Lower Limb Asymmetry After Anterior Cruciate Ligament Reconstruction in Adolescent Athletes: A Systematic Review and Meta-Analysis

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Objectives: To identify reported (1) common biomechanical asymmetries in the literature after anterior cruciate ligament (ACL) reconstruction in adolescents during landing and (2) timescales for asymmetry to persist postsurgery.

Data Sources: We identified sources by searching the CINAHL, PubMed, Scopus, and SPORTDiscus electronic databases using the following search terms: asymmetry OR symmetry AND landing AND biomechanics OR kinematics OR kinetics.

Study Selection: We screened the titles and abstracts of 85 articles using our inclusion criteria. A total of 13 articles were selected for further analysis.

Data Extraction: Three reviewers independently assessed the methodologic quality of each study. We extracted the effect sizes directly from studies or calculated them for biomechanical variables assessing asymmetry between limbs of participants with ACL reconstruction. We conducted meta-analyses on variables that were assessed in multiple studies for both double- and single-limb landings.

Data Synthesis: Asymmetry was more commonly identified in kinetic than kinematic variables. Anterior cruciate ligament reconstruction appeared to have a large effect on asymmetry between limbs for peak vertical ground reaction force, peak knee-extension moment, and loading rate during double-limb landings, as well as mean knee-extension moment and knee energy absorption during both double- and single-limb landings.

Conclusions: Our findings suggested that return-to-sport criteria after ACL reconstruction should incorporate analysis of the asymmetry in loading experienced by each limb rather than movement patterns alone.

Key Words: anterior cruciate ligament injury, landing, biomechanics

Key Points
• Asymmetries between surgical and nonsurgical limbs were more frequently identified in kinetic than in kinematic variables.
• The most common asymmetries were peak knee-extension moment and peak vertical ground reaction force during double-limb landing; both values were frequently lower in the surgical than in the nonsurgical limb.
• In most cases, lower limb kinematics did not display asymmetry between limbs.
• Anterior cruciate ligament reconstruction appeared to have a large effect on asymmetry in peak vertical ground reaction force, peak knee-extension moment, and loading rate during double-limb landing and mean knee-extension moment and knee energy absorption during both double- and single-limb landings.
• Return-to-sport criteria after anterior cruciate ligament reconstruction should include analysis of the asymmetry in loading experienced by each limb rather than the movement patterns alone.

Anterior cruciate ligament (ACL) injury most often occurs during noncontact situations (72% of cases),1,2 such as landing, side stepping or cutting, and change of direction, in which no direct blow to the knee occurs at the time of injury. After ACL injury, surgery to reconstruct the ruptured ACL is the most frequent option for patients, with 90% of patients electing to proceed.3 Most ACL reconstructions (ACLRs) are performed in the adolescent population.4,5 After ACLR, adolescent athletes typically aim to return to competitive sport participation. This requires extensive rehabilitation, with the overarching goal of returning the surgical limb to a similar level of function (ie, range of motion, strength, and coordination) as existed before the injury.6–8 However, preexisting levels of function are usually unknown, so the goal instead becomes returning the surgical limb to symmetric function with the nonsurgical limb,8 which is subsequently used by a health care professional as a marker for the athlete’s clearance to return to sport.6,9–11

Despite considerable efforts to improve surgical procedures and rehabilitation practices after ACLR, secondary ACL injury is common in athletes who return to sport.9,12–15 Between 6% and 29% of patients who undergo ACLR either injure the graft of the surgical limb or sustain an ACL injury to the contralateral limb.9,12–15 This risk of subsequent ACL injury after reconstruction is highest
among adolescent patients.\textsuperscript{15–18} Shelbourne et al\textsuperscript{16} reported that the prevalence of rupture to either the contralateral or reconstructed ACL within 5 years of ACLR was 9.6\% (4.3\% for the reconstructed ACL, 5.3\% for the contralateral knee) for the general population (N = 1415). This, however, rose to 17.4\% (8.7\% for both the ACL-reconstructed and contralateral knees) in patients aged < 18 years compared with 6.7\% in patients aged 18 to 25 years and 3.9\% in patients > 25 years.\textsuperscript{16} Furthermore, Shelbourne et al\textsuperscript{16} noted that most secondary ACL injuries occurred during sport participation, with the majority sustained during basketball (52\%) or soccer (15\%) compared with only 6.6\% (9 of 136 secondary ACL injuries) sustained during nonsport-related activities.

The reasons for the high prevalence of secondary injury after ACLR are likely deficiencies in the strength of the muscles controlling knee movement, as well as altered movement and loading patterns when performing athletic activities, such as landing, squatting, and cutting.\textsuperscript{9} Asymmetry in landing mechanics after ACLR has been proposed as a major risk factor for both primary\textsuperscript{19} and secondary ACL injury.\textsuperscript{9} Investigators\textsuperscript{8–11,20–24} observed that after ACLR, athletes who exhibited less asymmetry of lower limb biomechanics during sporting activities had a reduced risk of sustaining a second ACL injury. However, one of the main challenges for health care professionals treating patients with ACLR is how to identify asymmetry between limbs and, therefore, properly clear an athlete to return to sport. Some researchers\textsuperscript{7,25} have attempted to develop clinical assessment criteria to appropriately define return to sport after ACLR. These criteria typically include consideration of time since surgery; knee-joint stability; symmetry between surgical and nonsurgical limbs in postural control, strength, power, endurance, agility, and hop distance; and qualitative movement analysis during sporting tasks.\textsuperscript{25} Yet most of these criteria rely on subjective measures and only indirectly assess knee function and loading. For example, a measure of hopping distance provides little information about the lower limb movement and loading patterns that have been identified as risk factors for secondary injury during dynamic movements.\textsuperscript{9,22,26} This suggests that the current methods used to clear the athlete to return to play after ACLR may not adequately determine mechanical symmetry between limbs. Consequently, many athletes will likely return to competition prematurely, before their reconstructed knee has regained full function in terms of range of motion, strength, and muscle-activity patterns.

Most researchers who examined asymmetries after ACLR have focused on adult populations.\textsuperscript{26,27} In a recent systematic review and meta-analysis, Lepley and Kuenze\textsuperscript{28} evaluated hip and knee biomechanics after ACLR during double- and single-limb landing tasks. Patients who underwent ACLR demonstrated a reduced knee-extension moment and reduced ground reaction force (GRF) on the surgical side compared with the nonsurgical side, which suggested potential unloading of the surgical limb. In our study, we aimed to build on the work of Lepley and Kuenze\textsuperscript{28} by focusing on adolescent athletes because of their increased risk of secondary ACL injury and by including more variables in the analysis, specifically ankle biomechanics. During adolescence, the body undergoes considerable change in structure and maturation of motor coordination and control.\textsuperscript{29,30} These changes result in altered landing mechanics.\textsuperscript{4,5} Given the large number of ACLRs performed during adolescence, asymmetry in lower limb mechanics is likely to have a more profound effect on young athletes wanting to return to sport participation after ACLR. Therefore, the purpose of our systematic review and meta-analysis was to identify reported (1) common biomechanical asymmetries in the literature after ACLR in adolescents during landing movements and (2) time-scales for asymmetry to persist postsurgery.

\section*{METHODS}

\subsection*{Literature Search Strategy}

We identified relevant sources by searching the following electronic databases from their inceptions to January 2019: CINAHL (1961), PubMed (1966), Scopus (2004), and SPORTDiscus (1930). The following search terms were used: \textit{asymmetry OR symmetry AND landing AND biomechanics OR kinematics OR kinetics}. We excluded articles not written in English, reviews, meta-analyses, non-peer-reviewed sources, and abstracts unaccompanied by full-text journal articles, which left 164 articles.

\subsection*{Study Selection}

We downloaded the article data, including authors, title, abstract, and journal, into RefWorks (ProQuest, Ann Arbor, MI) citation management software; duplicate citations were deleted. This reduced the number of articles to 85. Next, we reviewed article titles and abstracts to apply our inclusion criteria: human adolescents (mean age > 11 and < 18 years) who had ACLR and > 1 kinetic or kinematic measure of asymmetry that compared the surgical and nonsurgical limbs. Kinetic variables included GRF, joint moments (turning effects produced by forces acting around joints), and energy absorption (amount of work performed at a joint, calculated from the joint moment multiplied by the change in joint angle). Kinematic variables included joint angles and angular velocities. Lastly, the task performed was required to be either a double-limb (bilateral) or single-limb (unilateral) landing maneuver. Two independent reviewers (G.H., S.C.) assessed all articles, and any disagreements were resolved through oral discussion after all articles had been reviewed.

After the inclusion criteria were applied, 12 papers remained. We inspected the reference lists of each paper and identified 1 more study, bringing the total to 13. The literature search and study-selection procedures are outlined in Figure 1.

\subsection*{Data Extraction and Analysis}

We extracted the following information from each article: study design, aim, participants (mean age, sex, sporting background, time post-ACLR), task, measure of asymmetry used, and key findings. Three reviewers (G.H., P.M., S.C.) independently assessed each study’s methodologic quality using 14 relevant criteria from the Downs and Black\textsuperscript{31} revised checklist. This checklist was chosen because it is a valid and reliable tool for assessing the methodologic quality of randomized and nonrandomized studies in health care.\textsuperscript{31} A study that was scored ≤ 8 was considered to be \textit{low quality}; 9 to 10, \textit{moderate quality}; and > 11, \textit{high quality}.\textsuperscript{28,32} We again resolved disagreements
through a consensus meeting. The means and standard deviations of each variable that assessed asymmetry were extracted. When we then extracted effect sizes directly from the studies or calculated them by dividing the mean difference between groups by the pooled standard deviation. Given that previous authors have shown different asymmetries in lower limb biomechanics between single- and double-limb landing tasks, the data were stratified based on landing task. We interpreted Cohen d effect sizes (trivial (<0.2), small (<0.5), moderate (0.51–0.79), or large (>0.8)). For 1 study, we estimated effect sizes based on the data presented in figures, and for another study, we were unable to calculate effect sizes based on the statistical information provided. We conducted meta-analyses on variables that were assessed multiple times (at least 2 measurements of a particular variable) using the metafor package in R software (Vienna, Austria).

RESULTS

Study Quality

Of the studies assessed, were scored as high quality, 7,38,39,42,43,44 were scored as moderate quality, and only 1 was scored as low quality (Supplemental Table, available online at http://dx.doi.org/10.4085/1062-6050-244-19.S1). The average score was 10.2 out of 14, suggesting moderate quality overall. All criteria were met by the 12 investigations; however, only 1 group specifically stated that all participants were recruited during the same time period, and only 1 group determined sample size by conducting an a priori power analysis.

Participants

A total of 180 males and 330 females participated in the 13 studies. All authors tested both male and female patients with ACLR. The average sample sizes for patients with ACLR were 13.8 ± 6.0 for males and 25.5 ± 12.1 for females. The smallest number of participants tested who had undergone ACLR was 15, and the largest number was 68. The mean age across all participants was 16.4 ± 0.8 years. All participants intended to return to competitive sports at a level similar to their preinjury level.

Time After ACLR

Participants were tested at approximately 4, 5, 6, 7, 8, 10, 12, 38–40, 6, 7, 8, 10, 38, 39, 40, 43–45 months after ACLR. Ithurburn et al. reported the time from being cleared to return to sport rather than the time from ACLR (4 weeks after being cleared to return to sport and 2 years later). Schneider et al. simply stated that testing took place within 1 year after ACLR, and Paterno et al. did not clearly specify the time after ACLR (Figure 2).

Landing Task

The landing task differed among studies, with some using single-legged vertical jump landing (participants were instructed to jump as high possible on 1 limb and land under control), single-legged vertical drop landing (participants dropped from a 31-cm box and were instructed to maintain a controlled landing in single-limb stance), double-legged vertical drop jump (participants dropped off a 31- or 40-cm box, landed on both feet, and immediately jumped straight up as high as possible), and a vertical stop jump (participants ran forward, took off on 1 foot, landed on 2 feet, and took off again from 2 feet).

Outcome Measures

Most researchers examined asymmetries only in the sagittal plane; only 3 groups assessed variables in all 3 planes of motion. Kinematic and kinetic joint variables were evaluated 58 times in the sagittal plane (28 kinematic and 30 kinetic analyses) compared with only 14 times in the frontal plane and 6 times in the transverse plane. Differences between surgical and nonsurgical limbs were commonly observed in the sagittal plane: 32% (9/28 included data points) of the time differences for kinematics and 70% (21/30 included data points) for kinetics. Few kinematic variables differed between the surgical and nonsurgical limbs in the frontal and transverse planes (only 1 difference among 13 variables measured), but for kinetic measures in the frontal and transverse planes, 6 differences were demonstrated for only 7 variables measured (5 frontal plane, 2 transverse plane; Tables 1 and 2).

With respect to which lower limb joints were assessed for asymmetries, 5 studies examined the knee and at least 1 other joint (hip or ankle), 5 studies examined only the knee joint, 2 studies examined only the GRF, and 1 study examined only leg stiffness.

Most investigators included both kinematic and kinetic measures of asymmetry, with 5 studies examining only kinetic variables. No authors examined purely kinematic measures of asymmetry. Differences between the surgical and nonsurgical limbs were more frequently observed in kinetic variables than in kinematic variables, whereby 76% (44/58 included data points) of the time, a between-limbs difference was present for kinetic variables compared with only 24% (10/41 included data points) for kinematic variables.

Figure 1. Flow diagram of literature search strategy.
The most commonly measured variable was peak vertical GRF, which was assessed in 10,23,35,37–44 of the 13 studies. This variable was also most often different between limbs, with 9 studies,23,35,37–43 showing reduced vertical GRF for the surgical limb compared with the nonsurgical limb. The only researchers44 who measured peak vertical GRF and did not find a difference between limbs used a single-limb landing task. The meta-analysis indicated asymmetry between the surgical and nonsurgical limbs for peak vertical GRF with large summary effect sizes for double-limb landings (b = −1.67; 95% confidence interval [CI] = −2.53, −0.80; standard error [SE] = 0.44; z = −3.78; P < .001) but a trivial effect size for single-limb landings (b = −0.06; 95% CI = −0.36, 0.23; SE = 0.15; z = −0.42; P = .23; Figure 3A). The second most commonly measured variable to assess asymmetry was peak knee-extension moment, which was measured in 7,37,40,42,43,45 of the 13 studies and found to be reduced in the surgical limb compared with the nonsurgical limb in 6,37,40,42,44 of the 7 studies, all of which employed a double-limb landing task (Table 2). The meta-analysis indicated an asymmetry between the surgical and nonsurgical limbs for peak knee-extension moment with a large summary effect size for double-limb landings (b = −2.86; 95% CI = −4.56, −1.17; SE = 0.86; z = −3.31; P < .001; Figure 3B).

The other kinetic variables in which the meta-analyses identified asymmetry were loading rate, mean knee-extension moment, knee-energy absorption, ankle-energy absorption, mean ankle sagittal-plane moment, and mean knee frontal-plane moment. Large effect sizes were observed for loading rate during double-limb landings (b = −2.08; 95% CI = −3.39, −0.76; SE = 0.49; z = −3.58; P < .001; Figure 3C), mean knee-extension moment during double-limb (b = −1.63; 95% CI = −2.35, −0.92; SE = 0.36; z = −4.48; P < .001) and single-limb (b = −0.90; 95% CI = −1.33, −0.48; SE = 0.22; z = −4.13; P < .001) landings (Figure 3D) and knee-energy absorption during double-limb (b = −1.38; 95% CI = −1.76, −1.01; SE = 0.19; z = −7.23; P < .001) and single-limb (b = −0.99; 95% CI = −1.50, −0.48; SE = 0.26; z = −3.81; P < .001) landings (Figure 3E). Large summary effect sizes were noted during double-limb landings for ankle-energy absorption (b = −1.04; 95% CI = −1.44, −0.64; SE = 0.20; z = −5.08; P < .001 Figure 3F) and mean ankle sagittal-plane moment (b = −1.00; 95% CI = −1.27, −0.74; SE = 0.14; z = −7.42 P < .001; Figure 3G), whereas effect sizes were small or trivial and not different during single-limb landings for ankle-energy absorption (b = 0.17; 95% CI = −0.15, 0.49; SE = 0.16; z = 1.06; P = .29; Figure 3F) and mean ankle sagittal-plane moment (b = 0.43; 95% CI = −0.43, 1.29; SE = 0.44; z = 0.97; P = .33; Figure 3G). Moderate effect sizes were demonstrated for mean knee frontal-plane moment during double-limb (b = −0.68; 95% CI = −0.94, −0.41; SE = 0.14; z = −5.01; P < .001) and single-limb (b = −0.53; 95% CI = −0.82, −0.23; SE = 0.15; z = −3.52; P < .001) landings (Figure 3H).

The only kinematic variables in which the meta-analyses identified differences between the surgical and nonsurgical limbs were peak knee-flexion angle and peak ankle-dorsiflexion angle. A moderate summary effect size was
Table 1. Summary of the Kinematic Variables Measured to Assess Biomechanical Asymmetry in Each Study

| Variable                                      | Butler et al. (2016) | Butler et al. (2014) | Ithurburn et al. (2017) | Mueske et al. (2018) | Mueske et al. (2018) | Myer et al. (2012) | Paterno et al. (2010) | Paterno et al. (2011) | Renner et al. (2018) | Schmitt et al. (2015) | Schneider et al. (2017) | Wren et al. (2018) |
|-----------------------------------------------|----------------------|----------------------|-------------------------|----------------------|----------------------|---------------------|-----------------------|-----------------------|----------------------|-----------------------|-----------------------|----------------------|
| Study quality scoreb                          | Double               | Double               | Single                  | Double               | Double               | Double              | Double                | Double                | Double               | Single                 | Combined              | Double               |
| Limb symmetry index calculatedc               |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Sagittal-plane kinematics                    |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Hip-flexion angle at initial contact          |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Hip range of motion                           |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Peak hip-flexion angle                        |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Knee-flexion angle at initial contact         |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Knee range of motion                          |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Peak knee-flexion angle                       |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Peak knee-flexion angular velocity            |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Knee-flexion angular velocity at initial contact |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Knee-flexion angle at peak angular velocity   |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Ankle plantar-flexion angle at initial contact |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Peak ankle-dorsiflexion angle                 |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Frontal-plane kinematics                      |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Hip-flexion angle at initial contact          |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Peak hip-flexion angle                        |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Mean hip-flexion angle                        |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Knee-flexion angle at initial contact         |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Knee range of motion                          |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Peak knee-flexion angle                       |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Mean knee-flexion angle                       |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Transverse-plane kinematics                   |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Hip-flexion angle at initial contact          |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Peak hip-flexion angle                        |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |
| Mean hip-flexion angle                        |                      |                      |                         |                      |                      |                    |                      |                      |                      |                      |                      |                     |

a Where differences were reported, effect sizes are given (1 value if 1 group tested, 2 values if 2 groups tested, and range of values if ≥3 groups tested).
b Out of 14 points (≤8 = low, 9–10 = moderate, ≥11 = high).
c Calculated as (involved limb/uninvolved limb) × 100.
d Variable was measured, but no difference was reported between the surgical and nonsurgical limbs.
e Greater in the surgical limb.
f Less in the surgical limb.
g Significant effect.
Table 2. Summary of the Kinetic Variables Measured to Assess Biomechanical Asymmetry in Each Study

| Variable                                | Study (Year) | Study (Year) | Summary Effect Size | Double | Single | Combined |
|-----------------------------------------|--------------|--------------|---------------------|--------|--------|----------|
| Limb landing type                        |              |              |                     |        |        |          |
| Study quality score<sup>b</sup>          | Double       | Double       |                     | 10     | 10     |          |
| Limb symmetry index calculated<sup>c</sup> | X            | X            |                     |        |        |          |

**Sagittal-plane kinetics**

| Variable                                | Study (Year) | Study (Year) | Summary Effect Size | Double | Single | Combined |
|-----------------------------------------|--------------|--------------|---------------------|--------|--------|----------|
| Peak hip moment                          |              |              |                     |        |        |          |
| Hip energy absorption                    |              |              |                     |        |        |          |
| Peak knee-extension moment               |              |              |                     | 1.46, 1.03 | 1.33<sup>f</sup> | 1.23<sup>f</sup> | 1.00, 0.60<sup>f</sup> |
| Mean knee-extension moment               |              |              |                     | 1.32<sup>f</sup> | 0.8–2.3<sup>f</sup> |        |          |
| Knee-extension moment at peak angular velocity | 1.00<sup>f</sup> |        |                     |        |        |          |
| Knee-energy absorption                   |              |              |                     |        |        |          |
| Peak ankle moment                        |              |              |                     | 0.55, 0.33<sup>f</sup> |        |        |          |
| Mean ankle moment                        |              |              |                     | 0.8–1.3<sup>f</sup> | 1.00, 1.00<sup>f</sup> |        |          |
| Ankle-energy absorption                  |              |              |                     | 0.9–1.6<sup>f</sup> | 1.18, 0.39<sup>f</sup> |        |          |

**Frontal-plane kinetics**

| Variable                                | Study (Year) | Study (Year) | Summary Effect Size | Double | Single | Combined |
|-----------------------------------------|--------------|--------------|---------------------|--------|--------|----------|
| Mean hip moment                          |              |              |                     |        |        |          |
| Mean knee moment                         |              |              |                     | 0.5–1.1<sup>a</sup> | 0.45, 0.57<sup>a</sup> |        |          |

**Transverse-plane kinetics**

| Variable                                | Study (Year) | Study (Year) | Summary Effect Size | Double | Single | Combined |
|-----------------------------------------|--------------|--------------|---------------------|--------|--------|----------|
| Mean hip moment                          |              |              |                     | 0.6<sup>a</sup> |        |          |

**Ground reaction force**

| Variable                                | Study (Year) | Study (Year) | Summary Effect Size | Double | Single | Combined |
|-----------------------------------------|--------------|--------------|---------------------|--------|--------|----------|
| Peak vertical                           |              |              |                     | 0.9, 0.57 | 0.72<sup>f</sup> | 0.79<sup>f</sup> | 0.7–1.5<sup>f</sup> | 1.33, 1.00<sup>f</sup> | 0.98<sup>f</sup> | 2.44–5.51<sup>f</sup> | 0.28, 1.70<sup>f</sup> |        |          |
| Peak posterior                           |              |              |                     | 0.47<sup>f</sup> |        |        |          |
| Loading rate                             |              |              |                     | 0.51<sup>f</sup> |        |        |          |
| Vertical impulse                         |              |              |                     |        |        |          |
| Anteroposterior impulse                  |              |              |                     |        |        |          |
| Peak vertical stiffness                  |              |              |                     | 1.25–3.25 | 0.32<sup>f</sup> |        |          |

<sup>a</sup> Where differences were reported, effect sizes are given (1 value if 1 group was tested, 2 values if 2 groups were tested, and range of values if ≥3 groups were tested).

<sup>b</sup> Out of 14 points (<span class="math" value="8 = low; 9–10 = moderate; ≥11 = high"></span>high).

<sup>c</sup> Calculated as (involved limb/uninvolved limb) × 100.

<sup>d</sup> Variable was measured, but no difference was reported between the surgical and nonsurgical limbs.

<sup>e</sup> Greater in the surgical limb.

<sup>f</sup> Less in the surgical limb.

<sup>g</sup> Significant effect.
observed for peak knee-flexion angle during double-limb (β = -0.66; 95% CI = -1.02, -0.30; SE = 0.18; z = -3.62; P < .001) and single-limb (β = -0.51; 95% CI = -1.01, -0.01; SE = 0.25; z = -2.02; P = .044) landings (Figure 3I) and for peak ankle-dorsiflexion angle (β = -0.58; 95% CI = -0.89, -0.28; SE = 0.15; z = -3.78; P < .001) during double-limb landings, but only a small summary effect size was detected for this variable during single-limb landings (β = -0.23; 95% CI = -0.65, 0.19; SE = 0.21; z = -1.07; P = .28; Figure 3J).

The meta-analyses indicated no asymmetry between the surgical and nonsurgical limbs for knee flexion at initial ground contact, peak hip-flexion angle, mean hip sagittal-plane moment, and hip-energy absorption during both double- and single-limb landings. Trivial summary effect sizes were present for knee-flexion angle at initial ground contact during double-limb (β = 0.04; 95% CI = -0.34, 0.42; SE = 0.19; z = 0.19; P = .85) and single-limb (β = -0.16; 95% CI = -0.45, 0.14; SE = 0.15; z = -1.05; P = .29).
landings, peak hip-flexion angle during double-limb ($b = 0.14; 95\% \text{ CI } = -0.10, 0.37; \text{ SE } = 0.12; z = 1.14; P = .26$) and single-limb ($b = -0.20; 95\% \text{ CI } = -0.96, 0.57; \text{ SE } = 0.39; z = -0.50; P = .62$) landings, mean hip sagittal-plane moment during double-limb ($b = 0.18; 95\% \text{ CI } = -0.08, 0.45; \text{ SE } = 0.14; z = 1.36; P = .18$) and single-limb ($b = 0.05; 95\% \text{ CI } = -0.25, 0.34; \text{ SE } = 0.15; z = 0.32; P = .75$) landings, and hip-energy absorption during double-limb ($b = -0.05; 95\% \text{ CI } = -0.31, 0.22; \text{ SE } = 0.14; z = -0.35; P = .73$) and single-limb ($b = -0.15; 95\% \text{ CI } = -0.99, 0.70; \text{ SE } = 0.43; z = -0.34; P = .73$) landings.

**DISCUSSION**

In this systematic review and meta-analysis, we aimed to identify the common biomechanical asymmetries during landing movements reported in the literature after ACLR in adolescents. A total of 13 studies were assessed for quality, with 5 studies\(^{23,37,38,40,41}\) rated as high quality, \(^{735,39,42-46}\) rated as moderate quality, and 1\(^{9}\) rated as low quality (average score = 10.2/14). Sagittal-plane knee kinetics (8 studies: 4 high,\(^{37,38,40,41}\) 3 moderate,\(^{39,42,43}\) and 1 low\(^{9}\) quality) and vertical GRF (8 studies: 5 high\(^{23,37,38-41}\) and 3 moderate\(^{39,42,43}\) quality) during double-limb landings were the most frequent variables that were both measured and
shown to be asymmetric between the surgical and nonsurgical limbs. This result is supported by a recent systematic review and meta-analysis of Lepley and Kuenze, who also found asymmetry in these variables during landing in adults with ACLR. The close link between these factors was identified by Dai et al., who determined that asymmetries in GRF accurately predicted asymmetries in knee-extension moment. Anterior cruciate ligament reconstruction had a large effect on asymmetry between limbs in peak vertical GRF, peak knee-extension moment, mean knee-extension moment, knee-energy absorption, and loading rate during double-limb landing. In all cases in which asymmetries were identified for these variables, the loading of the surgical limb was less than in the nonsurgical limb. The meta-analyses more often identified asymmetries with larger effect sizes for double-limb landings than for single-limb landings. This may be partly due to the larger number of data points for double-limb landings but also suggests that during double-limb landings, athletes recovering from ACLR typically put less

Figure 3. Continued from previous page. Continued on next page.
load on their injured limb to protect it from further injury by increasing the load on the uninjured limb. This observation is supported by Lepley and Kuenze, who found lower peak knee-extension moments in the surgical limb during double-limb landing but not during single-limb landing. Asymmetry in landing mechanics after ACLR has been proposed as a risk factor for secondary ACL injury to the surgical or nonsurgical limb, whereby increasing the load on the uninjured limb may increase the risk of injury. The only study (moderate quality) that measured peak vertical GRF and did not find that it was lower in the surgical than the nonsurgical limb involved a single-legged landing task in which it was not possible to unload the surgical limb by placing additional load on the nonsurgical limb.
limb. Anterior cruciate ligament reconstruction had a large effect on asymmetry during single-limb landings only for mean knee-extension moment and knee-energy absorption. This result suggests that, whereas it is not possible to unload the injured limb by increasing loading on the uninjured limb, athletes may still attempt to reduce the peak loading on the knee by spreading the loading over a longer time.

Generally, researchers reported differences far more commonly in kinetic than in kinematic variables. Lepley and Kuenze demonstrated no conclusive effect of asymmetry in hip or knee kinematics during landing. The only kinematic variables for which the meta-analyses identified asymmetry were peak knee-flexion angle during both double- and single-limb landings and peak ankle-dorsiflexion angle during double-limb landing, but these variables had only moderate effect sizes. In all studies, comparable 3-dimensional motion-analysis techniques were implemented to measure joint kinematics (between 8 and 10 camera systems sampling at either 120 or 240 Hz). While several different marker sets were used, it is fair to assume that the motion-analysis techniques used by all authors would elicit high-quality kinematic data. Although some investigators reported differences in sagittal-plane
kinematics (9 differences at 28 times measured across 8 studies, 4 high and 4 moderate quality), only once (moderate-quality study) did a frontal- or transverse-plane kinematic variable differ between limbs in the 13 measured cases. This is, therefore, an area for future work, particularly because frontal- and transverse-plane kinematic variables, such as knee-valgus angle and hip internal rotation, have been strongly implicated as risk factors for ACL injury. However, these findings relate only to asymmetry between surgical and nonsurgical limbs and not to comparisons between injured and healthy individuals or between pre- and post-ACLR injury. Consensus is lacking on the extent of asymmetries in lower limb biomechanics between dominant and nondominant limbs in the general healthy population, with some groups reporting no differences and others reporting some differences.

Of the 13 studies included in this systematic review, only 2 (1 high and 1 moderate quality) described which limb (dominant or nondominant) was injured, and no apparent control for limb dominance was included in any statistical analyses. The authors who supplied the percentage of injuries to the dominant limb provided values of 48% (11/23) and 54% (33/61). Supporting previous research that showed no relationship between the side of primary ACL injury and limb dominance.

Whereas kinetic variables in the frontal and transverse planes were not commonly measured, investigators in the 3 studies (2 high and 1 moderate quality) did so identify asymmetry. In our review, the only frontal-plane kinetic variable that was different between limbs was mean knee frontal-plane moment (average adduction moment during the landing maneuver) during double- and single-limb landings, which demonstrated a moderate effect size. This highlights the need for further investigation of frontal- and transverse-plane asymmetries between surgical and nonsurgical limbs. Although 5 groups (reflecting 3 high and 2 moderate quality studies) examined mechanical asymmetries at the hip and ankle joints, most of the asymmetric variables were at the knee joint. The only variables that were asymmetric at the ankle were ankle-energy absorption and mean ankle sagittal-plane moment during double-limb landings, with large effect sizes. No meaningful effect of asymmetry was apparent in peak hip-flexion angle, mean hip sagittal-plane moment, or hip-energy absorption after ACLR. This contrasts with the findings of Lepley and Kuenze, who observed large effects for peak hip sagittal-plane moment during double-limb landings in adult participants. Given that the knee was the site of the surgical reconstruction, it is perhaps to be expected that most asymmetry would occur at that joint, which emphasizes the need for rehabilitation practices to focus there, with less concern about compensatory movements in other joints of the kinetic chain.

Among adult participants after ACLR, asymmetries were present in both loading and movement patterns. These asymmetries included reductions in knee flexion, knee sagittal-plane moment, and vertical GRF on the surgical side compared with the nonsurgical side. We determined that these variables also affected between-limbs symmetry in adolescent participants after ACLR. Therefore, asymmetry in landing biomechanics after ACLR may be similar between adults and adolescents, and differences in secondary ACL injury prevalence between these populations do not necessarily depend on variations in landing asymmetry but may be linked to other factors, such as skeletal maturity and eagerness to return to participation in competitive sports.

For the studies included in the review, participants were tested approximately 4 to 12 months after ACLR. As expected, asymmetries were more commonly noted in participants who were tested closer to the time of surgery. However, authors of the 3 studies (2 high and 1 moderate quality) that involved >1 test session reported that many asymmetries were still present approximately 8 to 12 months after ACLR. When the same participants were tested on multiple occasions, the asymmetry was reduced as the time after reconstruction increased, showing that any rehabilitation practices the participants were pursuing were effectively reducing the asymmetry in landing mechanics.

**Clinical Implications**

Overall, asymmetries were more commonly identified in kinetic variables than in kinematic variables, which strongly supports the notion that return-to-play criteria for athletes after ACLR require assessment of between-limb loading asymmetry and should not rely on assessment of symmetry in movement patterns alone. Current criteria typically include consideration of the time since surgery, symmetry between the surgical and nonsurgical limbs in both strength and hop distance, and qualitative movement analysis during sporting tasks. Our review showed that some athletes were likely to exhibit symmetric movement patterns between limbs but potentially dangerous loading asymmetries. This was also supported by Orishimo et al, who showed that the hopping asymmetry ratio (surgical/nonsurgical limb × 100) in adult males after ACLR was 93%, whereas the peak knee-power asymmetry was 57%. Therefore, if return-to-play criteria include only a kinematic description of asymmetry between limbs, many athletes would likely be prematurely cleared to return to competition and subsequently risk secondary ACL injury. In addition, athletes returning from ACLR should focus more on achieving loading symmetry between limbs, particularly in vertical GRF and knee-extension moments, rather than on kinematic symmetry.

Thus, we recommend measuring these variables during the rehabilitation process to provide feedback on the loading of each limb during landing tasks. This is a challenge for medical professionals who do not always have access to expensive equipment for measuring GRF and knee-joint loading, such as force plates and 3-dimensional motion-analysis systems. However, with the increased availability and affordability of mobile monitoring technology, such as accelerometers, that provide valid and reliable measurements of impact forces during landing, cutting, and running tasks, clinicians involved in determining return to play after ACLR should consider incorporating such technology to analyze lower limb loading.

**Limitations**

The limitations of our study included difficulty in formulating an inclusion criterion for adolescent athletes because many authors reported only age means and
standard deviations rather than the range or information on maturity status. Researchers should consider developing improved return-to-play criteria after ACLR that include affordable techniques for analyzing lower limb loading during landing. Our study also highlighted the need for attention to asymmetric frontal- and transverse-plane mechanics after ACLR. Lastly, a small number of investigators examined single-limb landing tasks; therefore, comparisons between double- and single-limb tasks were limited for some variables.

CONCLUSIONS

Asymmetries between surgical and nonsurgical limbs were more frequently identified in kinetic than in kinematic variables. The most common asymmetries described were peak knee-extension moment and peak vertical GRF during double-limb landing, both of which were frequently less in the surgical than the nonsurgical limb. In most cases, lower limb kinematics did not display asymmetry. Our meta-analysis indicated that ACLR appeared to have a large effect on asymmetry in peak vertical GRF, peak knee-extension moment, and loading rate during double-limb landings and mean knee-extension moment and knee-energy absorption during both double- and single-limb landings. Large effect sizes were observed for asymmetry in ankle-energy absorption and mean ankle sagittal-plane moment during double-limb landings but not during single-limb landings. Moderate effect sizes were present for asymmetry in mean knee frontal-plane moment and peak knee-flexion angle during both double- and single-limb landings and peak ankle-dorsiflexion angle during double-limb landings. No meaningful asymmetry was demonstrated in peak hip-flexion angle, mean hip sagittal-plane moment, or hip-energy absorption. Our findings suggested that return-to-sport criteria after ACLR should incorporate analysis of the loading experienced by each limb rather than movement patterns alone.

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