Altered Neuromuscular Activity of the Lower-Extremities During Landing Tasks in Patients With Anterior Cruciate Ligament Reconstruction: A Systematic Review of Electromyographic Studies

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Context: Altered lower-limb biomechanics have been observed during landing task in patients with anterior cruciate ligament reconstruction (ACLR), which increases the risk of secondary anterior cruciate ligament injury. However, the alteration in neuromuscular activity of the lower-extremity during landing task is not clear. **Objective:** To compare the muscle activity pattern assessed by electromyography between the involved limb of patients with ACLR and the contralateral limb or control limb of matched healthy subjects during landing task. **Evidence Acquisition:** Database of PubMed, Ovid, Scopus, and Web of Science from the inception of the databases until July 2019, using a combination of keywords and their variations: (anterior cruciate ligament OR ACL) AND (electromyography OR EMG) AND (landing OR land). Studies that assessed lower-extremity muscle activity patterns during landing task in patients with ACLR and compared them either with the contralateral side or healthy controls were included. **Evidence Synthesis:** Of the 21 studies, 16 studies reported altered muscle activity pattern during landing tasks when compared with either the healthy controls or the contralateral side. For the specific muscle activity patterns, the majority of the studies showed no significant difference in reactive muscle activity, and comparisons across studies revealed a possible trend toward the early onset of quadriceps and hamstring activity and increased cocontraction of the involved limb. There are inconsistent findings regarding the alteration in muscle timing and preparatory muscle activity. **Conclusions:** Patients with ACLR displayed an altered muscle activity pattern during landing tasks, even though they were considered to be capable for sport return. Nevertheless, a firm conclusion could not be drawn due to great heterogeneity in the subject selection and study methods.

Keywords: muscle activity, neuromuscular control, ACL injury, rehabilitation

Anterior cruciate ligament (ACL) injury is one of the most common knee injuries in sports such as soccer, handball, basketball, and rugby.¹ Approximately 175,000 ACL reconstruction (ACLR) surgeries are performed in the United States each year to restore knee stability and function. Despite undergoing surgical reconstruction and rehabilitation, a high noncontact ACL reinjury rate of 25.4% (either the reconstructed side or the contralateral side) has been reported in athletes who returned to high risk (Level I or 2) sports, and the ACL injury risk after ACLR is 15 times that of the healthy population.²

Landing in athletic maneuvers such as hopping and drop jumping has been shown to have one of the highest risks for ACL injury.^{3,4} Landing tasks have been widely used for biomechanics analysis after ACL injury and reconstruction. Previous systematic reviews have summarized that altered biomechanics, such as decreased peak knee-flexion and knee-extension moments, are commonly observed in patients after ACLR when compared with healthy people during landing.^{5,6} Aberrant biomechanical patterns may persist subsequent to patients returning to sport after ACLR, and this may explain the high rate of a second ACL injury.^{7,8}

To prevent ACL reinjury, the knee joint must be stabilized and protected by the passive restraint (ligaments) and the active restraint (muscles). However, deficits in muscle strength, muscle

activity, and motor control can be found after ACLR.^{9–11} Despite the recovery of normal strength symmetry, deficits in neuromuscular control can still be observed.^{8,12} Neuromuscular control is defined as “an unconscious activation of dynamic restraints, occurring in preparation for and in response to joint motion and loading, for the purpose of maintaining and restoring functional joint stability.”¹³ Adequate neuromuscular control helps to accommodate muscle contractions and attenuate forces when there are impact forces on the knee.¹⁴ Neuromuscular control can be evaluated by the pattern of muscle activity during movements, which consists of amplitude, timing, and frequency assessed by electromyography (EMG). Earlier onset of muscle activity prior to landing increases the stiffness of the joints, which allows the muscles to have enough time to generate force, providing less impact force on the knee during landing.^{15,16} A case study suggests that delayed muscle activity onset may be associated with ACL injury.¹⁷ Individuals who did not experience a secondary ACL reinjury used greater levels of hamstring activity prior to landing.¹⁸ It has been reported that greater quadriceps and gluteus activity, with less hamstring and gastrocnemius activity, are correlated with smaller knee-flexion angles. This may predispose an individual to increased impact forces during landing.¹⁹ Coactivation of knee musculature during dynamic activity is identified as an attempt to stabilize the joint and to reduce forces on the knee.²⁰

A previous systematic review was conducted to evaluate the changes in muscle activity such as walking and running in patients with ACLR.²¹ However, the activity pattern in patients with ACLR during landing has not been systematically reviewed. Some researchers have found decreased quadriceps activity and greater

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hamstring activity during landing when compared with healthy controls, whereas other researchers have not reported similar findings.^{22,23} These neuromuscular alterations may be associated with biomechanical deficits, which contribute to ACL reinjury. Given that muscle activity is a modifiable factor that can be improved through neuromuscular exercises,^{24,25} it is essential to understand the muscular strategy adopted by patients with ACLR during landing tasks, as rehabilitation can modify this outcome. The aim of this review was to evaluate the changes in neuromuscular activity of the lower-extremities during landing tasks in patients with ACLR assessed by EMG.

Methods

The method of this systematic review was chosen according to preferred reporting items for systematic reviews and meta-analysis.²⁶ The protocol was prospectively registered on the PROSPERO International register for systematic reviews (<http://www.crd.york.ac.uk/PROSPERO>) (CRD42018095560).

Searching Strategy

An electronic database search was performed of PubMed, Ovid, Scopus, and Web of Science from the inception of the databases until July 2019. A combination of the following keywords and their variations were used: (anterior cruciate ligament OR ACL) AND (electromyography OR EMG) AND (landing OR land). The search was complemented by reviewing the reference lists of papers selected from the original database search. All articles were screened by 2 reviewers independently (X.H. and O.Y.L.). Any disagreement was discussed, and unresolved items were passed to a third reviewer (H.T.L.) for consensus. The search results were imported into reference manager software (Endnote X5; Thomson, New York, NY) to avoid the duplication of records.

Selection Criteria

After removing the duplicates, all the titles and abstracts were reviewed to determine their possible eligibility for inclusion. The inclusion criteria were as follows: (1) patients with ACLR were recruited; (2) at least 1 landing task under nonfatigue condition was performed, including drop landing, jump landing, and hop landing; (3) muscular activity amplitude, timing (onset/duration), or frequency of lower limb prior to or during landing assessed by EMG was reported; and (4) healthy subjects or the contralateral uninvolved limbs were included as a control group. Non-English language publications, review articles, comments, editorials, letters, animal studies, and cadaveric studies were excluded. Studies in which subjects landed with any external support, such as a knee brace, were also excluded. No limitations were placed on the year of publication, age, gender, type of graft, or time since surgery.

Quality Assessment

The methodological quality of the included studies was rated using the modified version of the Downs and Black checklist, which only includes criteria that are relevant to assessing potential sources of bias. The modified Downs and Black checklist is a valid and reliable instrument used for assessing both randomized and non-randomized investigations.²⁷ With a maximum score of 15, a total score of ≥ 12 indicates high methodological quality, a score of 10 or

11 indicates moderate quality, and a score ≤ 9 indicates low quality.²⁸ Two reviewers (X.H. and O.Y.L.) independently reviewed and scored each article based on the criteria (see the [Supplemental Material A](#)). Any disagreement was discussed, and unresolved items were passed to a third reviewer (H.T.L.) for consensus. The intraclass correlation coefficient was calculated using SPSS for Windows (version 24; SPSS Inc, Chicago, IL) to measure the interrater agreement between the 2 reviewers.

Data Extraction and Statistical Analysis

The relevant data were extracted from all included studies: (1) general information (author and year of publication), (2) subjects' characteristics (age, gender, and activity level), (3) time since surgery, (4) graft type, (5) functional status/sport involvement, (6) task(s) performed, (7) muscle(s) tested, and (8) control group (contralateral side/healthy controls). The EMG results used for the medial hamstrings were gathered either from the semitendinosus muscle or the semimembranosus muscle, given their similar function and the high degree of cross talk in their surface EMG signals.²⁹ Data regarding the muscle activity pattern (onset/time to peak/amplitude/cocontraction) and corresponding phase, normalization method, and main findings were also extracted. The data were analyzed by limb using 2 comparisons: (1) the ACLR limb compared with the contralateral uninjured limb and (2) the ACLR limb compared with a healthy matched control limb. In addition, the type of landing task (single-leg or double-leg landing) was also used to stratify the data.

Statistical Analysis

The results were not precisely reported by the authors. To calculate the effect size and 95% confidence interval (CI), the sample size and mean (SD) of the parameters are needed. When the comprehensive data were not provided, we contacted the corresponding author via email to request the data. The effect sizes were calculated for the involved limbs in comparison with the healthy control/contralateral limbs using the following formula: Cohen $d = \text{mean (injured side)} - \text{mean (control)}/\text{SD (pooled)}$. Based on Cohen suggestion, the effect size of ≤ 0.4 represents a small effect, >0.5 – 0.8 a moderate effect, and ≥ 0.8 is considered a large effect.³⁰

Results

Literature Search

A total of 326 studies were identified using the search strategy (Figure 1). After removing all duplicates, 209 studies were evaluated by title and abstract. The full texts of 35 studies were retrieved, with 21 studies meeting the selection criteria. Only 5 of these studies provided separate data for cohorts within the ACLR groups. Coats-Thomas et al³¹ and Nyland et al²² reported individual data for males and females, Nyland et al³² reported data by sport participation or capacity, and Bryant et al³³ and Rocchi et al³⁴ separated data by graft type.

Methodological Quality

The methodological quality scores ranged from 10 to 14 (of 15), with an average score of 11.43 (see [Supplementary Table A](#) [available online]). Among the included studies, 6 (28.6%) were classified as high quality,^{22,32–36} whereas 15 (71.4%) were considered to be moderate quality.^{16,18,23,31,37–47} All these studies

Figure 1 — The flowchart and the results from the search strategy. ACLR indicates anterior cruciate ligament reconstruction.

scored positively on Items 1 (clear aim), 2 (outcome described), 3 (subjects described), 5 (distribution of confounding factors described), 6 (main finding clearly described), 7 (estimate of random variability), 18 (appropriate statistics), 20 (clearly described method), and 21 (subjects recruited from the same population), and negatively on item 11 (subjects asked represent population). Only 4 studies reported results with adjustment for confounding factors.^{22,33,34,35} The intraclass correlation coefficient of rating was .855 (95% CI, .652 to .940) between 2 reviewers.

Subjects' Characteristics. A total of 398 subjects (208 males and 190 females, with mean age ranging from 16.0 to 29.4 years) were derived from the 21 studies. The reported time post ACLR ranged from 6 months to 6 years. Twenty studies reported the graft type used for ACLR. Three studies used bone patellar tendon-bone grafts,^{16,18,46} 3 studies used semitendinosus–gracilis tendon grafts,^{23,36,37} and 2 studies used allograft.^{22,32} The remaining studies used a mixture of bone-patellar tendon-bone grafts, semitendinosus tendon grafts, semitendinosus–gracilis tendon grafts, or allograft. Eighteen studies reported the preinjury activity level of the ACLR subjects. Briem et al³⁷ included 27 professional athletes from top leagues in football, handball, and basketball, and Jordan et al⁴⁰ included 11 elite ski racers. The remaining studies included recreational sport players. From 14 studies, 308 subjects returned to sport/were cleared for sport return.^{18,22,32,34,36,37,39–42,44–47} Only 3 studies^{22,32,34} reported the criteria for a return to sports, which included passive knee stability, more than 85% symmetry in isokinetic/isometric quadriceps and hamstring muscle strength, and single-leg hop/jump performance. The study characteristics are presented in Table 1.

Primary Outcome. Of the included studies, various muscle activity patterns were assessed, including (1) muscle activity

onset of the quadriceps,^{16,33,34,38} hamstrings,^{16,33,34,38} gluteus maximus,¹⁶ gastrocnemius,^{16,38} and soleus¹⁶; (2) time to peak muscle activity of the quadriceps,^{31,33,36} hamstrings,^{31,33,36} and gastrocnemius³¹; (3) preparatory activity amplitude of the quadriceps,^{18,23,40} hamstrings,^{18,23,40} gastrocnemius,^{18,23} gluteus medius,³⁹ and adductor longus³⁹; (4) reactive activity amplitude of the quadriceps,^{18,22,23,33–36,38,40–47} hamstrings,^{18,22,23,33–38,40–45,47} gastrocnemius,^{18,22,23,32,38,43,47} gluteus maximus,^{22,32,41,42,44,45} gluteus medius,^{39,41} and adductor longus³⁹; and (5) the quadriceps and hamstring cocontraction ratio.^{23,31,35,36,44,47} Regarding the tasks performed, 7 studies investigated the single-leg hop tasks^{16,18,32,33,34,37,45} and 10 studies involved the single-leg drop landing tasks (height ranges from 20 to 40 cm).^{23,34,36,38,39,41–44,47} Five studies used single-leg or double-leg jump landing tasks.^{22,31,35,40,46} For the normalization procedure, 8 studies used maximum isometric voluntary contraction,^{22,23,32,34,37–40} 8 studies normalized the amplitude to peak amplitude during a dynamic task,^{18,35,36,41,42,44,45,47} and 2 studies reported the area under the EMG curve.³¹ Only one study normalized the amplitude to free standing.⁴³ Details of the method are summarized in [Supplementary Tables B1–B6](#) (available online).

Secondary Outcomes. In addition to the muscle activity measurements, other outcome measures were considered. Some studies implemented patient-reported outcomes, including the Cincinnati,³³ International Knee Documentation Committee,^{16,22,32} and Knee injury and Osteoarthritis Outcome Score (KOOS)³⁷ scores. Knee biomechanics were measured in 13 studies,^{22,23,31–34,36,41–45,47} including kinetic and kinematic variables, such as joint angles, ground reaction forces, tibial acceleration, and body mass center. In addition, functional assessments such as isokinetic muscle strength and hop/jump performance were reported in 6 studies.^{16,18,23,32,37,40}

Main Findings. Of the 21 studies, 16 studies reported an altered muscle activity pattern during landing tasks when compared with either the healthy controls or the contralateral side.^{16,18,22,23,31,32,34–40,43,44,47} Among them, 8 studies involved patients who returned to sport/were cleared for sport return,^{18,22,32,34,37,39,40,47} and 8 studies also reported altered kinematics/kinetics during landing.^{16,22,23,34,36,43,44,47} According to 6 studies,^{22,23,32,34,37,40} patients with ACLR demonstrated altered muscle activity patterns, even though muscle strength or functional performance had been restored (achieve more than 85% symmetry or no difference between groups).

Muscle activity onset: Four studies compared the muscle activity onset during single-leg landing between the ACLR-involved limb and healthy controls ([Supplementary Table B1](#) [available online]). Rocchi et al³⁴ found significant earlier onset of quadriceps and hamstring activity in the ACLR-involved limb when compared with healthy controls, and the effect size is large in both quadriceps ($d = 1.51$; 95% CI, 0.77 to 2.19; $P < .05$) and hamstrings ($d = 1.46$; 95% CI, 0.72 to 2.13; $P < .05$). Two studies found a trend of earlier onset of quadriceps activity in the ACLR-involved limb when compared with healthy controls; however, the effect sizes were small to moderate ($d = 0.22–0.75$, $P > .05$).^{33,38} Three studies exhibited a trend toward earlier onset in the hamstrings in the ACLR-involved limb when compared with healthy controls, with small to large effect sizes ($d = 0.01–1.13$, $P > .05$).^{16,33,38} Only one study by Gokeler et al¹⁶ compared the involved limb with the contralateral side for patients with ACLR. They reported an earlier onset of the quadriceps, hamstrings, gluteus maximus, gastrocnemius, and soleus, with effect sizes ranging from moderate to large ($d = 0.64–2.53$, $P < .05$).

Table 1 Study Characteristics of the Included Studies

Author (year)	ACL R subjects	Graft	Time post-ACL R	Functional status/sports involvement	Task	Muscles	Control group
Briem (2016) ³⁷	n = 18, females Age: 21.5 (2.7) y top leagues in football, handball, and basketball	STG	1–6 y	All returned to competition	Single-leg crossover hop test	MH and LH	n = 18, healthy controls
Bryant (2009) ³³	n = 27, males Age: BPTB graft: 30.9 (7.3) y STG graft: 22.9 (3.8) y Activity level: not reported	BPTB (n = 14), STG (n = 13)	BPTB: 15.1 (5.0) mo, STG: 14.2 (4.5) mo	1. All regained full ROM 2. Overall knee functional score: BPTB: 81.1 (16.1) STG: 87.5 (11.8)	Single-leg maximal, countermovement hop for distance	VL, VM, MH, and LH	n = 22, healthy controls
Coats-Thomas (2013) ³¹	n = 10, 4 males and 6 females Age: male 29.3 (6.1) y; female 24.7 (6.7) y Activity level: Tegner score ≥ 5	BPTB (n = 7), ST (n = 3)	>5 y	Not reported	Double-leg jump-cut maneuver	RF, VM, MH, LH MG, and LG	n = 10, healthy controls
Dashti Rostami (2018) ³⁸	n = 12, males Age: 23.83 (5.49) y Activity level: I and II sports	BPTB (n = 4), STG (n = 6), and allograft (n = 2)	23.75 (6.30) mo	Not reported	Single-leg vertical drop landing (30-cm box)	VL, VM, LH, MH, LG, and MG	n = 12, healthy controls
Dashti Rostami (2019) ³⁹	n = 12, males Age: 22.5 (4.1) y Activity level: recreationally active	BPTB (n = 4), STG (n = 6), and allograft (n = 2)	23.75 (6.3) mo	All allowed to return to sport activities	Single-leg vertical drop landing (30 cm)	GMed, and AL	n = 12, healthy controls
Gokeler et al (2010) ¹⁶	n = 9, 6 males and 3 females Age: 28.4 (9.7) y Activity level: levels I–II sports	BPTB	27 (1.5) wk	IKDC: 81 (7.1)	Single-leg hop	GMax, MH, LH, VM, VL, RF, MG, LG, and SO	n = 11, healthy controls
Jordan et al (2017) ⁴⁰	n = 11, 6 males and 5 females Age: male 26.5 (5.8) y; female 23.6 (1.8) y Activity level: elite ski racers	STG (n = 7), ST (n = 1), and allograft (n = 3)	3.0 (2.8) y	All were cleared to compete	Double-leg squat jump	VM, VL, MH, and LH	n = 11, healthy controls
Lessi and Serrão (2017) ⁴¹	n = 20, 13 males and 7 females Age: 25.1 (4.2) y Activity level: recreational (≥ 3 times/wk)	BPTB (n = 7) and ST (n = 13)	23.75 (6.30) mo	All were cleared to return to sport	Single-leg drop vertical jump (31-cm box)	VL, LH, GMed, and GMax	n = 20, healthy controls
Lessi et al (2018) ⁴²	n = 14, 7 males and 7 females Age: male 23.90 (2.80) y; female 24.7 (5.3) y Activity level: recreational (3.1–5.7 h/wk)	BPTB (n = 5) and ST (n = 9)	Male: 21.1 (6.8) mo Female: 24.2 (9.5) mo	All returned to sport	Single-leg drop vertical jump (31-cm box)	VL, LH, GMed, and GMax	Contralateral side
Lepley et al (2013) ³⁵	n = 12, 7 males and 5 females Age: 22.08 (4.7) y Activity level: not reported	BPTB (n = 7) and STG (n = 5)	248 (54.6) d (7–10 mo)	Not reported	Single-leg landing after double-leg jump (17 cm)	VL and LH	n = 13, healthy controls
Mielínska et al (2015) ⁴³	n = 6, males Age: 26.2 (2.3) y Activity level: not reported	Not reported	8 mo	Not reported	Double-leg Jumping down from 0.1-, 0.2-, and 0.3-m step heights	MH, MG, LG, and VM	n = 22, healthy controls
Nyland et al (2010) ²²	n = 70, 35 males and 35 females Age: not reported Activity level: 12.9% highly competitive, 31.4% frequently sporting, 35.7% sporting sometimes, and 20% nonsporting	Allograft	Male: 5.6 (3.2) y Female: 5.1 (2.6) y	All were cleared to return to sport IKDC: male 84.9 (15.3); female 81.4 (13.5)	Single-leg counter-movement jump	GMax, VM, MH, and MG	Contralateral side

(continued)

Table 1 (continued)

Author (year)	ACL R subjects	Graft	Time post-ACL R	Functional status/sports involvement	Task	Muscles	Control group
Nyland et al (2014) ³²	n = 65 32 males and 33 females Age: Group 1: 26.5 (95% CI, 21.9 to 31.8) y Group 2: 29.3 (95% CI, 24.1 to 34.4) y Group 3: 33.6 (95% CI, 26.4 to 39.1) y Activity capacity: Group 1: very capable (n = 20) Group 2: capable (n = 23) Group 3: not capable (n = 22)	Allograft	Post-op: Group 1: 4.6 (95% CI, 2.8 to 6.2) y Group 2: 5.4 (95% CI, 4.2 to 6.6) y Group 3: 5.2 (95% CI, 3.8 to 6.5) y	All were cleared to return to sport IKDC: Group 1: 91 (95% CI, 84.1 to 94.6) Group 2: 87.2 (95% CI, 82.1 to 92.4) Group 3: 76.8 (95% CI, 67.4 to 80.3)	Single-leg hop	GMax, VM, MH, and MG	Contralateral side
Ortiz et al (2008) ⁴⁴	n = 14, females Age: 25.4 (3.1) y Activity level: recreational	BPTB (n = 9), STG (n = 3), and allograft (n = 2)	7.2 (4.2) y	All engaged in recreational fitness activities, such as jogging, running, and weight lifting	1. Single-leg 40-cm drop jump 2. Single-leg 20-cm up-down hop	GMax, Qua, LH, and MH	n = 15, healthy controls
Ortiz et al (2011) ⁴⁵	n = 14, females Age: 25.4 (3.1) y Activity level: recreational	BPTB (n = 9), STG (n = 3), and allograft (n = 2)	7.2 (4.2) y	All engaged in recreational fitness activities, such as jogging, running, and weight lifting	1. Crossover hopping 2. Sidehopping	GMed, Qua, LH, and MH	n = 15, healthy controls
Ortiz et al (2014) ³⁶	n = 14, females Age: 28.5 (4.59) y Activity level: volleyball, basketball, and soccer at the college or intramural level	STG	1–5 y	All allowed to return to pre-injury activity	1. Single-leg drop jump (40-cm box) 2. Double-leg drop jump (60-cm box)	VM, VL, RF, MH, and LH	n = 16, healthy controls
Palmieri-Smith et al (2019) ¹⁸	n = 14, 10 males and 4 females Age: ACL-1: 17.14 (2.7) y ACL-2: 16.0 (1.1) y Activity level: Tegner score	BPTB	ACL-1: 230.71 (50.5) d ACL-2: 189.71 (10.7) d	All returned to unrestricted sport activities	Single-leg hop	VL, BF, and LG	n = 7, healthy controls
Rocchi et al (2018) ³⁴	n = 26, males Age: BPTB: 21 (3) y STG: 21 (5) y Activity level: Tegner score 7–9	BPTB (n = 15) and STG (n = 11)	6.0 (1.2) mo	All returned to unrestricted sport activities	Single-leg drop landing (20 cm) and hop landing	VM, RF, VL, BF, and ST	n = 15, healthy controls
Swanik et al (1999) ⁴⁶	n = 6, female Age: 29.4 (10.4) y Activity level: Tegner: 6.8 (1)	BPTB	6–30 mo	All attempted to return to previous level of activity	Single-leg jump landing (20.3 cm)	VM, VL, MH, and LH	n = 6, healthy controls
Tsai et al (2012) ⁴⁷	n = 10, females Age: 25.3 (2.4) y Activity level: recreational	Allograft and BPTB	1–5 y	All returned to unrestricted sport activities	Single-leg drop landing	VL, VM, RF, MH, LH, MG, and LG	n = 10, healthy controls
Vairo et al (2008) ²³	n = 14, 5 males and 9 females Age: 22.5 (4.1) y Activity level: moderate activity with minimum frequency of 3 d/wk, 30-min duration	STG	21.4 (10.7) mo	Not reported	Single-leg vertical drop (30 cm)	VM, VL, MH, LH, and MG	n = 11, healthy controls

Abbreviations: ACLR, anterior cruciate ligament reconstruction; AL, adductor longus; BF, biceps femoris; BPTB, bone patellar tendon bone graft; GMax, gluteus maximus; GMed, gluteus medius; IKDC, International Knee Documentation Committee score; LG, lateral hamstring; MG, medial gastrocnemius; MH, medial hamstring; Qua, quadriceps; RF, rectus femoris; ROM, range of motion; SO, soleus; ST, semitendinosus tendon graft; STG, semitendinosus-gracilis tendon graft; VL, vastus lateralis; VM, vastus medialis.

Time to peak muscle activity: Two studies reported the time to peak muscle activity during landing (Supplementary Table B2 [available online]). When comparing the ACLR-involved limb and healthy controls during double-leg landing, Coats-Thomas et al³¹ found delayed time to peak activity in the quadriceps ($d = 0.48$ – 1.48 , $P < .05$) and hamstrings ($d = 0.39$ – 1.94 , $P < .05$); however, Ortiz et al³⁶ reported no difference in both the quadriceps ($P = .74$) and hamstring ($P = .91$) activity. When comparing the ACLR-involved limb and healthy controls during single-leg landing, Ortiz et al³⁶ found significantly earlier time to peak activity in the quadriceps ($P = .01$) and hamstrings ($P = .01$), whereas Bryant et al³³ found no difference between them ($P > .05$).

Preparatory muscle activity amplitude: Four studies assessed the preparatory muscle activity amplitude prior to landing (Supplementary Table B3 [available online]). Jordan et al⁴⁰ showed that the ACLR-involved limbs land with increased hamstring activity prior to double-leg landing when compared with healthy controls, and the effect size is large ($d = 1.19$; 95% CI, 0.27 to 2.11; $P < .01$). In addition, they also found significantly decreased quadriceps activity in ACLR-involved limbs when compared with the contralateral side, with a moderate effect size ($d = -0.71$; 95% CI, -1.58 to 0.15 ; $P < .01$). Contrary to their findings, Vairo et al²³ found no difference in the quadriceps and hamstrings, either between group or between limb ($P > .05$); but they did find decreased medial gastrocnemius activity in the ACLR-involved limb when compared with their contralateral side prior to single-leg landing, and the effect size was large ($d = -0.92$; 95% CI, -1.70 to -0.15 ; $P = .01$). Palmieri-Smith et al¹⁸ also found no significant difference in quadriceps, hamstring, and gastrocnemius activity prior to single-leg landing ($P > .05$). Dashti Rostami et al³⁹ also reported no significant difference in gluteus medius ($P = .77$) and adductor longus activity ($P = .54$) between the ACLR-involved limb and healthy controls during single-leg landing.

Reactive muscle activity amplitude: Eleven studies compared the reactive muscle activity amplitude in the quadriceps between the ACLR-involved limbs and healthy controls during single-leg landing, and 6 studies found no significant difference ($P > .05$).^{34,38,41,45–47} Contrary to their findings, 3 studies reported an increase in quadriceps activity of the ACLR-involved limbs when compared with the healthy controls during single-leg landing.^{23,36,44} However, the effect size was calculated for only one study, which exhibited a large effect size in the vastus medialis ($d = 0.86$; 95% CI, 0.08 to 1.64; $P = .01$) and vastus lateralis ($d = 0.97$; 95% CI, 0.16 to 1.73; $P = .01$).²³ The other 2 studies found a decrease in vastus lateralis activity of the ACLR-involved limbs when compared with the healthy controls during single-leg landing with a large effect size ($d = -2.00$ to -1.29 , $P < .05$).^{18,35} Three studies reported the reactive muscle activity amplitude in quadriceps activity between the ACLR-involved limbs and healthy controls during double-leg landing.^{36,40,43} Ortiz et al³⁶ found a significant decrease ($d = 0.22$, $P = .01$) in the quadriceps activity of the ACLR-involved limbs when compared with the healthy controls during double-leg landing, whereas others found no significant difference.^{40,43}

Eleven studies compared the reactive muscle activity amplitude in the hamstrings between the ACLR-involved limbs and healthy controls during single-leg landing, and 8 studies found no significant difference ($P > .05$).^{18,34–36,38,41,44,45} Contrary to their findings, 2 studies found an increase in hamstring activity of the ACLR-involved limbs when compared with healthy controls during single-leg landing, and the effect size was moderate to large ($d = 0.76$; 95% CI, -0.01 to 1.53 ; $P = .02$ and $d = 1.12$; 95% CI,

0.16 to 2.08; $P = .02$).^{23,47} Three studies reported the reactive muscle activity amplitude in hamstring activity between the ACLR-involved limbs and healthy controls during double-leg landing.^{36,40,43} Ortiz et al³⁶ demonstrated a decrease in hamstring activity of the ACLR-involved limbs when compared with healthy controls during double-leg landing ($d = 0.18$, $P = .02$), but similar findings were not reported in the other 2 studies.^{40,43}

Three studies compared the reactive muscle activity amplitude in the gluteus maximus between the ACLR-involved limbs and healthy controls during single-leg landing.^{41,44,45} Ortiz et al⁴⁴ found significantly increased activity in the gluteus maximus of the ACLR-involved limb when compared with the healthy controls during single-leg landing ($d = 0.29$, $P = .003$), whereas others found no significant difference ($P > .05$).^{41,45} Only one study by Dashti Rostami et al³⁹ assessed the activity of the gluteus medius and adductor longus during single-leg landing and found a significant decrease in the activity of the gluteus medius, with a moderate effect size ($d = -0.75$; 95% CI, -1.55 to 0.10 ; $P = .02$), and no significant difference in adductor longus activity ($P = .11$) when compared with the healthy controls. Three studies compared the reactive muscle activity amplitude in the gastrocnemius between the ACLR-involved limbs and healthy controls during single-leg landing.^{23,38,47} Dashti Rostami et al³⁸ reported a significant decrease in the gastrocnemius activity of the ACLR-involved limbs when compared with the healthy controls during single-leg landing, whereas others found no significant difference ($P > .05$).^{23,47} Only one study by Mielnińska et al⁴³ reported the gastrocnemius activity during double-leg landing and found that it was increased when compared with the healthy controls ($P = .01$).

Six studies compared the reactive muscle activity amplitude in both the quadriceps and hamstrings between the ACLR-involved limbs and contralateral sides during single-leg landing, and no difference was found ($P > .05$).^{22,23,32,40–42} Four studies compared the reactive muscle activity amplitude in the gluteus maximus between the ACLR-involved limbs and contralateral sides during single-leg landing,^{22,32,41,42} of which, 2 studies found increased activity in the gluteus maximus of the ACL-involved limb when compared with the contralateral sides,^{22,32} and the effect size ranged from moderate to large ($d = 0.54$ – 0.85 , $P < .05$). However, the other 2 studies reported no difference in activity of the gluteus maximus of the ACL-involved limb when compared with the contralateral side ($P > .05$).^{41,42} Three studies compared the gastrocnemius activity between the ACLR-involved limbs and contralateral side during single-leg landing and reported contradictory findings.^{22,23,32} Nyland et al²² found increased activity in the medial gastrocnemius ($d = 0.60$; 95% CI, 0.12 to 1.08; $P < .001$) in male patients when compared with the contralateral side, whereas Vairo et al²³ found a significant decrease ($d = -0.79$; 95% CI, -1.56 to -0.01 ; $P = .01$). Nyland et al³² found no difference in activity of the medial gastrocnemius of the ACLR-involved limbs when compared with the contralateral sides ($P > .05$; Supplementary Table B4 [available online]).

Quadriceps and hamstring cocontraction: Cocontraction of the quadriceps and hamstrings represents synchronized activation of agonist and antagonist muscles. Two studies compared the quadriceps and hamstring cocontraction ratio between ACLR-involved limbs and healthy controls prior to landing and reported contrary findings.^{23,31} Vairo et al²³ reported an increased cocontraction using the more activated muscle as a divisor ($d = 0.70$; 95% CI, -0.14 to 1.49 ; $P = .03$) during single-leg landing; however, Coats-Thomas et al³¹ found no significant difference in the Q/H ratio during double-leg landing when compared with the

healthy controls ($P > .34$; [Supplementary Table B5](#) [available online]).

Five studies compared the quadriceps and hamstring cocontraction ratio between ACLR-involved limbs and healthy controls during single-leg landing,^{23,35,36,44,47} of which, 2 studies used similar ratio equations (more activated muscle used as a divisor), and they demonstrated significantly increased quadriceps and hamstring cocontraction of ACLR-involved limbs when compared with the healthy controls ($d = 0.25\text{--}0.74$, $P < .05$).^{23,44} However, Lepley et al³⁵ reported no significant difference ($P = .45$), and Ortiz et al³⁶ found a decreased quadriceps and hamstring cocontraction of the ACLR-involved limbs when compared with healthy controls using the same equation ($P = .02$). Tsai et al⁴⁷ reported an increased cocontraction ratio of the ACLR-involved limbs when compared with the healthy controls with the equation of $H+G/Q$ ($d = 1.26$; 95% CI, 0.26 to 2.16; $P = .004$). Two studies compared the quadriceps and hamstring cocontraction ratio between ACLR-involved limbs and healthy controls during double-leg landing and generated contrary findings.^{31,36} Coats-Thomas et al³¹ reported greater Q/H cocontraction ($P = .06$), whereas Ortiz et al³⁶ found no significant difference using the equation of EMG amplitude of the less activated muscle (EMGS)/EMG amplitude of the more activated muscle (EMGL) ($P = .22$). Only one study by Vairo et al²³ compared the quadriceps and hamstring cocontraction ratio between the ACLR-involved limbs and the contralateral sides during single-leg landing, but no difference was found ($P = .26$; [Supplementary Table B6](#) [available online]).

Discussion

In this review, we systematically evaluated the muscle activation patterns of ACLR limbs during landing tasks when compared with the contralateral side or healthy group. Over 70% of the included studies found altered muscle activity patterns during landing tasks in patients more than 6 months after ACLR, even though they were considered to be capable of returning to sport. It is not surprising that an ACLR limb adopts a different muscle strategy during landing, which is in agreement with the aberrant biomechanical patterns that persist in patients returning to sport after ACLR.^{6,7} However, the evidence for the alteration in some specific muscle activity patterns is controversial due to the great heterogeneity.

The results show that patients after ACLR tend to activate the quadriceps and hamstring muscles of the involved limb earlier than healthy people or the contralateral side. This indicates that patients with ACLR, unconsciously or consciously, increase the pretension of the lower limb muscles before landing.⁴⁸ This may serve as a compensatory strategy to resist a given load during landing. Rocchi et al³⁴ and Gokeler et al¹⁶ found significant earlier onset time of the quadriceps and hamstrings during single-leg hopping, whereas Dashti Rostami³⁸ and Bryant et al³³ found a trend toward earlier muscle onset during drop landing or countermovement hop landing, though the findings were not significant. The different results could be mainly due to the variations in the time since surgery. The average time since surgery reported by Rocchi et al³⁴ and Gokeler et al¹⁶ was around 6 months, whereas that reported by Dashti Rostami et al³⁸ and Bryant et al³³ was more than 12 months. Neuromuscular function may be recovered for those who are rehabilitated well, which explains the nonsignificant results. In addition, the onset determination and landing tasks involved are different among these studies, which may contribute to different results. Even for similar tasks, some degree of variability can be found between studies regarding its implementation.

It appears that patients with ACLR adopt similar reactive activity patterns of the quadriceps and hamstrings during landing tasks when compared with healthy controls or the contralateral side.^{34,38,40,41,43,45} The “quadriceps–avoidance” pattern has been observed during gait and hop landing in ACLD subjects. ACLD subjects alter their gait or landing strategy with decreased quadriceps activation to minimize anterior translation.^{21,49,50} However, this review does not support the existence of this pattern. Of the 14 studies that reported the reactive quadriceps activity amplitude during single-leg landing, only 2 studies found a significant decrease in vastus lateralis activity.^{18,35} The majority of the included studies found no significant difference in quadriceps and hamstring reactive muscle activity amplitude. These results were also different from previous studies, which reported greater hamstring activity in ACL-deficient patients.^{21,51} It should be noted that the majority of the patients included in this review were all rehabilitated and capable of return to play, with the time post ACLR ranging from 6 months to 6 years. Therefore, the reactive activation capacity of the quadriceps and hamstrings may be restored. The results for alterations in the gluteus maximus and gastrocnemius are inconsistent, when taking the variations in gender, graft type, phase determination, and normalization method into consideration. It is likely that the findings are biased by the fact that the authors did not consider the patients’ previous experience of landing maneuvers and the variations in instructions, as well as the post-op rehabilitation protocols.^{52,53}

Patients with ACLR tend to use increased quadriceps and hamstring cocontraction during single-leg landing when compared with healthy people. This indicates the potential capacity of the quadriceps and hamstring muscles to act collectively in stabilizing the knee joint. During landing, while the quadriceps muscles contracting is an attempt to control knee flexion through eccentric contraction, cocontraction of the hamstrings is essential to prevent excessive ACL loading due to the anterior shear force produced by the quadriceps.^{54,55} It may be that patients have adapted based on their negative experiences, such as a knee giving way episode before surgery, or modified their motor programming by increasing the cocontraction of the knee muscles to “tense up” in an attempt to increase dynamic knee stability.^{20,56} However, we can only find trending results due to the great heterogeneity in the methodologies. There is no standardized equation for the quadriceps and hamstring cocontraction ratio. The equations $EMGS/EMGL \times (EMGS + EMGL)$ or $EMGS/EMGL$ were used in 4 studies to provide an estimate of the relative level of cocontraction, where EMGS is the level of activity in the less active muscle and EMGL is the level of activity in the more active muscle.^{23,35,36,44} Two other studies used either quadriceps or hamstrings as the divider.^{31,47} In addition, the EMG amplitude normalization procedure, muscles selected, and landing phase used for the calculation of the cocontraction ratios were different in all these studies, which also influenced the results.⁵⁷

The results regarding time to peak muscle activity, preparatory muscle activity amplitude, and quadriceps and hamstring cocontraction ratio prior to landing are inconclusive, as they are based on limited studies. A recent study indicated that the timing of noncontact ACL injury ranges from 17 to 50 ms after initial ground contact. Therefore, preparatory muscle activity is important for ACL injury prevention because it is too slow (>100 ms) for afferent mechanosensory feedback loops from the knee to stabilize the joint.^{58–61} Proper muscle timing allows muscle forces to be generated at the appropriate time to be successful in regard to the task at hand.¹⁵ In addition to the quadriceps and hamstring muscles, the gluteal

muscles also play an important role in lower limb movement control.⁶² However, there is limited evidence regarding the gluteus medius, which is associated with dynamic knee valgus.^{63,64} Therefore, more research is required to provide a definite conclusion about the alterations in these muscle activity patterns after ACLR.

There are some limitations in this systematic review that need to be considered. (1) Only English publications were included. (2) It should be stated that the majority of the studies did not adjust for some potentially confounding variables, such as gender, age, graft type, activity level, or functional status within the recruited population, which may influence our findings. Comparisons between sexes can be made, as greater quadriceps activation and lower hamstring activation have been found and linked to other factors that increase the risk of biomechanical injury in women.^{65,66} It has been demonstrated that the surgical technique can influence post-injury muscle recovery, potentially leading to impairments of neuromuscular control and functional performance.^{67,68} In this review, only 2 studies adjusted the results by graft type. Thus, future investigations are required to assess the role of different graft types on muscle activation pattern during landing tasks, and the ACLR group can be further classified according to the graft used. (3) The ACLR subjects also had a high variation in time since surgery, ranging from 6 months to 6 years, and the rehabilitation protocol was not specified. The large discrepancy in the participants' post-ACLR status in the selected studies may represent a critical source of variability. (4) Regarding the assessment methods, full protocol descriptions associated with the correct use of the surface EMG techniques, cross talk testing, or skin preparation were missing in the majority of these studies. Moreover, the normalization procedure for activation level and phase determination varied between the studies. In this review, the included studies investigated different landing tasks, like drop jump, vertical jump, or hop landing. Because of the heterogeneity in the methodologies and the absence of a gold standard execution protocol as mentioned above, caution is warranted regarding the interpretation of the results. (5) Some studies regarded the quadriceps and hamstring muscles as an entirety, but the fact is that the lateral and medial components of the muscle groups play different roles in knee stability. Increased dominance of the lateral quadriceps relative to the medial hamstrings is associated with knee valgus, which increases the risk of an ACL injury.^{46,51,69} Therefore, different components of these muscles should be taken into consideration.

Conclusion

This review suggests that patients with ACLR display altered muscle activity patterns during landing tasks, even though they are considered to be capable of returning to sport. Nevertheless, a firm conclusion could not be drawn due to the great heterogeneity in the subject selection and study methods. As proper recovery of neuromuscular activity after ACLR is important to regain appropriate mechanical function of the knee joint, future research is needed to understand the neuromuscular alterations depending on gender, graft type, and functional status and to investigate whether differential muscle activity patterns are associated with increased ACL reinjury risk. Specific modes of training, such as postural balance exercises, verbal instructions for soft landing, and plyometric jump and landing exercises, have been reported to be effective in improving neuromuscular activity patterns with increased hamstring activity and quadriceps to hamstring cocontraction during landing in healthy athletes.^{70,71} However, whether the altered neuromuscular activity during landing can be

modified as a result of rehabilitation after ACLR warrants further investigation.

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