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original research

Lower Limb Kinematics and Dynamic Postural Stability in Anterior Cruciate Ligament-Reconstructed Female Athletes

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Context: Deficits in lower limb kinematics and postural stability are predisposing factors to the development of knee ligamentous injury. The extent to which these deficits are present after anterior cruciate ligament (ACL) reconstruction is still largely unknown.
The primary hypothesis of the present study was that female athletes who have undergone ACL reconstruction and who have returned to sport participation would exhibit deficits in dynamic postural stability as well as deficiencies in hip- and knee-joint kinematics when compared with an age-, activity-, and sex-matched uninjured control group.

Objective: To investigate dynamic postural stability as quantified by the Star Excursion Balance Test (SEBT) and simultaneous hip- and knee-joint kinematic profiles in female athletes who have undergone ACL reconstruction.

Design: Descriptive laboratory study.

Setting: University motion-analysis laboratory.

Patients or Other Participants: Fourteen female athletes who had previously undergone ACL reconstruction (ACL-R) and 17 age- and sex-matched uninjured controls.

Intervention(s): Each participant performed 3 trials of the anterior, posterior-medial, and posterior-lateral directional components of the SEBT.

Main Outcome Measure(s): Reach distances for each directional component were quantified and expressed as a percentage of leg length. Simultaneous hip- and knee-joint kinematic profiles were recorded using a motion-analysis system.

Results: The ACL-R group had decreased reach distances on the posterior-medial ($P < .01$) and posterior-lateral ($P < .01$) directional components of the SEBT. During performance of the directional components of the SEBT, ACL-R participants demonstrated altered hip-joint frontal-, sagittal-, and transverse-plane kinematic profiles ($P < .05$), as well as altered knee-joint sagittal-plane kinematic profiles ($P < .05$).

Conclusions: Deficits in dynamic postural stability and concomitant altered hip- and knee-joint kinematics are present after ACL reconstruction and return to competitive activity. The extent to which these deficits influence potential future injury is worthy of investigation.

Key Words: anterior cruciate ligament, reconstruction, kinematics, postural stability

Key Points

- Female athletes who have undergone anterior cruciate ligament (ACL) reconstruction and returned to full sport participation have decreased dynamic postural stability as quantified by the posterior-medial, and posterior-lateral reach directions of the Star Excursion Balance Test (SEBT).
- Female athletes who have undergone ACL reconstruction and returned to full sport participation have altered kinematic patterns when performing the anterior, posterior-medial, and posterior-lateral reach directions of the SEBT.
- Rehabilitation after ACL reconstruction should incorporate the SEBT as a dynamic postural-stability training tool and an evaluative tool for monitoring rehabilitation progression.
- Ongoing neuromuscular-training programs should be incorporated into daily training and practice sessions of athletes who have undergone ACL reconstruction.

Anterior cruciate ligament (ACL) rupture is a sport injury frequently incurred by athletes who are engaged in field and court sports and is of particular concern for clinicians who specialize in the treatment and rehabilitation of such athletes. A high proportion of ACL injuries are the result of a noncontact mechanism, with reports in the literature[1–3] suggesting that female athletes have a higher prevalence of noncontact ACL injuries than male athletes.

Of particular concern to clinicians and surgeons is the risk of a subsequent ACL injury after return to sport participation after ACL reconstruction. Wright et al[4] reported a reinjury incidence of 1 in 17 athletes, which is considerably higher than other reported[5,6] rates for initial ACL injury of 1 in 60 to 100 athletes. In a 5-year follow-up study of ACL-reconstructed (ACL-R) patients, Shelbourne et al[7] noted that the risk of subsequent ACL injury to either knee was 17% for patients younger than 18 years, 7% for

Table 1. IKDC Subjective Knee Form and KOOS Subscale Results[a]

	IKDC	$KOOS_{pain}$	$KOOS_{symptoms}$	$KOOS_{ADL}$	$KOOS_{sport}$	$KOOS_{KQoL}$
Control group	99.12 ± 3.62	99.82 ± 0.72	98.23 ± 2.61	99.82 ± 0.72	99.41 ± 2.42	99.29 ± 1.99
ACL-R group	82.18 ± 11.83[b]	92.00 ± 11.32[b]	85.78 ± 9.29[b]	98.07 ± 4.44	81.07 ± 15.83[b]	72.00 ± 15.15[b]
95% Confidence interval for the mean difference between groups	−23.93, −9.84	−14.40, −1.25	−17.93, −6.97	−4.33, 0.83	−27.53, −9.15	−36.08, −18.50
Effect size (η^2)	0.24 (large)	0.14 (large)	0.23 (large)	0.08 (medium)	0.21 (large)	0.29 (large)

Abbreviations: ACL-R, anterior cruciate ligament reconstructed; IKDC, International Knee Documentation Committee Subjective Knee Form; KOOS, Knee Injury and Osteoarthritis Outcome Score; $KOOS_{ADL}$, subscale for function in daily living; $KOOS_{KQoL}$, subscale for knee-related quality of life.

[a] Values are presented as mean ± SD.

[b] Different from control group.

patients aged 18 to 25 years, and 4% for patients older than 25 years.

The neuromuscular system comprises all of the sensory-, motor-, and central-integration and -processing components that govern the maintenance of joint homeostasis during dynamic movement and thus is responsible for overall functional joint stability.[8] The ACL plays an integral role in knee-joint proprioception,[9] and thus, ACL injury influences lower limb neuromuscular control and joint stability.[10] Authors of a number of recently published studies[11–13] have examined lower limb gait kinematics after ACL reconstruction; all showed that knee-joint mechanics are altered postsurgery. Studies using more challenging tasks, such as pivoting and jump landing, have also demonstrated deficits in knee-joint mechanics after ACL reconstruction.[14–16] The results of the aforementioned studies, although informative, are limited because the primary focus has been on knee-joint mechanics with little consideration being given to proximal structures. Delahunt et al[17] observed altered hip- and knee-joint angular displacements in female ACL-R athletes who had returned to sport participation when performing a high-velocity, high-load jump-landing sport-specific task. In a systematic review, Quatman et al[18] suggested that neuromuscular deficiencies involving the frontal, sagittal, and transverse planes are likely to be implicated in the mechanism of and predisposition to noncontact ACL injury. Direct support for the multiplanar mechanism of injury is evidenced in a cohort study that showed altered neuromuscular control of the hip and knee joint and deficits in postural stability predicted reinjury after ACL reconstruction.[19]

Observing knee and hip kinematics while ACL-R athletes perform a dynamic postural-control task may help to shed light on deficiencies during activity and may contribute to the development of more effective rehabilitation programs after ACL reconstruction. One mechanism to accomplish this would be to combine dynamic postural-stability evaluation as quantified by the Star Excursion Balance Test (SEBT) with simultaneous lower limb kinematic evaluation using a motion-analysis capture system. Performance on the SEBT places multiple demands on the neuromuscular system and, thus, may facilitate the identification of athletes who are at a greater risk of lower limb injury.[20] Previous authors[21,22] have reported that participants with chronic ankle instability (CAI) have decreased reach distances when compared with uninjured participants, reflecting a deficiency in dynamic postural stability. Furthermore, Gribble et al[22] indicated that the decreased reach distance observed in the CAI group could be a manifestation of a decreased knee-flexion angle during the test, an effect that was amplified by the induction of muscular fatigue. To date, to our knowledge, only 1 group[23] has investigated dynamic postural stability as quantified by the SEBT in ACL-injured athletes; reach distances were decreased in the ACL-deficient group when compared with an uninjured control group.

Considering the importance of dynamic postural stability as a neuromuscular factor and its importance as a clinical measure in predicting the risk of future injury,[19,20] our objective was to investigate dynamic postural stability as quantified by the SEBT and simultaneous hip- and knee-joint kinematics in participants with previous ACL reconstructions. We hypothesized that, when compared with an uninjured control group, the ACL-R female athletes would demonstrate decreased reach distances on the SEBT as well as deviations from the kinematic profiles observed in the uninjured control group.

Table 2. Star Excursion Balance Test Results[a]

	Reach Direction		
	Anterior	Posterior-medial	Posterior-lateral
Control group	71.25 ± 4.35	105.06 ± 7.68	98.87 ± 8.59
ACL-R group	68.54 ± 3.82	96.06 ± 7.56[b]	89.53 ± 7.42[b]
95% Confidence interval for the mean difference between groups	−0.33, 5.76	3.37, 14.63	3.36, 15.30
Effect size (η^2)	0.10 (moderate)	0.17 (large)	0.17 (large)

Abbreviation: ACL-R, anterior cruciate ligament reconstructed.

[a] Values are presented as mean ± SD and represent a percentage of limb length.

[b] Different from control group.

METHODS

Participants

Seventeen female athletes (age = 20.76 ± 1.14 years, height = 1.65 ± 0.06 m, body mass = 65.38 ± 7.36 kg, body mass index (BMI) = 23.82 ± 2.42 kg/m^2) volunteered as controls. None of these athletes had previously experienced a knee injury. All athletes played field or court-based sports (eg, Gaelic football, soccer, hockey, basketball) at the club or county level.

Fourteen recreational female athletes (age = 23.00 ± 3.37 years, height = 1.64 ± 0.05 m, body mass = 64.85 ± 8.67 kg, BMI = 24.03 ± 2.38 kg/m^2) volunteered to

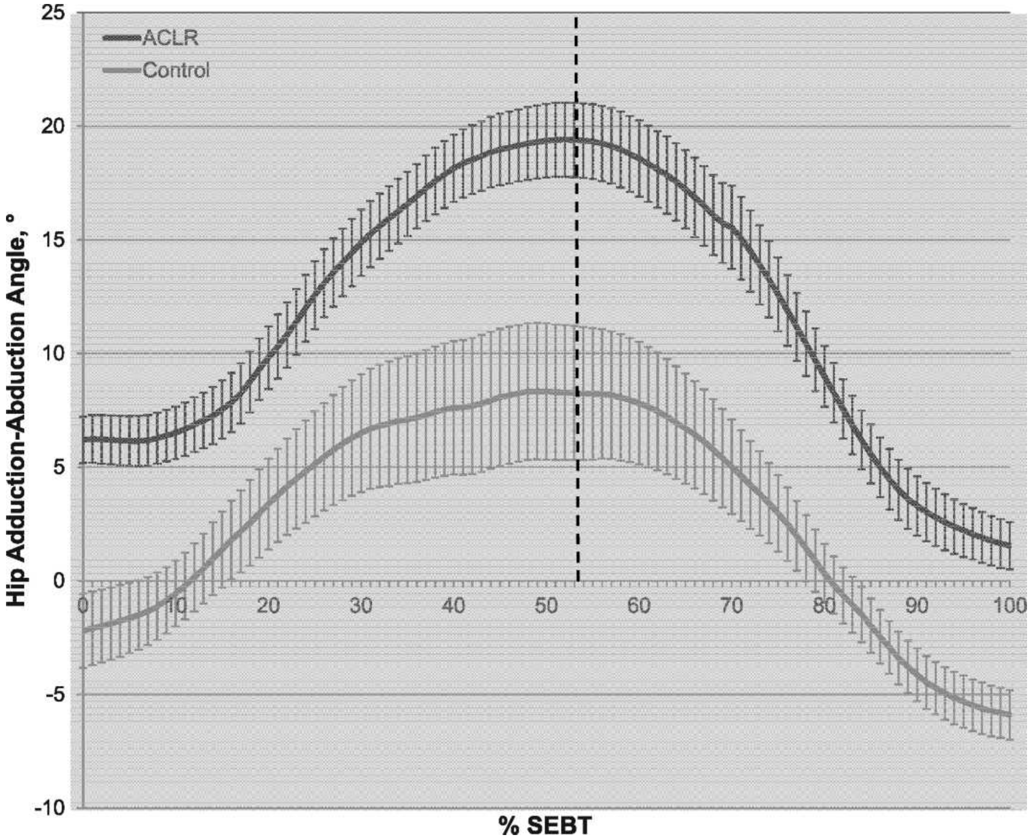

Figure 1. Hip-joint adduction-abduction angle during performance of the anterior directional component of the Star Excursion Balance Test (SEBT). Adduction is positive; abduction is negative; values are mean ± SEM. Shaded area = area of statistical significance. Dashed line = point of maximum reach. Abbreviation: ACLR, anterior cruciate ligament-reconstructed.

participate. All athletes had previously experienced an isolated noncontact ACL injury that required surgical stabilization. Seven athletes had surgical stabilization using a bone-patellar tendon-bone autograft, with the remaining athletes having had a hamstring autograft. The mean time from surgical stabilization to the study was 2.9 ± 2.8 years (range, 10 months–6 years). At the time of testing, all athletes were fully engaged in field or court-based sports (eg, Gaelic football, soccer, hockey, basketball) at the club or county level, and no athlete was undergoing any form of formal rehabilitation.

Procedures

All testing was undertaken in a university motion-analysis laboratory. Each participant attended the laboratory on 1 occasion. Upon arrival for the testing session, each participant was informed and familiarized with the testing procedure. All testing was supervised by a chartered physiotherapist. Each participant signed an informed consent form, which had previously been approved by the University Human Research Ethics Committee, which also approved the study.

Subjective Knee Questionnaires

All athletes were required to complete the International Knee Documentation Committee (IKDC) Subjective Knee Form as well as the Knee Injury and Osteoarthritis Outcome Score (KOOS) subscales.

The IKDC Subjective Knee Form and KOOS are site-specific instruments that were designed to measure symptoms, function, and sport activity in patients with a variety of knee conditions.[24,25] Both instruments have been validated for use with an ACL-R population.[25,26]

The IKDC Subjective Knee Form consists of 18 items related to knee-joint symptoms, function, and sport activity.[24] All items are summed to produce a single index score, which can be used to interpret knee function; higher scores represent higher levels of function and lower levels of symptoms. A score of 100 is considered no limitation in activities of daily living or sport activities and complete absence of symptoms.[24]

The KOOS is a 42 self-reporting instrument and comprises 5 subscales: $KOOS_{pain}$ (9 items), $KOOS_{symptoms}$ (7 items), $KOOS_{ADL}$ (function in daily living; 17 items), $KOOS_{sport}$ (5 items), and $KOOS_{KQoL}$ (knee-related quality of life; 4 items). For each subscale, the score is normalized to a 0–100 scale with higher scores representing better levels of knee status.

By using both scales, we endeavored to determine how ACL reconstruction influences overall knee-joint function and symptoms as well as important specific domains such as those included in the KOOS.

SEBT Performance

For the performance of the SEBT, participants initially stood barefoot with their left and right feet on 2 adjacent force plates. The directional components of the SEBT

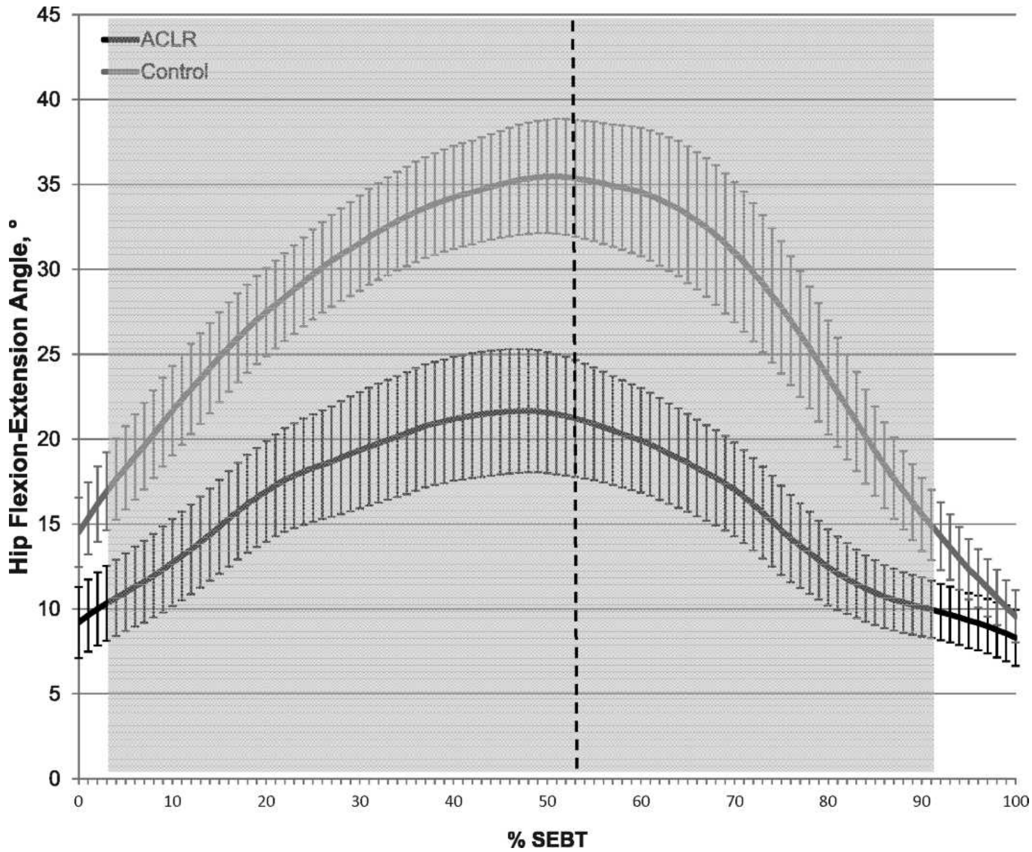

Figure 2. Hip-joint flexion-extension angle during performance of the anterior directional component of the Star Excursion Balance Test (SEBT). Flexion is positive; extension is negative; values are mean ± SEM. Shaded area = area of statistical significance. Dashed line = point of maximum reach. Abbreviation: ACLR, anterior cruciate ligament-reconstructed.

chosen for the present investigation were the anterior, posterior-medial, and posterior-lateral reach directions. The decision to use these specific reach directions was based on research by Plisky et al[20] and Hertel et al.[27]

Before each test session, participants were instructed in the correct performance of the test and allowed 4 practice trials in each of the chosen directional components, as advocated by Robinson and Gribble.[28] Three consecutive trials in each direction were performed after a short rest period. The order of performance of each directional component was randomized across participants using a random sequence of number generation.

While performing each reach direction, the participant initially stood with the big toe positioned at the center of a grid laid on the laboratory floor and extending from the force plate directly under the stance (test) leg. Each trial was initiated when the participant transitioned from double- to single-legged stance, and the trial ended when she returned to the double-legged stance position.[29] The vertical component of ground reaction force data was used to determine the onset and end of each trial as previously described in Delahunt et al.[29] For ease in quantifying each reach distance, the line of each SEBT directional component was simulated by a 1.5-m measuring tape. Reach distances were read from the center of the grid to the point of maximum reach, which was visually observed and noted by one of the investigators. Reach distances were divided by limb length, as measured from the anterior-superior iliac spine to the ipsilateral medial malleolus, and multiplied by 100 to calculate a dependent variable that represents reach distance as a percentage of limb length.[30]

During each trial, the participant placed her hands on her hips while reaching in the specified directional component. Furthermore, the participant was required to maintain contact between the force plate and heel of the stance (test) leg during each trial. A trial was deemed *unsuccessful* if she failed to keep her hands on her hips, moved or lifted the stance (test) foot, transferred weight onto the reach foot when touching the measuring tape, failed to touch the tape, failed to return the reach foot to the starting position, or lost her balance and was unable to maintain a unilateral stance position during the trial. Unsuccessful trials were discarded, and additional trials were completed accordingly.

Kinematic Analysis

Kinematic data acquisition occurred at 200 Hz using 3 CODA mpx1 units (Charnwood Dynamics Ltd, Leicestershire, UK), which were fully integrated with 4 AMTI (Watertown, MA) walkway embedded force plates (sampled at 100 Hz).

We marked each participant's specific anatomical landmarks with a skin-marker pencil before recording her anthropometric values and attaching the markers and marker wands as outlined in Monaghan et al.[31,32] The markers and marker wands were applied by the same investigator for all participants as follows. Markers were positioned on the lateral aspect of the knee joint line in the median frontal plane, the anterior aspect of the lateral

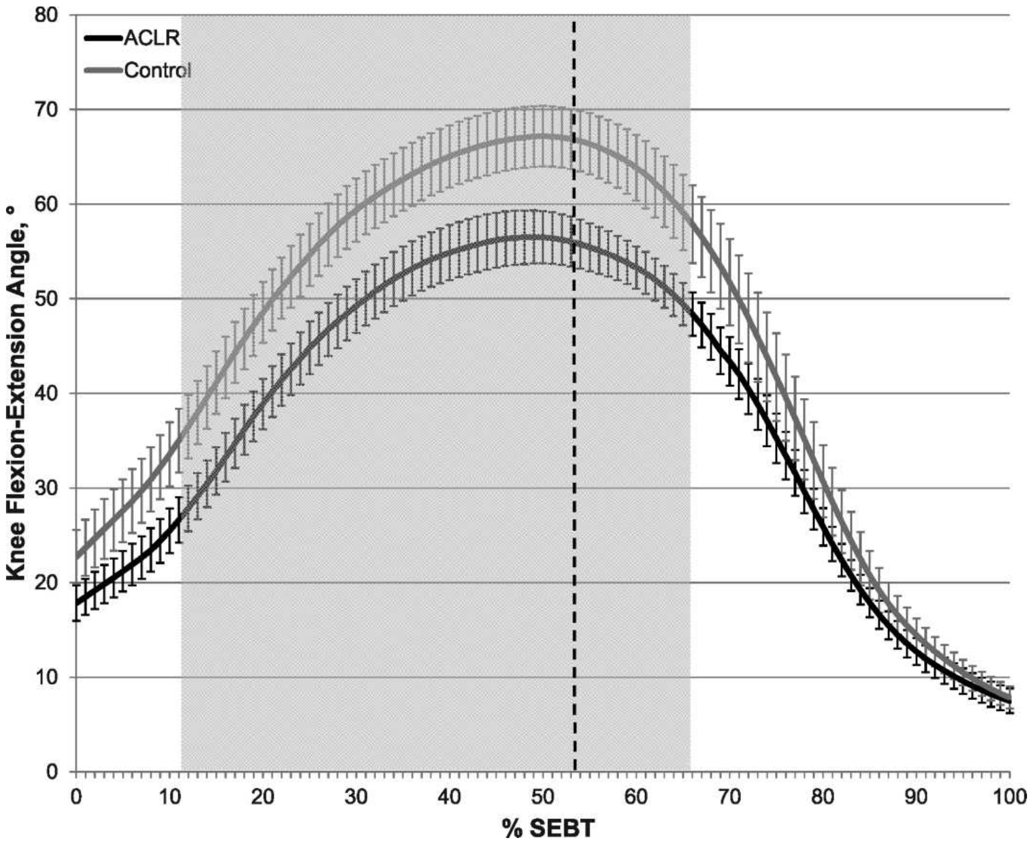

Figure 3. Knee-joint flexion-extension angle during performance of the anterior directional component of the Star Excursion Balance Test (SEBT). Flexion is positive; extension is negative; values are mean ± SEM. Shaded area = area of statistical significance. Dashed line = point of maximum reach. Abbreviation: ACLR, anterior cruciate ligament-reconstructed.

malleolus, the posterior-inferior lateral aspect of the heel, and the lateral aspect of the fifth metatarsal head. Wands with anterior and posterior markers attached were positioned on the pelvis and sacrum, the thigh, and the shank. This specific marker and wand setup has been previously used in our laboratory.[31–35] A neutral-stance trial was used to align the participant with the laboratory coordinate system and to function as a reference position for subsequent kinematic analysis.

Kinematic data were calculated by comparing the angular orientations of the coordinate systems of adjacent limb segments using the angular coupling set "Euler Angles" to represent clinical rotations in 3 dimensions. Marker positions within a Cartesian frame are processed into rotation angles using vector algebra and trigonometry (*CODA mpx30 User Guide*, Charnwood Dynamics Ltd, Leicestershire, UK). Joint angular displacements were calculated for the hip and knee joints in the sagittal, frontal, and transverse planes. Kinematic data were analyzed using the CODA software, with the following axis conventions: x axis = frontal-plane motion; y = sagittal-plane motion; z = transverse-plane motion. Kinematic data for each SEBT trial were extracted and converted to Microsoft Excel file format by converting the number of output samples to $100 + 1$ in the data-export option of the CODA software, which represented the complete SEBT trial as 100%, for averaging and further analysis. The 3 normalized trials for each participant for each reach direction were combined to create an average ensemble curve for each participant, with group profiles then being calculated. This specific analysis technique has previously been used in our laboratory.[31–35]

Statistical Analysis

The sample size calculation for the present study was based on data previously published by Herrington et al,[23] who showed a difference in SEBT performance between ACL-deficient and control participants. The computed effect size for the difference in reach distance between the ACL-deficient and control participants in the anterior direction was 1.3. An a priori sample size of 14 participants per group was computed using G*Power[36] considering the following values: $\alpha = .05$, $1 - \beta = .9$.

Independent-samples *t* tests were used to assess differences in the IKDC Subjective Knee Form and KOOS subscale scores (PASW Statistics, 24 Version 18.0, IBM Corporation, NY). Associated effect sizes (η^2) were calculated using the formula as described in Pallant:[37] $t^2/t^2 + (N1 + N2 - 2)$ and quantified according to Cohen[38] as 0.01 = small effect size, 0.06 = medium effect size, and 0.14 = large effect size. The level of significance was set at $P < .05$.

Independent-samples *t* tests were used to test for differences in normalized reach distances on the SEBT. Associated effect sizes (η^2) were calculated using the formula as described in Pallant:[37] $t^2/t^2 + (N1 + N2 - 2)$ and quantified according to Cohen[38] as noted earlier. The level of significance was set at $P < .05$. However, due to the highly correlational nature of these data, an adjusted *P*

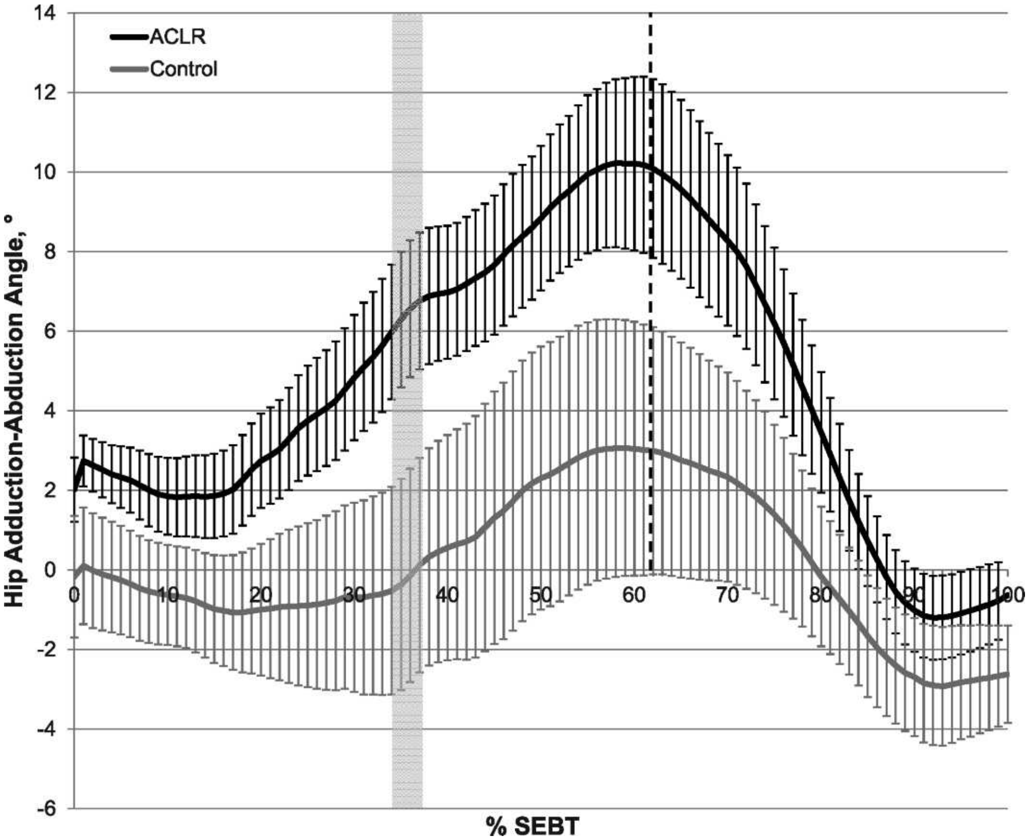

Figure 4. Hip-joint adduction-abduction angle during performance of the posterior-medial directional component of the Star Excursion Balance Test (SEBT). Adduction is positive; abduction is negative; values are mean ± SEM. Shaded area = area of statistical significance. Dashed line = point of maximum reach. Abbreviation: ACLR, anterior cruciate ligament-reconstructed.

value of (0.05/3) and therefore an α level of $P < .016$ was set for all comparisons.

Time-averaged profiles for hip- and knee-joint kinematics were calculated for each participant, with group mean profiles then being calculated. Differences in ACL-R and control group time-averaged profiles were tested for statistical significance using independent-samples t tests for each data point. This specific analysis technique has previously been used in our laboratory.[31–35] Effect sizes were not calculated for this part of the data analysis due to the number of separate comparisons for each kinematic variable. The level of significance was set at $P < .05$.

RESULTS

Subjective Knee Questionnaires

The Levene test for equality of variance revealed that the assumption of equal variance was violated for all subjective measures. The ACL-R participants differed from the control participants on the IKDC Subjective Knee Form ($P < .001$), as well as on the $KOOS_{pain}$ ($P < .05$), $KOOS_{symptoms}$ ($P < .001$), $KOOS_{sport}$ ($P < .05$), and $KOOS_{KQoL}$ ($P < .001$). The associated effects sizes were large (Table 1). No difference was seen between the ACL-R participants and the control participants on the $KOOS_{ADL}$ ($P > .05$).

SEBT Performance

A difference between groups was observed for both the posterior-medial ($P < .005$) and posterior-lateral reach directions ($P < .005$). The associated effect sizes were both 0.17, indicating a large effect size for both directions (Table 2). No difference between groups was observed for the anterior reach direction ($P > .016$), with an associated moderate effect size of 0.10 (Table 2).

Kinematics

Differences were observed between the kinematic profiles of the ACL-R group and control group during performance of the anterior, posterior-medial, and posterior-lateral directional components of the SEBT (Figures 1–9). Kinematic differences were observed for hip-joint frontal-, sagittal-, and transverse-plane motion, as well as knee-joint sagittal-plane motion.

During performance of the anterior reach direction, the ACL-R group differed from the control group ($P < .05$), exhibiting increased hip adduction (entire trial, Figure 1), less hip flexion (3%–89% of trial, Figure 2), and less knee flexion (12%–65% of trial, Figure 3).

During performance of the posterior-medial reach direction, the ACL-R group differed from the control group ($P < .05$), exhibiting increased hip adduction (34%–37% of trial, Figure 4), less hip flexion (59%–71% of trial, Figure 5), and less knee flexion (50%–95% of trial, Figure 6).

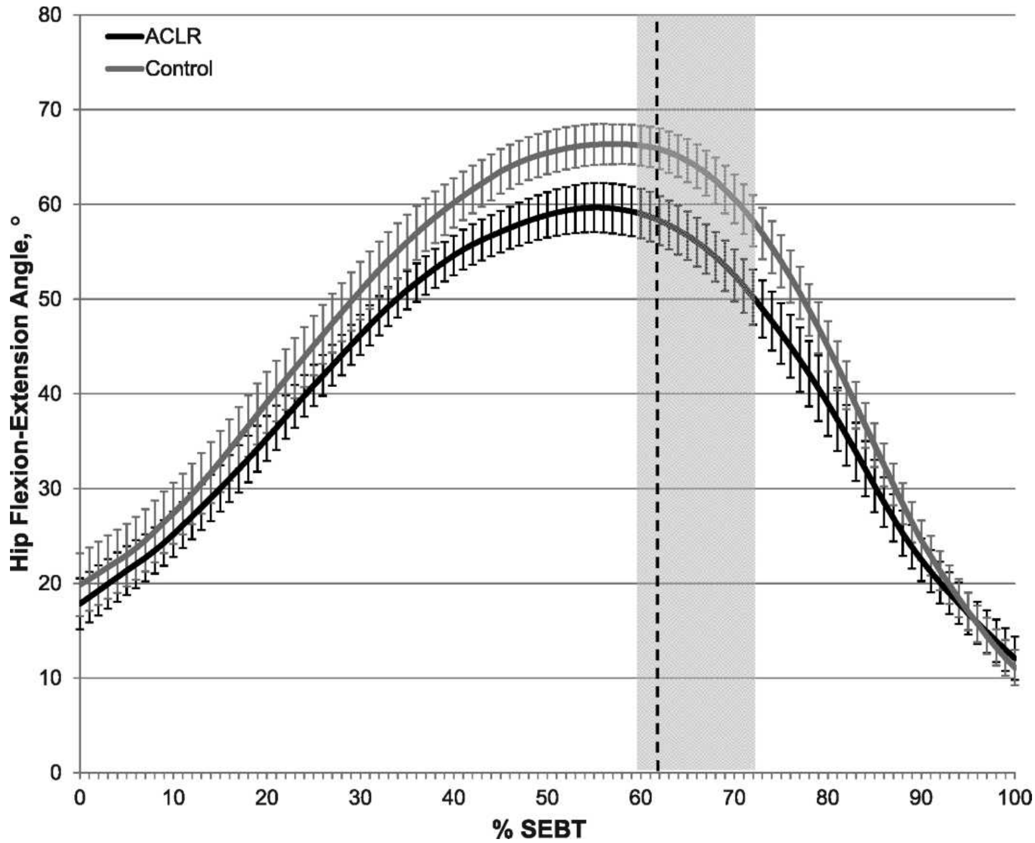

Figure 5. Hip-joint flexion-extension angle during performance of the posterior-medial directional component of the Star Excursion Balance Test (SEBT). Flexion is positive; extension is negative; values are mean ± SEM. Shaded area = area of statistical significance. Dashed line = point of maximum reach. Abbreviation: ACLR, anterior cruciate ligament-reconstructed.

During performance of the posterior-lateral reach direction, the ACL-R group differed significantly from the control group ($P < .05$), exhibiting increased hip adduction (94%–100% of trial, Figure 7), less hip external rotation (14%–53% and 79%–86%, Figure 8), as well as less knee flexion (19%–72% and 89%–100% of trial, Figure 9).

DISCUSSION

The specific aim of our study was to investigate dynamic postural stability, as quantified by the SEBT, and simultaneous hip- and knee-joint kinematic profiles in female athletes who have undergone ACL reconstruction. The results indicated that ACL-R athletes displayed decreased normalized reach distances on the posterior-medial and posterior-lateral reach directions of the SEBT when compared with an uninjured control group. Furthermore, specific kinematic differences were observed between the groups.

Subjective Knee Questionnaires

We observed a difference for the IKDC Subjective Knee Form scores between the ACL-R and control groups. The effect size was large, which is consistent with the clinically meaningful effect based on a >9-point difference between the groups.[12] Our results compare favorably with those of Lee et al,[39] who reported that, at 5 years after ACL reconstruction, the mean IKDC Subjective Knee Form score was 79.5.

We noted a difference between the ACL-R and control groups on 4 of the KOOS subscales. The associated effect sizes were all large, which is consistent with the clinically meaningful effect based on a 10-point difference between the groups,[26] which is also supported by previously published data.[40,41]

Even upon return to full sport participation, female athletes who have undergone ACL reconstruction still report deficits in knee function and ongoing knee symptoms, which affect their sport performance and quality of life. Taken together, the results of the IKDC Subjective Knee Form and KOOS subscales suggest that consideration should be given to ongoing therapeutic intervention after return to sport following ACL reconstruction; too often, interventions are discontinued by athletes and clinicians after return to play.

SEBT Performance

A recent systematic review has suggested that future authors examining postural stability in patients undergoing ACL reconstruction or after reconstruction should focus on assessments using dynamic postural-stability tasks.[42] The SEBT has been previously established as a reliable and sensitive measure of dynamic postural stability.[43,44] Although the SEBT has been most often used as a measure of dynamic postural stability in participants with CAI,[45–49] to date, only 1 paper has been published on SEBT performance and ACL injury.[23]

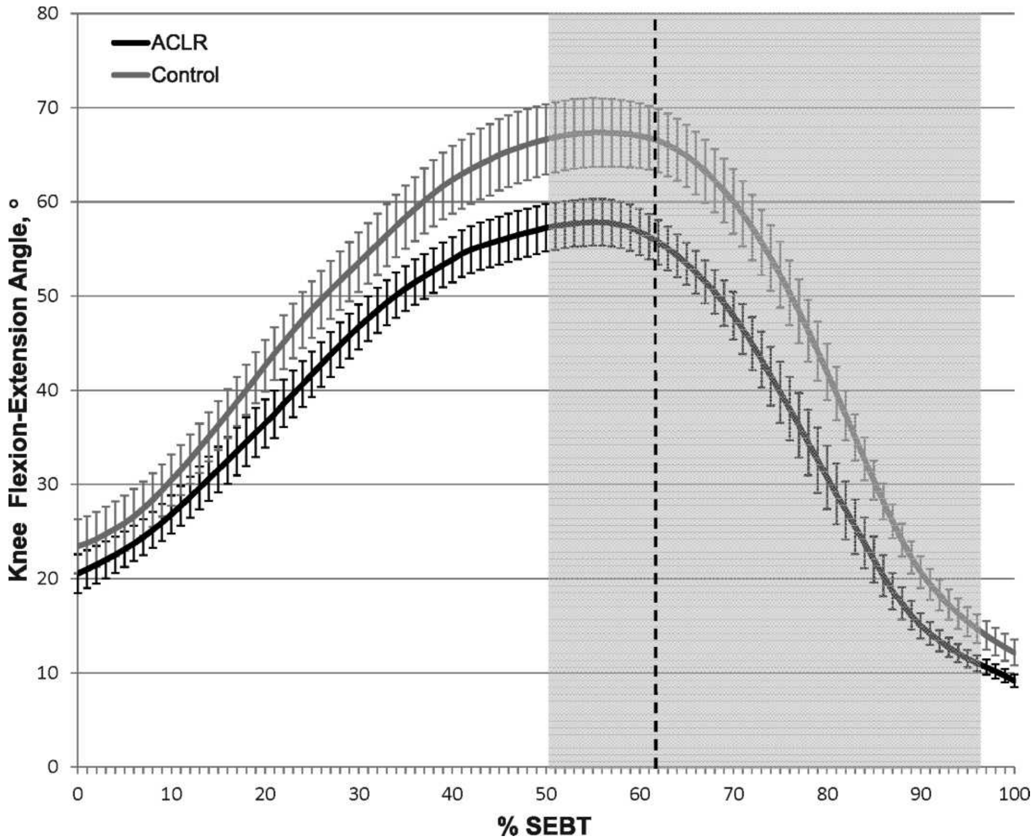

Figure 6. Knee-joint flexion-extension angle during performance of the posterior-medial directional component of the Star Excursion Balance Test (SEBT). Flexion is positive; extension is negative; values are mean ± SEM. Shaded area = area of statistical significance. Dashed line = point of maximum reach. Abbreviation: ACLR, anterior cruciate ligament-reconstructed.

Our results support our original hypothesis that ACL-R female athletes would demonstrate decreased postural stability on specific directional components of the SEBT when compared with an age-, sex-, and activity-matched uninjured control group and are in agreement with previous findings that competitive athletes who have returned to full sport participation after ACL reconstruction still exhibit postural-control deficits.[50,51]

In the present study, ACL-R participants' reach distances on the posterior-medial and posterior-lateral directions of the SEBT were decreased. These observations are in agreement with those of Herrington et al,[23] who reported similar deficits in reach distances in ACL-deficient athletes. We hypothesize that the decreased performance on the posterior-medial and posterior-lateral directional components could be a manifestation of the multiplanar neuromuscular demands and rotator torques required around the hip and knee joints associated with these directional components. The potential link between decreased reach distances and joint angular displacements will be discussed in the next section (Kinematics). Interestingly, no between-groups difference was observed for the anterior reach direction.

A deficit in postural stability is a risk factor for future lower limb injury.[20,52] Thus, intervention programs after ACL injury should emphasize both static and dynamic postural-stability training because we have shown that postural-stability deficits are still evident, even after return to full sport participation, in ACL-R female athletes.

Kinematics

Our ACL-R group was characterized by multiplanar hip- and knee-joint kinematic deficiencies when compared with the control group while undergoing dynamic postural-stability testing on the SEBT. Several theories regarding the mechanism of ACL injury exist in the published literature and are eloquently described by Quatman et al[18] in a recent systematic review. The sagittal-plane mechanism of ACL injury is based on the premise that the ACL is the primary restraint to anterior translation of the tibia[53,54] and that, at low knee-flexion angles, the sagittal-plane displacement of the tibia is increased.[55,56] Furthermore, it is postulated that the small knee-flexion angle commonly observed with ACL injury allows a powerful contraction of the quadriceps, which has sufficient force to cause excessive anterior tibial translation and subsequent ACL injury.[57–60] In our study, decreased knee flexion in the ACL-R group during performance of the 3 SEBT reach directions was a consistent finding, thus supporting previously published data concerning a sagittal-plane deficit association with ACL injury. The frontal-plane mechanism of ACL injury is based on the premise that knee-joint abduction collapse is the inciting event.[61,62] A prospective study by Hewett et al[63] indicated that female athletes who sustained a noncontact ACL injury during the study period exhibited a greater knee-valgus kinematic profile during a drop vertical jump when compared with athletes who did not sustain such an injury. More recently published literature[18,64] suggested that ACL injury is most likely the result of multiplanar

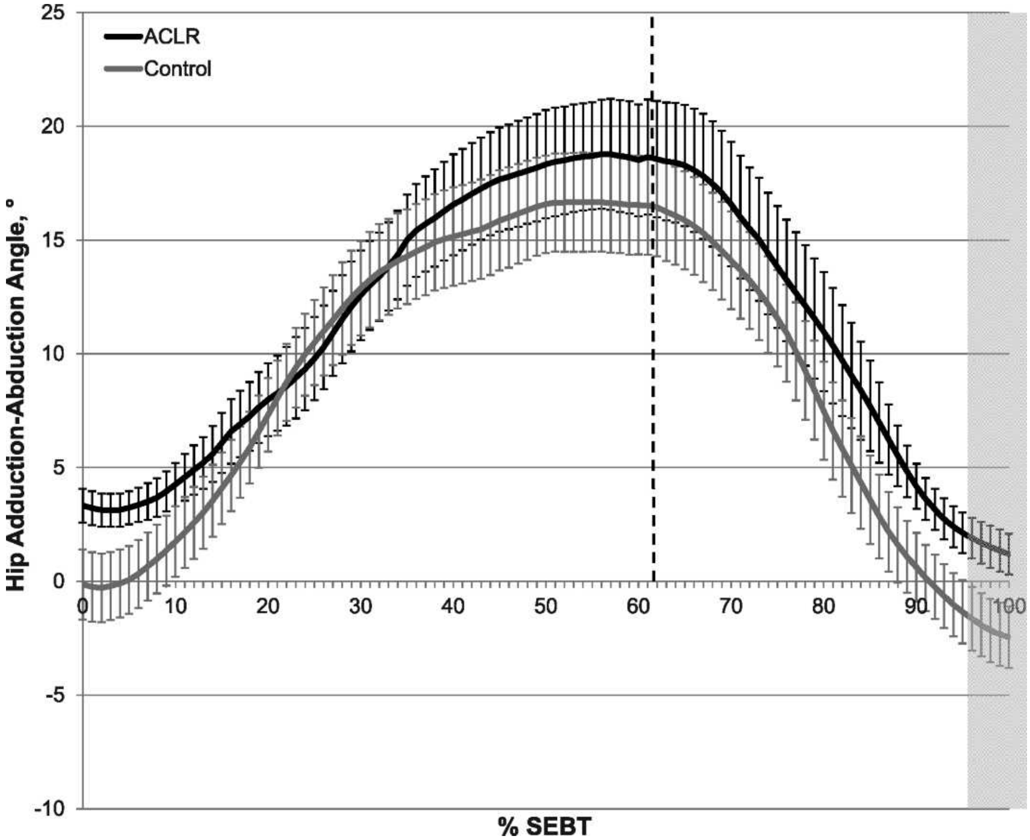

Figure 7. Hip-joint adduction-abduction angle during performance of the posterior-lateral directional component of the Star Excursion Balance Test (SEBT). Adduction is positive; abduction is negative; values are mean ± SEM. Shaded area = area of statistical significance. Dashed line = point of maximum reach. Abbreviation: ACLR, anterior cruciate ligament-reconstructed.

neuromuscular deficits. The present results are consistent with the literature suggesting that ACL injury is associated with multiplanar movement deficiencies. Specifically, differences in frontal- and transverse-plane hip-joint kinematics were observed between the ACL-R and control groups, with the ACL-R group being characterized by increased hip-joint adduction and internal rotation.

During performance of the anterior reach direction of the SEBT, the ACL-R group was characterized by a more adducted position of the hip joint throughout the entire trial. They also displayed less hip flexion from 3% to 89% of the trial as well as less knee flexion from 12% to 65% of the trial. However, even though the aforementioned kinematic deficits were observed, the ACL-R group did not differ from the control group in anterior reach distance. Previous researchers[65] have suggested that performance in the anterior reach direction of the SEBT is influenced by sagittal-plane kinematics. Participants with CAI are characterized by less hip and knee flexion while performing the anterior reach direction of the SEBT,[22] a finding consistent with our results. Even though significant emphasis has been placed on the importance of sagittal-plane kinematics for performance of the anterior direction of the SEBT,[65] the decreased hip and knee flexion in the ACL-R group did not translate to a decreased anterior reach distance. We believe that the absence of a between-groups difference in reach distance anteriorly may be attributed to the observed ipsilateral increased hip adduction in the ACL-R group. This ipsilateral increased hip adduction essentially creates a Trendelenburg position, with lengthening of the contralateral limb and a subsequent increased anterior reach, a finding supported by Zeller et al,[66] who observed that single-legged squat mechanics are influenced by frontal-plane hip-joint position. However, further support of this theory needs full validation.

During performance of the posterior-medial reach direction of the SEBT, the ACL-R group displayed a more adducted position of the hip joint from 34% to 37% of the trial, as well as less hip flexion from 59% to 71% of the trial. They also exhibited less knee flexion from 50% to 95% of the trial. The decreased hip and knee flexion observed during the trial may be a manifestation of a deficit in quadriceps strength, but this would require further validation because we did not measure this variable.

During performance of the posterior-lateral reach direction of the SEBT, the ACL-R group was characterized by more hip internal rotation from 14% to 53% and 79% to 86% of the trial. Less knee flexion from 19% to 72% and 89% to 100% of the trial was also observed. In contrast to the anterior reach direction, we believe that the increased adducted position of the hip joint during the posterior-medial reach direction and the increased internally rotated position of the hip joint during the posterior-lateral reach direction could be contributing to the observed decreased reach distance in both these directions. To a greater extent, the body's trunk and center of mass are influenced by hip-joint frontal- and transverse-plane motion while reaching in the posterior-medial and posterior-lateral reach directions of the SEBT when compared with the anterior reach direction. Greater hip adduction during the posterior-medial

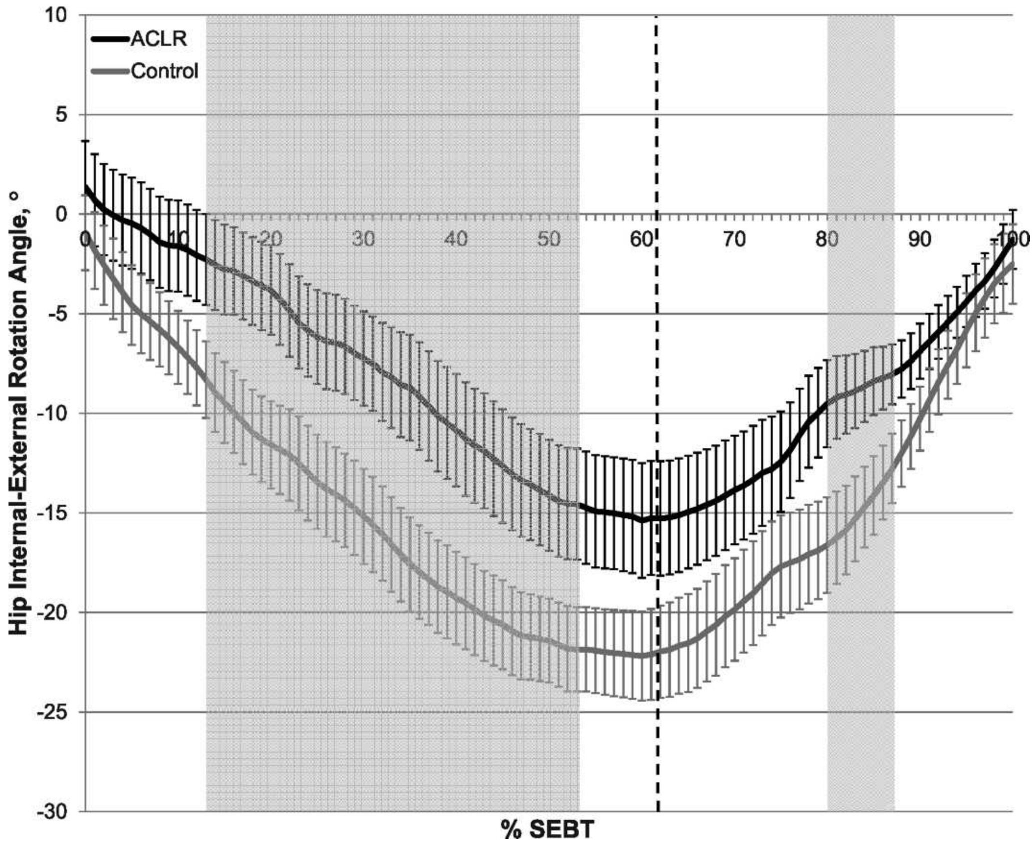

Figure 8. Hip-joint internal-external rotation angle during performance of the posterior-lateral directional component of the Star Excursion Balance Test (SEBT). Internal rotation is positive; external rotation is negative; values are mean ± SEM. Shaded area = area of statistical significance. Dashed line = point of maximum reach. Abbreviation: ACLR, anterior cruciate ligament-reconstructed.

reach direction and greater hip internal rotation during the posterior-lateral reach direction cause lateral deviation of the trunk. Consequently, these changes in hip-joint frontal- and transverse-plane motion place greater rotary loads on the knee joint than those observed with sagittal-plane reaching. This may result in greater apprehension on the part of the ACL-R group, with a consequent decrease in reach distance in the posterior-medial and posterior-lateral reach directions. Further research is necessary to determine whether this is the case. However, recent evidence to support the connection among trunk position, knee-joint loading, and subsequent ACL injury has been put forth by Hewett et al,[67] whereby lateral deviation of the trunk with respect to the ACL-injured limb was observed as part of the injury mechanism.

These observations concur with previous findings in the literature that female athletes perform jump landings with less hip and knee flexion.[47] Furthermore, Delahunt et al[17] reported altered hip-joint frontal- and transverse-plane angular displacements in ACL-R female athletes during drop vertical-jump testing. Thus, these deficits seem to be consistent, even during a less demanding task such as dynamic postural stability, as assessed by performance in specific reach directions of the SEBT. Our results suggest that, after return to athletic participation, ACL-R female athletes still exhibit deficits in hip-joint sagittal-, frontal-, and transverse-plane kinematics, as well as knee-joint sagittal-plane kinematics. The exact consequence of these deficits and their potential influence on future injury, however, cannot yet be fully elucidated. Thus, prospective studies are now required to determine the extent to which altered lower limb kinematics influence future injury risk in ACL-R athletes.

Altered lower limb kinematics during the performance of different landing tasks after ACL reconstruction are commonly reported in the literature.[14–17] However, no previous authors have reported on the kinematic profiles of female ACL-R athletes during the performance of a dynamic postural stability task such as the SEBT. Nonetheless, it is possible to suggest that the same rehabilitation principles could be applicable to both situations. Deficits in neuromuscular control as manifested by aberrant lower limb kinematic profiles are a modifiable risk factor for future injury or reinjury after initial injury.[68] Neuromuscular training programs incorporating correction of landing techniques, posterior chain and core strengthening, plyometrics, and postural stability have been successfully implemented to reduce the risk of initial ACL injury.[68] We suggest that similar protocols should be implemented after ACL reconstruction. It is the clinician's responsibility to complete a thorough evaluation and develop an exercise program that addresses those specific deficits that are present in ACL-R athletes. This will ensure better functional outcomes after ACL reconstruction and help prevent recurrent injury, as well as improve physiotherapeutic and athletic training methods in general. We suggest that performance on the SEBT could be used as an evaluative tool to monitor improvements in dynamic postural-stability performance, lower limb alignment, coordination, and neuromuscular

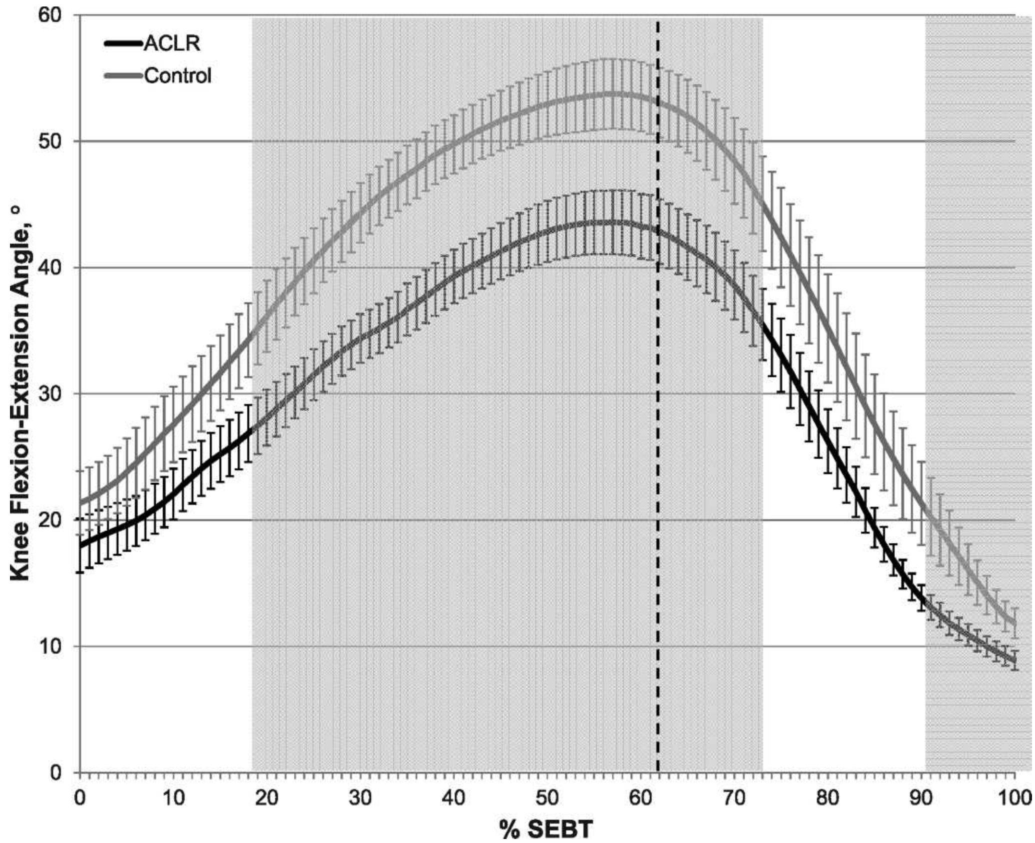

Figure 9. Knee-joint flexion-extension angle during performance of the posterior-lateral directional component of the Star Excursion Balance Test (SEBT). Flexion is positive; extension is negative; values are mean ± SEM. Shaded area = area of statistical significance. Dashed line = point of maximum reach. Abbreviation: ACLR, anterior cruciate ligament-reconstructed.

control after ACL reconstruction. Treating clinicians should be aware of the correct execution of movement patterns while providing continuing feedback to athletes regarding potentially injurious movement patterns, which have been shown to be linked with ACL injury mechanisms.[19,20,64,67]

The potential mechanisms underlying the kinematic differences observed in the present study can only be hypothesized. Two potential mechanisms exist. Firstly, the observed aberrant lower limb kinematic profiles may have been present before the ACL injury. Recently published literature[69,70] suggests that lower limb kinematic and kinetic changes during puberty may result in an increased risk of knee injury in female athletes when compared with age-matched male athletes. Thus, it is possible that the aberrant lower limb kinematic profiles we observed were present even before the inciting event. Alternatively, the observed aberrant lower limb kinematics could be a manifestation of altered motor programming. Johansson et al[9] suggested that ligament injury, through its influence on the γ muscle spindle system, could cause sensory feedback that does not fit the existing motor program. Consequently, this may in turn induce errors in the normal activation sequence of muscles, resulting in altered joint kinematics. However, we did not measure lower limb muscle activity; thus, future research is warranted to investigate the altered motor-programming mechanism.

Clinical Applications

The presence of the observed aberrant lower limb kinematics at an average of 2.9 years after ACL reconstruction warrants consideration. Evidence-based clinical practice involves the conscientious, judicious, and explicit use of current clinical evidence to support decisions regarding patient care.[71] Although empirical clinical judgments are often indicated, to maintain the highest standards of rehabilitation care, physiotherapists and athletic trainers must ensure that they have a correct understanding of those neuromuscular deficits that are present after ACL injury. Recent evidence regarding the neuromuscular deficits present in participants with CAI suggests that this may not be the case,[72] with experienced clinicians displaying a less-than-satisfactory understanding of the neuromuscular deficits associated with CAI. We hypothesize that this may be the case regarding ACL injury. Further research should be undertaken to determine clinicians' understanding of the neuromuscular deficits associated with ACL injury. Furthermore, the results of the present study indicate that rehabilitation should not stop after athletes are deemed ready for return to full sporting participation. Continuing neuromuscular programs should be incorporated into daily training and practice sessions under the guidance of a suitably qualified rehabilitation specialist. We would also advocate the use of video-based biomechanical screening of high-velocity, high-load athletic tasks as part of the decision process regarding suitability for return to play.

CONCLUSIONS

One of the most important risk factors for ACL injury is a history of previous ACL injury. This is particularly true for athletes who return to sport participation. Deficits in postural stability and lower limb kinematics have been previously shown to be risk factors for ACL injury. The extent to which athletes recover postural stability and associated lower limb kinematics profiles after ACL reconstruction has yet to be investigated. Thus, our aim was to clarify this issue. The ACL-R athletes included in the present study reported significantly and clinically meaningful decreased functional status as quantified by the IKDC Subjective Knee Form and KOOS subscales at a mean of 2.9 years after ACL reconstruction. Deficits in dynamic postural stability were evident during performance of the posterior-medial and posterior-lateral directional components of the SEBT. Associated deficits in hip-joint sagittal frontal-, and transverse-plane and knee-joint sagittal-plane kinematic profiles were also evident. The observed deficits during performance of the directional components of the SEBT are modifiable and thus emphasis should be placed on rehabilitation programs after ACL reconstruction, which could address such postural-stability deficits and associated aberrant kinematic profiles.

REFERENCES

1. Agel J, Arendt EA, Bershadsky B. Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: a 13-year review. *Am J Sports Med*. 2005;33(4):524–530.
2. Arendt E, Dick R. Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. *Am J Sports Med*. 1995;23(6):694–701.
3. Waldén M, Hägglund M, Werner J, Ekstrand J. The epidemiology of anterior cruciate ligament injury in football (soccer): a review of the literature from a gender-related perspective. *Knee Surg Sports Traumatol Arthrosc*. 2011;19(1):3–10.
4. Wright RW, Dunn WR, Amendola A, et al. Risk of tearing the intact anterior cruciate ligament in the contralateral knee and rupturing the anterior cruciate ligament graft during the first 2 years after anterior cruciate ligament reconstruction: a prospective MOON cohort study. *Am J Sports Med*. 2007;35(7):1131–1134.
5. Gomez E, DeLee JC, Farney WC. Incidence of injury in Texas girls' high school basketball. *Am J Sports Med*. 1996;24(5):684–687.
6. Messina DF, Farney WC, DeLee JC. The incidence of injury in Texas high school basketball: a prospective study among male and female athletes. *Am J Sports Med*. 1999;27(3):294–299.
7. Shelbourne KD, Gray T, Haro M. Incidence of subsequent injury to either knee within 5 years after anterior cruciate ligament reconstruction with patellar tendon autograft. *Am J Sports Med*. 2009;37(2):246–251.
8. Riemann BL, Lephart SM. The sensorimotor system, part I: the physiologic basis of functional joint stability. *J Athl Train*. 2002; 37(1):71–79.
9. Johansson H, Sjölander P, Sojka P. A sensory role for the cruciate ligaments. *Clin Orthop Relat Res*. 1991;268:161–178.
10. Bonfim TR, Jansen Paccola CA, Barela JA. Proprioceptive and behavior impairments in individuals with anterior cruciate ligament reconstructed knees. *Arch Phys Med Rehabil*. 2003;84(8):1217–1223.
11. Webster KE, Feller JA. Alterations in joint kinematics during walking following hamstring and patellar tendon anterior cruciate ligament reconstruction surgery. *Clin Biomech (Bristol, Avon)*. 2011; 26(2):175–80.
12. Gao B, Zheng NN. Alterations in three-dimensional joint kinematics of anterior cruciate ligament-deficient and -reconstructed knees during walking. *Clin Biomech (Bristol, Avon)*. 2010;25(3):222–229.
13. Butler RJ, Minick KI, Ferber R, Underwood F. Gait mechanics after ACL reconstruction: implications for the early onset of knee osteoarthritis. *Br J Sports Med*. 2009;43(5):366–370.
14. Claes S, Neven E, Callewaert B, Desloovere K, Bellemans J. Tibial rotation in single- and double-bundle ACL reconstruction: a kinematic 3-D in vivo analysis. *Knee Surg Sports Traumatol Arthrosc*. 2011;19(suppl 1):S115–S121.
15. Deneweth JM, Bey MJ, McLean SG, Lock TR, Kolowich PA, Tashman S. Tibiofemoral joint kinematics of the anterior cruciate ligament-reconstructed knee during a single-legged hop landing. *Am J Sports Med*. 2010;38(9):1820–1828.
16. Gokeler A, Hof AL, Arnold MP, Dijkstra PU, Postema K, Otten E. Abnormal landing strategies after ACL reconstruction. *Scand J Med Sci Sports*. 2010;20(1):e12–e19.
17. Delahunt E, Sweeney L, Chawke M, et al. Lower limb kinematic alterations during drop vertical jumps in female athletes who have undergone anterior cruciate ligament reconstruction. *J Orthop Res*. 2012;30(1):72–78.
18. Quatman CE, Quatman-Yates CC, Hewett TE. A 'plane' explanation of anterior cruciate ligament injury mechanisms: a systematic review. *Sports Med*. 2010;40(9):729–746.
19. Paterno MV, Schmitt LC, Ford KR, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med*. 2010;38(10):1968–1978.
20. Plisky PJ, Rauh MJ, Kaminski TW, Underwood FB. Star Excursion Balance Test as a predictor of lower extremity injury in high school basketball players. *J Orthop Sports Phys Ther*. 2006;36(12):911–919.
21. Olmsted LC, Carcia CR, Hertel J, Shultz SJ. Efficacy of the Star Excursion Balance Tests in detecting reach deficits in subjects with chronic ankle instability. *J Athl Train*. 2002;37(4):501–506.
22. Gribble PA, Hertel J, Denegar CR, Buckley WE. The effects of fatigue and chronic ankle instability on dynamic postural control. *J Athl Train*. 2004;39(4):321–329.
23. Herrington L, Hatcher J, Hatcher A, McNicholas M. A comparison of Star Excursion Balance Test reach distances between ACL deficient patients and asymptomatic controls. *Knee*. 2009;16(2):149–152.
24. Irrgang JJ, Anderson AF, Boland AL, et al. Development and validation of the international knee documentation committee subjective knee form. *Am J Sports Med*. 2001;29(5):600–613.
25. Roos EM, Roos HP, Lohmander LS, Ekdahl C, Beynnon BD. Knee Injury and Osteoarthritis Outcome Score (KOOS)–development of a self-administered outcome measure. *J Orthop Sports Phys Ther*. 1998;28(2):88–96.
26. Risberg MA, Holm I, Steen H, Beynnon BD. Sensitivity to changes over time for the IKDC form, the Lysholm score, and the Cincinnati knee score: a prospective study of 120 ACL reconstructed patients with a 2-year follow-up. *Knee Surg Sports Traumatol Arthrosc*. 1999; 7(3):152–159.
27. Hertel J, Braham RA, Hale SA, Olmsted-Kramer LC. Simplifying the Star Excursion Balance Test: analyses of subjects with and without chronic ankle instability. *J Orthop Sports Phys Ther*. 2006;36(3): 131–137.
28. Robinson RH, Gribble PA. Support for a reduction in the number of trials needed for the star excursion balance test. *Arch Phys Med Rehabil*. 2008;89(2):364–370.
29. Delahunt E, McGrath A, Doran N, Coughlan GF. Effect of taping on actual and perceived dynamic postural stability in persons with chronic ankle instability. *Arch Phys Med Rehabil*. 2010;91(9):1383–1389.

30. Gribble PA, Hertel J. Considerations for normalizing measures of the Star Excursion Balance Test. *Measurements Phys Educ Exerc Sci*. 2003;7:89–100.
31. Monaghan K, Delahunt E, Caulfield B. Ankle function during gait in patients with chronic ankle instability compared to controls. *Clin Biomech (Bristol, Avon)*. 2006;21(2):168–174.
32. Monaghan K, Delahunt E, Caulfield B. Increasing the number of gait trial recordings maximises intra-rater reliability of the CODA motion analysis system. *Gait Posture*. 2007;25(2):303–315.
33. Delahunt E, Monaghan K, Caulfield B. Altered neuromuscular control and ankle joint kinematics during walking in subjects with functional instability of the ankle joint. *Am J Sports Med*. 2006; 34(12):1970–1976.
34. Delahunt E, Monaghan K, Caulfield B. Ankle function during hopping in subjects with functional instability of the ankle joint. *Scand J Med Sci Sports*. 2007;17(6):641–648.
35. Delahunt E, Monaghan K, Caulfield B. Changes in lower limb kinematics, kinetics, and muscle activity in subjects with functional instability of the ankle joint during a single leg drop jump. *J Orthop Res*. 2006;24(10):1991–2000.
36. Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods*. 2007;39(2):175–191.
37. Pallant J. *SPSS Survival Manual*. 3rd edition. Berkshire, UK: Open University Press; 2007.
38. Cohen J. *Statistical Power Analysis* for the *Behavioral Sciences*. 2nd edition. Hillsdale, NJ: Lawrence Erlbaum Associates; 1988.
39. Lee DY, Karim SA, Chang HC. Return to sports after anterior cruciate ligament reconstruction: a review of patients with minimum 5-year follow-up. *Ann Acad Med Singapore*. 2008;37(4):273–278.
40. Lind M, Menhert F, Pedersen AB. The first results from the Danish ACL reconstruction registry: epidemiologic and 2 year follow-up results from 5,818 knee ligament reconstructions. *Knee Surg Sports Traumatol Arthrosc*. 2009;17(2):117–124.
41. Granan LP, Forssblad M, Lind M, Engebretsen L. The Scandinavian ACL registries 2004–2007: baseline epidemiology. *Acta Orthop*. 2009;80(5):563–567.
42. Howells BE, Ardern CL, Webster KE. Is postural control restored following anterior cruciate ligament reconstruction? A systematic review. *Knee Surg Sports Traumatol Arthrosc*. 2011;19(7):1168–77.
43. Miller S, Denegar C. Intratester and intertester reliability during the Star Excursion Balance Test. *J Sport Rehabil*. 2000;9(2):104–116.
44. Kinzey SJ, Armstrong CW. The reliability of the star-excursion test in assessing dynamic balance. *J Orthop Sports Phys Ther*. 1998; 27(5):356–360.
45. Gribble PA, Hertel J, Denegar CR. Chronic ankle instability and fatigue create proximal joint alterations during performance of the Star Excursion Balance Test. *Int J Sports Med*. 2007;28(3):236–242.
46. Hale SA, Hertel J, Olmsted-Kramer LC. The effect of a 4-week comprehensive rehabilitation program on postural control and lower extremity function in individuals with chronic ankle instability. *J Orthop Sports Phys Ther*. 2007;37(6):303–311.
47. Hertel J, Braham RA, Hale SA, Olmsted-Kramer LC. Simplifying the Star Excursion Balance Test: analyses of subjects with and without chronic ankle instability. *J Orthop Sports Phys Ther*. 2006;36(3): 131–137.
48. McKeon PO, Ingersoll CD, Kerrigan DC, Saliba E, Bennett BC, Hertel J. Balance training improves function and postural control in those with chronic ankle instability. *Med Sci Sports Exerc*. 2008; 40(10):1810–1819.
49. Sesma AR, Mattacola CG, Uhl TL, Nitz AJ, McKeon PO. Effect of foot orthotics on single- and double-limb dynamic balance tasks in patients with chronic ankle instability. *Foot Ankle Spec*. 2008;1(6): 330–337.
50. Zouita Ben Moussa A, Zouita S, Dziri C, Ben Salah FZ. Single-leg assessment of postural stability and knee functional outcome two years after anterior cruciate ligament reconstruction. *Ann Phys Rehabil Med*. 2009;52(6):475–484.
51. Webster KA, Gribble PA. Time to stabilization of anterior cruciate ligament-reconstructed versus healthy knees in National Collegiate Athletic Association Division I female athletes. *J Athl Train*. 2010; 45(6):580–585.
52. McGuine TA, Greene JJ, Best T, Leverson G. Balance as a predictor of ankle injuries in high school basketball players. *Clin J Sport Med*. 2000;10(4):239–244.
53. Butler DL, Noyes FR, Grood ES. Ligamentous restraints to anterior-posterior drawer in the human knee: a biomechanical study. *J Bone Joint Surg Am*. 1980;62(2):259–270.
54. Markolf KL, Mensch JS, Amstutz HC. Stiffness and laxity of the knee: the contributions of the supporting structures. A quantitative in vitro study. *J Bone Joint Surg Am*. 1976;58(5):583–594.
55. Daniel DM, Malcom LL, Losse G, Stone ML, Sachs R, Burks R. Instrumented measurement of anterior laxity of the knee. *J Bone Joint Surg Am*. 1985;67(5):720–726.
56. Fukubayashi T, Torzilli PA, Sherman MF, Warren RF. An in vitro biomechanical evaluation of anterior-posterior motion of the knee: tibial displacement, rotation, and torque. *J Bone Joint Surg Am*. 1982; 64(2):258–264.
57. Li G, Rudy TW, Sakane M, Kanamori A, Ma CB, Woo SL. The importance of quadriceps and hamstring muscle loading on knee kinematics and in-situ forces in the ACL. *J Biomech*. 1999;32(4): 395–400.
58. Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GA, Slauterbeck JL. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res*. 1995;13(6):930–935.
59. Pandy MG, Shelburne KB. Dependence of cruciate-ligament loading on muscle forces and external load. *J Biomech*. 1997;30(10):1015–1024.
60. Yu B, Lin CF, Garrett WE. Lower extremity biomechanics during the landing of a stop-jump task. *Clin Biomech (Bristol, Avon)*. 2006; 21(3):297–305.
61. Boden BP, Dean GS, Feagin JA Jr, Garrett WE Jr. Mechanisms of anterior cruciate 613 ligament injury. *Orthopedics*. 2000;23(6):573–578.
62. Krosshaug T, Nakamae A, Boden BP, et al. Mechanisms of anterior cruciate ligamentinjury in basketball: video analysis of 39 cases. *Am J Sports Med*. 2007;35(3):359–367.
63. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med*. 2005;33(4):492–501.
64. Koga H, Nakamae A, Shima Y, et al. Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. *Am J Sports Med*. 2010;38(11):2218–2225.
65. Gribble PA, Robinson RH, Hertel J, Denegar CR. The effects of gender and fatigue on dynamic postural stability. *J Sport Rehabil*. 2009;18(2):240–257.
66. Zeller BL, McCrory JL, Kibler WB, Uhl TL. Differences in kinematics and electromyographic activity between men and women during the single-legged squat. *Am J Sports Med*. 2003;31(3):449–456.
67. Hewett TE, Torg JS, Boden BP. Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism. *Br J Sports Med*. 2009;43(6): 417–422.
68. Hewett TE, Myer GD, Ford KR. Reducing knee and anterior cruciate ligament injuries among female athletes: a systematic review of neuromuscular training interventions. *J Knee Surg*. 2005;18(1):82–88.

69. Ford KR, Myer GD, Hewett TE. Longitudinal effects of maturation on lower extremity joint stiffness in adolescent athletes. *Am J Sports Med*. 2010;38(9):1829–1837.
70. Ford KR, Shapiro R, Myer GD, Van Den Bogert AJ, Hewett TE. Longitudinal sex differences during landing in knee abduction in young athletes. *Med Sci Sports Exerc*. 2010;42(10):1923–1931.
71. Sackett DL, Rosenberg WM, Gray JA, Haynes RB, Richardson WS. Evidence based medicine: what it is and what it isn't. 1996. *Clin Orthop Relat Res*. 2007;455:3–5.
72. Kerin F, Delahunt E. Physiotherapists' understanding of functional and mechanical insufficiencies contributing to chronic ankle instability. *Athl Train Sports Health Care*. 2011;3(3):125–130.

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