). The average ± SD experience in each athlete's respective sport was 10.6 ± 3.2 years. To be included in the study, potential subjects had to be at least 18 years old and could not have significant physical limitations or pain in the lower extremities or lumbar region, surgery for a lower extremity or low back injury in the past 6 months, or a history of serious past lower extremity injury or surgery, such as ligament tear or reconstruction. Recruitment was performed through group invitations to athletes at their team meetings and prior to practice sessions. All athletes were tested when they were outside of their competitive season. Six of the 37 athletes reported receiving some form of jump landing training in the past. The amount of training reported by those 6 athletes was 2, 4, 16, and 36 hours, and the remaining 2 athletes reporting over 100 hours. The athletes with 4, 16, and 36 hours completed their training 2 months before testing and the remaining 3 athletes in this subgroup completed their training more than 6 months prior to testing. Prior jump landing training was not part of the exclusion criteria, as the amount of training needed to elicit a change in landing pattern and the lasting effects of training on landing patterns has not been definitively established. All athletes provided signed informed consent as approved by the Institutional Review Board

for Human Subjects Research at Eastern Washington University.

Testing Protocol

McNair and colleagues[18] have shown that even brief instruction can positively alter an athlete's landing strategy, so we chose to use a repeated-measures design that utilized within-day comparisons as a first attempt towards understanding the influence strength may have on the magnitude of landing-pattern improvement. Athletes underwent 1 testing session that lasted no more than 2 hours. The order of procedures was 5 minutes of stationary bicycling with no resistance, followed by lower extremity strength testing, placement of reflective markers, standing kinematic data calibration, motion analysis assessments of the DVJ task, 5 minutes of jump landing instruction, reassessment of the DVJ, and strength assessment of the trunk extensors and flexors. Only the dominant lower extremity was tested, with the strength measures and limb dominance determined by asking the athletes which foot they would chose to kick a ball for distance (36, right; 1, left). Typically, athletes would attend data collections in groups of 2 to 3 at a time; so testing of athletes was often completed concurrently. For example, 1 athlete might have been on the stationary cycle, while another was completing motion analysis, and another was completing trunk strength assessment.

Strength Testing

The muscle groups that were tested were the trunk extensors and flexors, hip abductors and extensors, knee extensors and flexors, and ankle plantar flexors. Trunk extensor and flexor strength were measured by counting the number of half sit-ups and back extensions that were completed in a minute. These tests are easy to administer and clinically reproducible. For both measures, the tester would count out loud with the successful completion of each repetition. In addition, the athletes were informed when the tests were "half way done" (ie, 30 seconds) and when there was "10 seconds left." Two test repetitions were completed prior to initiating an actual test trial to familiarize the athlete with the test procedure.

The trunk extensors were tested first with the athlete starting in prone on a padded treatment table with their anterior superior iliac spines positioned near the edge of the table. The athlete started in a flexed position with her trunk aligned perpendicular to the floor, arms crossed over the chest, and hands on shoulders. The athlete was stabilized in place with inelastic straps encircling the table and the athlete's shanks and pelvis. Upon the command of "go," the athlete was asked to repeatedly raise up to parallel with the floor, then lower down back to the starting position, for as many repetitions possible in a minute. The tester placed the athlete's hand above the athlete, at the position where the athlete would reach parallel, to cue the athlete that the repetition was completed. If the athlete did not fully extend to touch the testers hand or did not return all the way to the starting position, then the repetition was not counted. In a study by Moreland et al,[19] timed trunk extension tests exhibited acceptable reliability (ICC = 0.78) and preferential reliability, when compared to extensor isometric force measurement with a handheld dynamometer (HHD).

Trunk flexor measurement was derived from the American College of Sports Medicine's exercise testing and prescription handbook.[1] The athlete was in supine on a padded plinth, with knees flexed to 90°, and shoes positioned flat on the treatment table surface. Knee angle was assessed with a plastic long-arm goniometer. The feet were secured to the table with an inelastic strap that encircled the feet and the table surface. The athlete rested her arms on the table surface, with hands flat on the table and fingers extended. A piece of tape was placed 12 cm distal to the tip of the fingers across the table. The athlete was asked to flex her trunk towards her knees, as if performing an abdominal crunch exercise, while reaching with her arms on the table for the piece of tape. A repetition consisted of starting flat on the table, rising to touch the tape with her fingers, and returning to the start position. This timed half situp test has a moderate correlation (r = 0.433) with isometric abdominal strength and an acceptable intratester reliability (ICC = 0.853) when testing women.[5]

Athletes performed 3 warm-up trials at submaximal intensity and up to 3 repetitions of a maximal voluntary isometric contraction (MVIC) lasting 3 seconds for the muscles of the hip, knee, and ankle. Strong verbal encouragement was provided with each strength trial to help evoke maximal voluntary responses. Between each MVIC repetition, athletes rested for approximately 1 minute.

Hip muscle strength was tested using a MICROFET 2 (Hoggan Health Industries, Draper, UT) HHD. The moment arm, or shortest perpendicular distance between the line of action of the resistant force of the HHD (center of the HHD on the skin), and the axis of the hip joint (superior tip of the greater trochanter) were measured for each hip muscle strength test using a flexible tape measure. The muscle torque produced during MVIC was determined by multiplying the peak force measured by the HHD during contraction by the corresponding moment arm.

For the hip muscle testing, the athletes were positioned and tested based on the tenets of traditional manual muscle testing procedures, as described by Kendall et al.[12] For the hip abductors, the positioning mimicked the previous description of Bolgla et al[3] and Willson et al.[28] Athletes lay on their nondominant side atop a padded treatment table, with their knee in contact with the table, bent to 90° of flexion, and hip placed in slight flexion. The tested lower extremity was positioned straight, with zero to slight hip abduction, and supported by pillows to negate the influence of gravity on strength measurements. The HHD was secured between the thigh and the table using an inflexible seatbelt strap positioned 5 cm proximal to the knee joint line. A second strap was placed just above the waist to

secure the torso. A folded pillowcase was placed between the HHD and limb to reduce discomfort during hip strength testing. The HHD force transducer was zeroed prior to MVIC to eliminate the force exerted on the HHD, by strapping the lower extremity in place.

For hip extensor muscle testing, each athlete was positioned in prone on a padded treatment table, with her knee bent at 90° and lower extremity supported by the table, as described by Robinson et al.[27] One pillow was placed beneath the pelvis so the subject was in slight hip flexion. The HHD was secured to the thigh, using a seatbelt strap that surrounded the subject and the table just proximal to the knee joint line on the proximal aspect of the thigh. A second strap secured the torso. Previous reports using similar methodology report that the use of HHD to determine hip muscle strength has an acceptable level of intratester reliability for the purposes of this study (hip abduction: Willson et al,[28] ICC = 0.95; Piva et al,[25] ICC = 0.85; hip extension: Robinson et al,[27] ICC = 0.97).

Measurement of MVIC of the knee extensors, knee flexors, and ankle plantar flexor muscles was performed with an electromechanical dynamometer (Kin-Com 125 e+; Chattecx Corp, Hixon, TN). For each test, the axis of the dynamometer was oriented to match the axis of the test joint. The Kin-Com has a data screen that provides realtime visual feedback of force production to augment verbal encouragement to help motivate maximal muscle contraction. The forces generated during strength testing were sampled at 200 Hz, utilizing a BIOPAC MP 150 (Biopac Systems Inc, Santa Barbara, CA) data acquisition workstation with Acqknowledge, Version 3.7 software. The digital data were processed with a 6-Hz low-pass filter prior to determining MVIC.

For knee extensor testing, athletes were seated with their hip flexed to 90° and the knee flexed to 90°. The distal edge of the shin attachment was placed 5 cm proximal to the lateral malleolus. A waist strap was used for stabilization. During strength testing of the knee flexors, athletes were positioned in prone with a towel placed proximal to the patella to prevent potential anterior knee discomfort during testing. The knee was positioned at 15° of flexion, and the distal end of the shin attachment was placed 5 cm proximal to the lateral malleolus. An inflexible seatbelt was placed around the subject's thigh to control leg movement during testing. For testing of the ankle plantar flexors, the axis of the ankle joint was aligned with the axis of the dynamometer. The ankle was strapped at the ankle joint and over the toes to hold the foot in a position of 0° plantar flexion. The lower leg was stabilized in place using an inelastic belt.

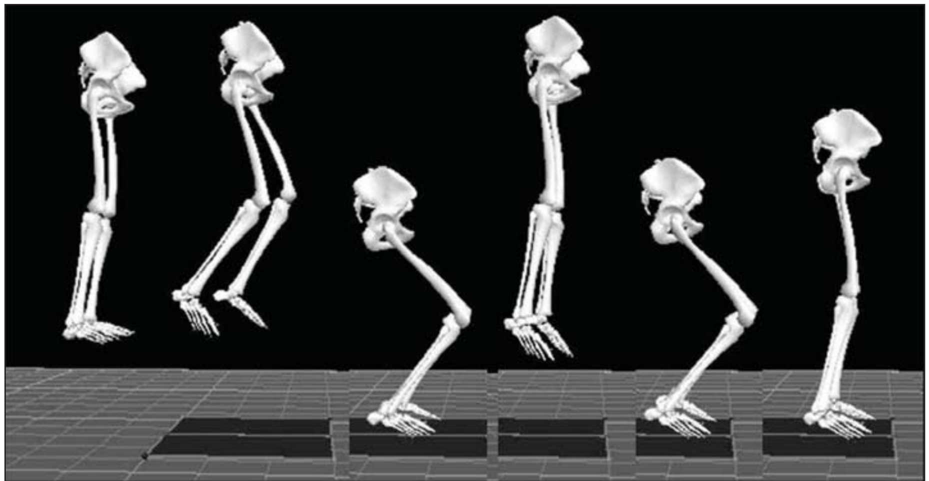

FIGURE 1. Representative series of still frames from the bone model created in Visual 3D software during the drop vertical jump task. The dark rectangles on the floor represent the force plates. The individual lands on the plates from the 31-cm box, jumps up vertically, and lands again on the same platforms without forward displacement.

Drop Vertical Jump

We chose to use the DVJ task described by Hewett et al,[8] as it is one of the most studied landing tasks in the literature and the landing kinetics of athletes during this task have some predictive capacity for knee ACL injury risk.[7] The athletes were asked to complete 3 practice trials and 3 successful test trials of a DVJ (**FIGURE 1**). Athletes stood on top of a 31-cm-high box at the start of the trial. The box was positioned 3 cm away from the force plates and positioned so that each foot would land on a separate force plate during landing. Athletes were instructed to drop directly down off the box and immediately perform a maximum vertical jump. Athletes were instructed to keep their elbows bent, with their hands at the level of their shoulders, when dropping off the box to land. During the jump up phase they were instructed to extend both arms upward to maximal height, as if they were completing a volleyball blocking drill. A successful trial was counted when the entire surface of each foot landed on its respective force plate for the initial landing from the first drop and subsequent landing after the vertical jump.

Motion Capture

Motion analysis of the DVJ was performed using a 7-camera motion analysis system (VICON 624c Datastation; Workstation, Version 4.6 software; M2 cameras; Oxford Metrics, London, UK). Two force plates (Kistler Instruments, Amherst, NY) were positioned in the floor to capture the ground reaction forces for each lower extremity during landing. Retroreflective markers (14-mm diameter) were placed bilaterally to identify the joint centers of the ankle, knee, and hip, as well as the top of the iliac crest for defining the pelvis (**FIGURE 2**). Rigid, thermoplastic shells with 4 markers affixed to their surfaces were attached bilaterally to the shank and thigh using elastic wraps (SuperWrap; Fabrifoam, Inc, Exton, PA). A shell was also affixed over the sacrum by Velcro sewn into elastic shorts to track the pelvis. Two

markers were placed on the heel counter of the shoe, which, with the markers on the first and fifth metatarsals, provided a quartet of markers to track foot movement. Each marker set was used to create a segment's coordinate system to track its 3-dimensional position. A standing calibration was performed prior to completing the jumping trials to identify joint centers with respect to each segment's coordinate system. Force plate data were sampled at 1500 Hz and video data were sampled at 250 Hz. Marker trajectories and force plate data were respectively low-pass filtered at 6 and 50 Hz with fourth-order phase-corrected Butterworth filters. Joint kinematics was calculated using Euler angles, and joint kinetics was calculated with inverse dynamics, using rigid-body analysis and Visual 3D, Version 3.34 software (C-Motion Inc, Rockville, MD). Joint angles and moments were normalized from initial contact on the force plate to peak knee flexion during landing (ie, the landing phase), to enable the calculation of an ensemble average across trial for each subject. Ground reaction forces were combined from each plate to determine a summed force normalized to each athlete's body mass. Joint moments were expressed as external moments in the data tables and normalized to body mass (Nm/kg). External moments are the joint torques created by the ground reaction force vector, as opposed to internal, or muscle, moments, which are the net muscular produced torque and are equal but in the opposite direction to the external moments. Thus, an external knee valgus moment is a torque at the knee produced by the ground reaction force vector that would tend to make the joint move toward a greater valgus angle.

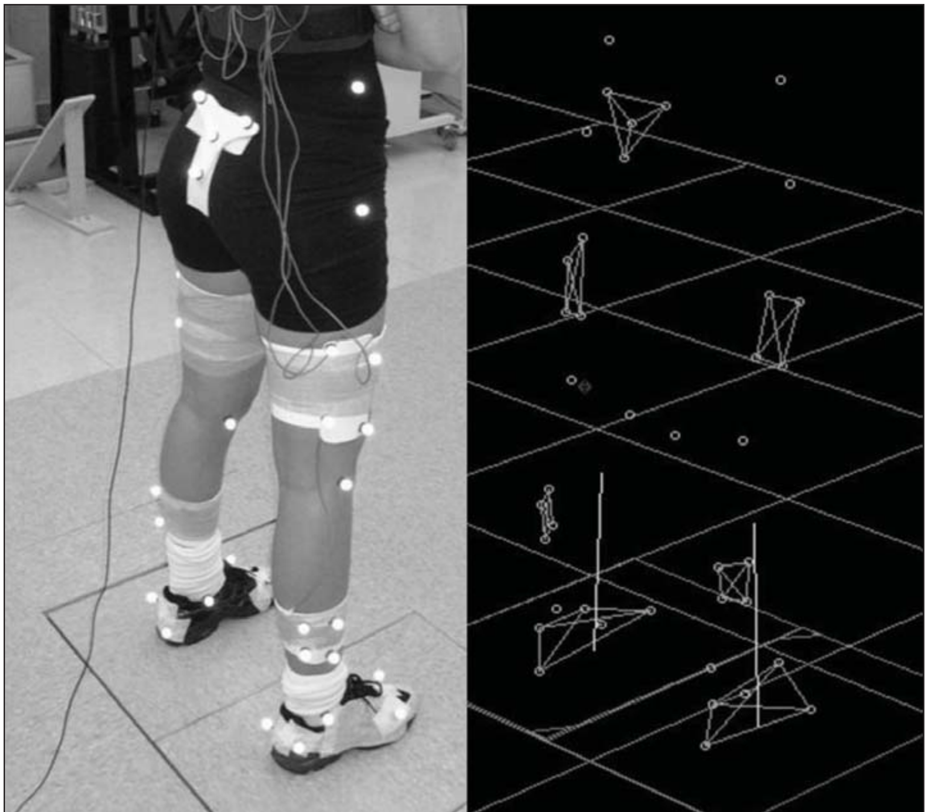

FIGURE 2. Marker set for the data collections with the corresponding visual depiction of the markers from the VICON Workstation software.

Landing Instruction

After completing the first set of DVJ, all athletes were given a brief set of verbal landing instructions that were derived chiefly from prior publications by Hewett and McNair.[9,18] The scripted instruction asked the athletes to try to land as softly as they could. They were also instructed to increase the amount of bending in their knees when they landed, and to land on their toes. They were instructed to keep their chest over their knees and their knees over their toes and avoid knee valgus during landing. Upon landing, athletes were asked to recoil like a spring, with a focus on jumping straight up like an arrow. The script also included suggestions for the athletes to minimize the sound of their landing (to be as quiet as possible) and cues for the athletes to focus on shock absorption during landing. The landing instruction started with a demonstration by the investigator of what is perceived as poor and potentially dangerous landing technique, including limited knee flexion and excessive knee valgus, followed immediately with a demonstration of the desired technique. All athletes performed at least 4 practice trials, with feedback provided after each trial related to the amount of success the athlete had in changing her landing pattern. None of the athletes had more than 5 minutes of total instruction and practice time. After instruction, motion analysis and force plate data for another 3 trials of DVJ were collected.

The peak height of the middle marker in the pelvic tracking array during the hop off of the box was used to determine the maximal height of the subject prior to landing on the ground after leaving the box (**FIGURE 3**). This hop height would be compared before and after instruction, to ensure that the same potential energy was maintained. Jump height following landing on the force plates was determined by tracking the peak height of the middle marker in the pelvic array (**FIGURE 2**) after the subject landed on the plates. The middle pelvic marker's height, obtained from the static standing calibration, was subtracted from both the hop height and jump height measurements.

Statistical Analysis

Determination of differences in the means of the variables of interest from preinstruction to postinstruction was accom-

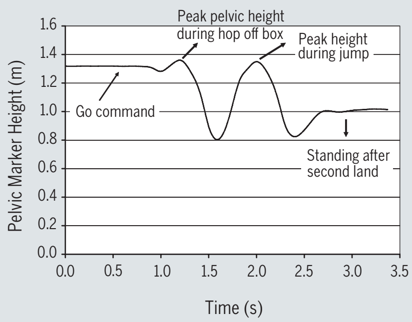

FIGURE 3. Representative trial of height of the middle marker in the pelvic tracking array during the drop vertical jump task. Time points of peak pelvic height during the hop off the box and the peak height during subsequent jump after landing are identified on the graph.

TABLE 1 Lower Extremity Kinetic and Kinematic Variables and Performance Variables Before and After Landing Instruction (Mean ± SD)

Joint Angles/Motion	Preinstruction	Postinstruction	Effect Size*	*P* Value
Peak hip angle (°)				
Flexion	52.4 ± 13.3	61.9 ± 13.0	0.71	<.001†
Adduction	1.0 ± 5.3	–0.2 ± 5.1	0.23	.013
Peak knee angle (°)				
Flexion	86.4 ± 7.3	97.7 ± 7.9	1.55	<.001†
Abduction	7.1 ± 4.5	5.9 ± 4.5	0.27	<.001†
Peak ankle angle (°)				
Dorsiflexion	28.6 ± 4.3	29.6 ± 7.8	0.23	.356
Eversion	8.6 ± 6.4	8.8 ± 5.5	0.03	.802
Moments/Motion				
Peak hip moment (BM)				
Flexion	2.09 ± 0.46	1.75 ± 0.34	0.74	<.001†
Adduction	0.10 ± 0.21	0.04 ± 0.14	0.29	.161
Peak knee moment (BM)				
Flexon	1.85 ± 0.29	1.73 ± 0.25	0.41	.006†
Abduction	0.50 ± 0.25	0.39 ± 0.18	0.44	<.001†
Peak ankle moment (BM)				
Dorsiflexion	1.50 ± 0.29	1.38 ± 0.20	0.41	.005†
Eversion	0.03 ± 0.03	0.02 ± 0.03	0.33	<.001†
Other				
Peak vGRF (BM)	3.35 ± 0.61	2.68 ± 0.33	1.10	<.001†
Pelvis height with hop (m)	1.359 ± 0.073	1.360 ± 0.073	0.01	.792
Jump height (cm)	36.1 ± 5.2	36.2 ± 4.7	0.02	.597
Landing time (sec)	0.216 ± 0.046	0.260 ± 0.045	0.96	<.001†

Abbreviations: BM, body mass; vGRF, vertical ground reaction force.
** Effect sizes were calculated by taking the absolute value of the differences in mean preinstruction to postinstruction and dividing by the standard deviation of the preinstruction measurement.*
† Denotes statistically significant differences between preinstruction and postinstructions.

plished using paired *t* tests. The capacity of strength to predict changes in each landing variable of interest was assessed using stepwise linear regression. We chose to use a stepwise linear regression model because we were interested in finding out which strength measure would best predict the magnitude of change in the landing pattern. We believe there is insufficient scientific evidence to support a preferential importance for any given muscle in the data set to merit an ordered regression analysis. The independent variables of interest for the regression analysis were the strength of the trunk extensors, trunk flexors, hip abductors, hip extensors, knee extensors, knee flexors, and ankle plantar flexors. The dependent variables of interest were percent changes in the landing variables of interest during the DVJ. Percent changes in the landing variables of interest were calculated by determining the difference between the preinstruction and postinstruction values, then dividing this difference by the preinstruction value. Positive changes with instruction were considered longer force absorption time, less vertical ground reaction force, greater knee flexion angle, less knee abduction angle, and less external knee abduction moment. Thus we performed 5 regression analyses to form predictive models for each individual dependent variable using the 7 independent variables.

The probability for entry of a given independent variable into the regression equation was a *P* value greater than or equal to .05 for the F test statistic, and the criterion for removal from the final regression equation was an F test statistic of greater than or equal to 0.10. Kleinbaum and colleagues[13] have suggested that at least 5 observations per predictor variable be included in regression analysis. There are 7 independent variables in the regression analysis, so the sample size of 37 exceeded the minimum suggested requirement of 35 athletes.

The direction and strength of relationship between the independent and dependent variables was assessed using Pearson correlation coefficients. The data were analyzed using SPSS, Version 15.0, with an alpha level set at $P \leqslant .05$ for all the analyses. To correct for potential type I errors in our paired *t* test analyses, we performed a sequential step-down Bonferroni correction for multiple comparisons. The first corrected alpha level used in the sequentially rejective (step-down) procedure was an alpha of .0031 (0.05/16 comparisons).

RESULTS

Descriptive data for the DVJ variables and muscle strength assessments are contained in **TABLE 1** and **TABLE 2**. After instruction, there was longer landing time, lower vertical ground reaction force, greater peak knee flexion angle, less knee valgus angle, and lower external knee abduction moments (**TABLE 1, ONLINE**

TABLE 2 DESCRIPTIVE DATA FOR FEMALE ATHLETE STRENGTH*

Muscle Group	Mean ± SD	Maximum	Minimum
Trunk extensors	47 ± 7	63	35
Trunk flexors	55 ± 11	85	32
Hip abductors	1.64 ± 0.27	2.25	1.19
Hip extensors	1.47 ± 0.29	2.02	0.90
Knee extensors	4.03 ± 0.73	5.48	2.07
Knee flexors	1.89 ± 0.32	2.63	1.41
Ankle plantar flexors	1.30 ± 0.34	2.00	0.42

** Units are number of repetitions in 1 minute for the trunk musculature and Nm per kg of body mass for the lower extremity musculature.*

VIDEO). There was no statistically significant difference between preinstruction and postinstruction peak pelvis heights for the drop off the box or the vertical jump portions of the DVJ task (**TABLE 1**). The $ICC_{2,1}$ values of the landing variables of interest for the 3 trials of the preinstruction DVJ were as follows: landing time, 0.82; vertical ground reaction force, 0.83; knee flexion angle, 0.86; knee valgus angle, 0.94; and knee abduction moment, 0.90. None of the stepwise regression models between the muscle strength measures and the landing variables of interest achieved a sufficient level of significance ($P>.05$). A correlation matrix between the strength measures and the change scores in variables showed no significant relationship between any of the muscle strength values and any of the changes scores for the landing variables (**TABLE 3**).

DISCUSSION

As expected, the brief bout of landing instruction produced significant short-term changes in the kinetics and kinematics of landing patterns for female collegiate athletes. Instruction induced softer landings (lower peak vertical ground reaction force) from the hop off the box during the DVJ with reduced knee moments and more flexed joint postures. Strength of the major muscles of the trunk, hip, knee, and ankle were not predictive of the degree to which landing patterns changed after landing instruction. While the landing pattern was substantially altered in a way that should reduce knee injury risk, there was no detrimental effect in the task objective of maximal vertical jump height after landing.

There is strong evidence that muscle weakness is present in female athletes when compared to male athletes,[4,15] but the results from the current investigation suggest that this weakness does not preclude female athletes from making substantial alterations in how they land from a jump. To the best of our knowledge, this project was the first to investigate the possible implications of a broad range of muscle strength on the efficacy of ACL injury prevention landing instruction in female athletes. Our sample size was adequate to test the suggested hypothesis and athletes represented a wide variety of sports in which ACL injuries are prevalent.

As the athletes' muscle strength was not predictive of changes with instruction, other neuromuscular control factors that influence how well an athlete may utilize muscle strength may play a greater role in influencing the potential for changing landing patterns. For example, coordination of muscle firing may play a more significant role than peak muscle strength in predicting the benefit of injury prevention training. There is some evidence that the amount of knee valgus during single-leg landing in female athletes corresponds with a gender-specific increase in cocontraction from the lateral knee muscles compared to the medial muscles.[23] Thus, female athletes may utilize an undesirable pattern of muscle recruitment that could promote greater dynamic knee valgus during landing.

The results of this study have good ex-

TABLE 3 PEARSON CORRELATION MATRIX BETWEEN MUSCLE STRENGTH VALUES AND PERCENT CHANGE IN THE VARIABLES OF INTEREST DURING LANDING*

	Muscle Strength Variables						
Percent Change Variables	Trunk Extensors	Trunk Flexors	Hip Abductors	Hip Extensors	Knee Extensors	Knee Flexors	Ankle Plantar Flexors
Absorption time	0.16	–0.09	–0.01	0.25	0.00	–0.13	0.00
Vertical ground reaction force	0.15	0.00	–0.19	0.00	0.09	0.00	–0.04
Jump height	–0.08	–0.06	–0.13	0.19	–0.09	–0.08	0.03
Knee flexion angle	0.03	–0.04	0.01	0.24	0.04	–0.03	0.01
Knee abduction angle	–0.06	–0.18	0.08	0.06	–0.10	–0.07	–0.02
External knee abduction moment	0.02	–0.05	–0.04	0.15	0.05	0.11	–0.03

** None of the correlations reached statistical significance (P>.05).*

ternal validity, based on comparable landing pattern changes in prior investigations. The work of McNair and colleagues[18] was used in forming the instructional script for our study, and they reported peak vertical ground reaction forces of 3.1 times body mass prior to their instruction and 13% reduction in peak force after instruction in a group of men and women. These results compare favorably to the current female-only data set, with its slightly larger peak vertical ground reaction force of 3.35 times body mass and 20% reduction in vertical ground reaction force after instruction, as females tend to land with greater relative peak vertical ground reaction force than male athletes. The average peak knee flexion angle of 86° during the initial DVJ condition tended toward a more bent position compared to prior investigations, which reported 72° and 82° in female high school athletes.[8,20] A 22% reduction in external knee valgus moment was impressive for such a short instruction session and is similar to the 21% reduction reported by Myer et al[21] after a comprehensive neuromuscular training protocol that lasted for 6 weeks. It should be noted that, while the changes in landing were substantial, it is likely that the effect is short-lived and continued instruction and training are needed for a more lasting change in landing pattern.

It could be argued that changes in landing pattern achieved during this study were merely a result of continued experience with the DVJ task. This hypothesis seems unlikely, as the variables had good consistency between trials during the preinstruction data collection. The drop heights off of the box were statistically the same between trials, so a softer landing after instruction was not due to the athletes reducing their drop height prior to landing in the postinstruction condition.

There is some previous research which suggests that muscular strength may play a role in influencing female athletes' lower limb posture during sports simulated maneuvers.[11,28] Perhaps the lack of significant correlation between strength and postinstruction changes in landing pattern were that our athletes had adequate strength and already landed in desirable joint postures, leaving little room for improvement. Such a scenario is conceivable but seems unlikely, as there were reasonable changes after instruction and there was good consistency within the landing pattern in the preinstructional condition. Strength probably has some mild impact on how athletes land, but there are likely other neuromuscular factors which have greater potential to be a limiting factor in improvements with training.

While athletes were able to make substantial changes in their landing pattern with brief instruction, they maintained comparable success in the task requirement of "jumping as high as you can" after landing from the box. So it is possible to change the landing patterns of female athletes in a manner that should potentially reduce ACL injury risk without negatively influencing their ultimate jump height. Previous investigations have shown that weeks of injury prevention training induce an improvement in jumping ability[21]; but those changes are typically accompanied by concomitant increases in muscle strength. Therefore, it is difficult to decipher if the change in jumping ability is related to the differences in movement pattern or to the increase in muscle force-producing ability. There are no strength changes between test conditions in the current investigation, so the findings may provide a more true estimation of what altering the landing pattern does to jump height performance. The athletes did spend a longer time on the ground during landing, which may be viewed as a potentially undesirable trait for some athletic maneuvers, but maximal jump height was not adversely affected.

There are several specific limitations we would like to address in regard to this study. First, we tested our hypothesis only in healthy noninjured collegiate female athletes. These findings may not carry over to athlete populations with less muscle strength, such as those athletes recovering from knee injury. It is possible that there is a threshold when muscles are too weak to provide meaningful changes in landing technique. The method of testing trunk strength could also be a potential limitation when interpreting our findings. Strength testing using a dynamometer is the most commonly utilized assessment for lower extremity strength, but there is some debate regarding the most clinically efficacious manner to test trunk musculature. Utilizing the number of repetitions completed in 1 minute is adequately reliable and could be easily reproduced in a clinic[5]; however, different findings could result when utilizing other methods of assessing trunk strength. We used the established reliability of previous investigations for our strength measures to support our choice of methodology. It is conceivable that the nuances of the strength assessments performed in our laboratory may have altered the measures' reliability. Thirdly, the inclusion of the 6 athletes with some training experience could potentially confound our study against finding differences with our instruction, as the prior training may impact their preinstruction landing pattern. There were substantial group differences in landing pattern preinstruction to postinstruction, so we felt it was acceptable to keep those 6 athletes in the analysis. Finally, the outcomes of this investigation focused only on collegiate female athletes, as they are gender biased toward knee injury in cutting and pivoting sports. The application of the findings in the current investigation should therefore be applied with caution beyond the female collegiate athlete population.

CONCLUSIONS

Female collegiate athletes were able to make desirable changes in their landing kinematics and kinetics during a drop jump within a single session of brief instruction and technique cueing. The alterations in landing pattern did not compromise the athletes' performance in vertical jump height. Muscle strength levels did not predetermine the female athletes' ability to alter their landing with instruction. Factors other than

muscle strength are ultimately more important in driving the short-term corrections of landing pattern. ◉

KEY POINTS

FINDINGS: The muscular strength of female athletes is not predictive of their substantial short-term changes in landing pattern that occur with brief instruction. It is possible to change the landing pattern in a way that should reduce ACL injury risk, without compromising the outcome of jump height after landing.
IMPLICATION: Factors other than muscle strength are ultimately more important in driving the short-term corrections of landing pattern made using instruction.
CAUTION: Only Division I collegiate female athletes were studied in this investigation, as they are gender biased toward knee injury in cutting and pivoting sports. The application of findings beyond this population, such as to athletes with muscle weakness due to injury, should be made with caution.

ACKNOWLEDGEMENTS: *We would like to acknowledge the effort and support from the student research assistants who worked on this project and were supported by a Community Service Project grant from the State of Washington's Higher Education Coordinating Board. We would also like to give special recognition to those athletes and their coaches who volunteered to participate; without their generous support and time this project could not have been completed.*

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