

Review Paper: Longitudinal Kinetic and Kinematic Changes in Functional Tasks After Reconstructing Anterior Cruciate Ligament: A Systematic Review



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ABSTRACT

Introduction: The return to sport after Anterior Cruciate Ligament Reconstruction (ACL) is among the main issues encountered by rehabilitation medicine, injured athletes, and coaches. A main factor preventing safe return to sports is a biomechanical asymmetry between the limbs during reconstruction, which plays a significant role in the risk of re-injury. Accordingly, injury-related biomechanical changes were systematically examined in individuals with ACLR as performed functional tasks.

Materials and Methods: Articles relevant to biomechanical asymmetries between (ACL & uninjured) limbs in English were searched in the Google Scholar, Science Direct, PubMed MEDLINE, and Scopus databases without time limit until 2021, using the following keywords: "Anterior cruciate ligament reconstruction", "ACL reconstruction", "biomechanical", "Kinetic", "Kinematic", and "Asymmetry".

Results: In total, 122 articles were found, of which 18 met the inclusion (PRISMA) criteria. Most of the kinetic and kinematic parameters were observed in the intervals of 3, 6, 9, 12, and 18 months after ACLR between the athletes' vertical Ground Reaction Force (vGRF), peak hip abduction moment, peak knee valgus angle, peak knee flexion moment and angle, during the functional tasks; also changes were detected in the articles up to 28 months, although research in this area was limited.

Conclusion: The present systematic review suggested that biomechanical variables may vary among the limbs of patients with ACLR, between 18 and over 28 months. Accordingly, an asymmetry between the limbs increases the risk of re-injury. Therefore, a better understanding of the biomechanics of the limbs in the time intervals after ACLR can provide a safer and sooner return to sports activities.

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Introduction

The Anterior Cruciate Ligament (ACL) is the most commonly injured ligament in the knee with approximately 200,000 ACL ruptures per year [1-5]. Even after ACL Reconstruction (ACLR) surgery and long rehabilitation interventions, the biomechanical function of the knee joint is often not completely restored [6]. Having experienced ACL reconstruction, also, a high proportion of patients has not returned to pre-injury levels of activity and degenerative changes in the knee sooner than 10 to 20 years [7-9]. Return-to-Sports timing is a key issue, i.e., widely discussed [10]. Based on clinical reports, it is directly associated with improving the biomechanical symmetry of the limb during functional tasks at any time after ACLR [11, 12]. Furthermore, nearly one-third of the younger cohort that resumes sports participation will sustain a second ACL injury within the first 2 years after ACLR. The incidence rate of second injuries is significantly greater in the first year, compared to the second year after ACLR. Concerning the second year, some athletes may encounter lower relative risks, such as achieving baseline joint health and function well after the current expected timeline (6-12 months) to be released in an unrestricted activity. This highlights a considerable debate in the return-to-sport decision process as to whether an athlete should wait up to 2 years to return to unrestricted sports activities after ACLR [13-15].

A series of reports indicated that the asymmetry of the limbs identified after ACLR predicts future ACL injury, especially asymmetries in sagittal plane knee moments and angles at initial contact during landing-jump tasks [16]. Additionally, side-to-side differences exist in vertical Ground-Reaction Force (vGRF) and loading rate that persisted for up to 2 years after ACLR [12, 13]. As per other studies, the difference between limbs in biomechanical variables, especially in the sagittal (knee extension angle & moment) and frontal (knee valgus moment) planes of the knee joint during jump testing double-legged drop jump and single-legged drop jump demonstrated 9 months after ACLR [17]. In the 4-12 months after ACLR, the asymmetry between surgical and non-surgical limbs, reduced hip flexion and dorsiflexion angles, knee abduction moments on the side of the surgical limb was observed during drop jump landing [18]. Robert et al. outlined a symmetry increase at the sagittal plane moments at the knee and hip during a bilateral stop jump task which occurred in patients between 6 months and 1 year after ACL-R. However, the

symmetry of the knee extension moment was not established until 12 months after surgery [19].

However, restoring or maintaining symmetry and performance should be considered a constant priority for both limbs, regardless of sports predictions, return to sports, and continued participation in sports [20]; this was recently associated with the risk of osteoarthritis and re-injury [21, 22]. Due to the importance of safe return and the need to recognize the biomechanical changes of this population in the time elapsed after reconstruction during the performance of functional tasks on the second injury. No systematic review study compared kinetic and kinematic parameters examining cross-sectional and longitudinal data. Therefore, this systematic review aimed to investigate longitudinal (3, 6, 9, 12, 18, 24 & 27 months) kinetic and kinematic changes in functional tasks between both (the injured & uninjured) limbs in individuals experiencing ACLR. Furthermore, we aimed to answer the following questions: How long does the biomechanical change between the limbs continue after the injury? Is the time spent on returning to pre-injury levels of activity-dependent on biomechanical changes during the reconstruction period?

Materials and Methods

Criteria for selecting articles

Having searched several databases, per Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) instructions, all the identified articles were initially added to the Endnote software, and duplicates were removed. After omitting duplicates, all titles and abstracts were reviewed to identify articles relevant to the research topic (Figure 1). The inclusion criteria of the study included research studies that have compared the kinetics and kinematics of the injured lower ACLR limb with the uninjured one as a reference as well as with healthy individuals during functional tasks in different periods. Moreover, the research population had physical activities (e.g. athletes) or any sports experience and post-reconstruction under physiotherapy supervision, including adults aged >18 years. The exclusion criteria consisted of failure to state the main idea, including review studies, expert opinions, studies under review, such as annual meetings, MA theses, interventions, i.e., effective on the injury, and non-biomechanical assessments that only reported performance, like differences hop distance between limbs and animal studies and functional tasks measured patients' performance. Furthermore, studies were limited to those published in English [23-28].

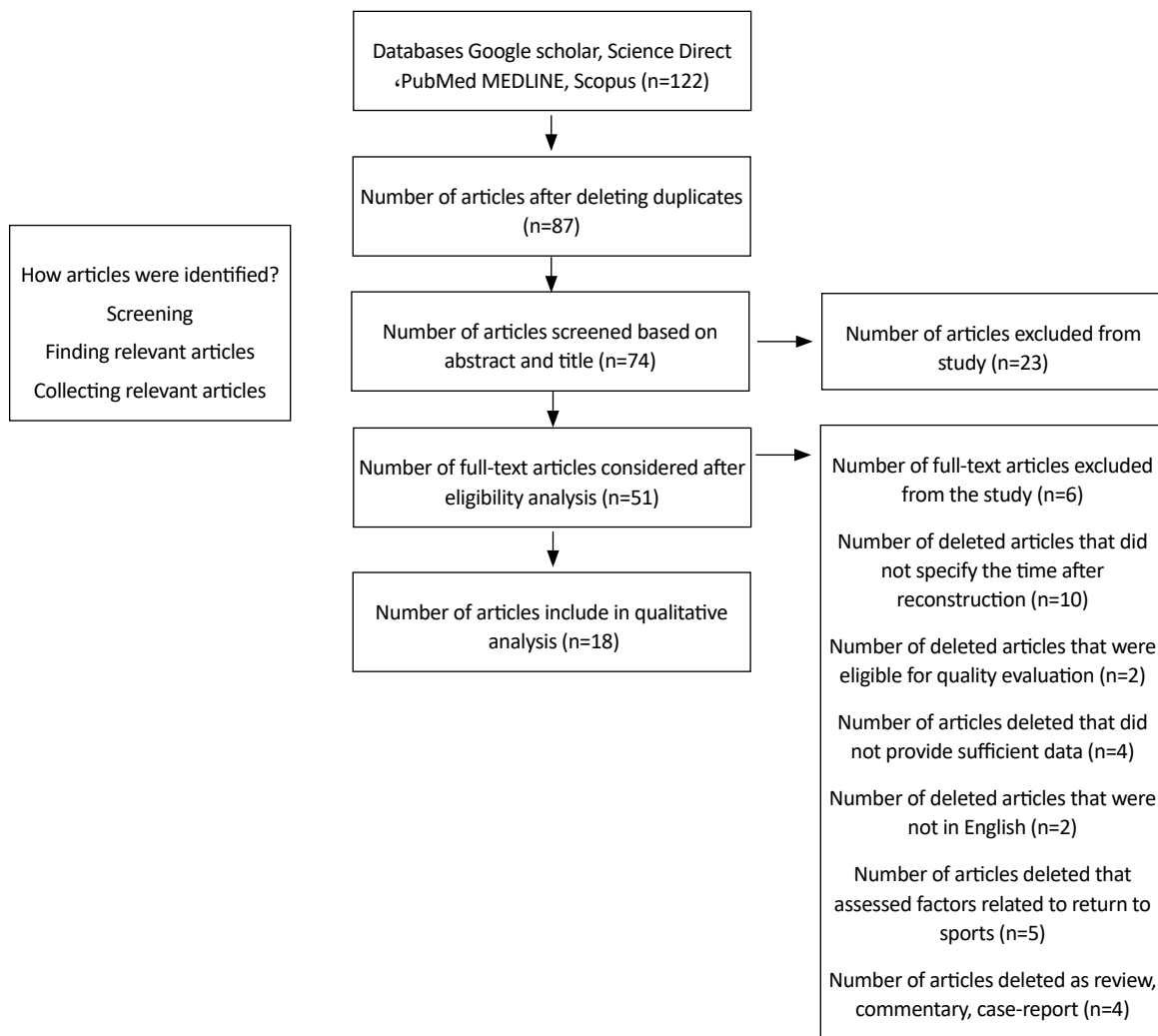


Figure 1. PRISMA process flowchart

Search strategy

As targeted, a systematic review was performed to explore all biomechanical changes ACLR-related without a time limit until 2021. We searched articles containing the following keywords: “(ACL reconstruction OR Anterior cruciate ligament reconstruction) AND (biomechanical OR Kinetic OR Kinematic) AND (Asymmetry)” in the following databases: Google Scholar, Science Direct, PubMed MEDLINE, and Scopus (see Appendix 1 for full search strategy). The search was performed using database Mesh in PubMed by two browsers; they independently checked all incoming articles. Moreover, the third browser randomly checked some articles; in case of disagreement between the two browsers in entering or deleting the article, the third browser was consulted. A manual search of the reference lists of the included articles was also conducted.

Inclusion criteria

Studies were limited to those published in English, observational study designs (prospective cohort, case-control, & cross-sectional studies) or Randomized Clinical Trials (RCTs) with a control group or comparison with the contralateral uninjured side in functional tasks, examining human subjects aged over 18 years with unilateral ACLR, without injury or deformity in the lower extremities (e.g. meniscus & the valgus of the knee), at least 3 months after reconstruction, as well as the examination of kinetic and kinematic parameters. The studies’ titles and abstracts were screened to review eligibility and reference lists of major articles searched for further relevant articles [18, 23].

Data extraction

The Physiotherapy Evidence Database (PEDro) scale was used to evaluate the quality of articles; consider-

Table 1. Evaluating incoming articles based on PEDro scale

Study	Eligibility Criteria Were Specified ¹	Random Allocation of Subjects ²	Allocation Was Concealed ³	Groups Similar at Baseline ⁴	There Was Blinding of All Subjects ⁵	Blinding of Therapists ⁶	Blinding of Assessors ⁷	>1 Key Outcome ... ^{81*}	All Subjects ... ^{92**}	The Results of Between-Group Statistical ... ^{103***}	The Study Provides Both Point Measures ... ^{114****}	Total Score
Gokeler et al. (2010)	1	-	1	1	1	1	1	1	-	1	1	9
Di Stasi et al. (2013)	1	-	1	1	1	1	1	1	-	1	1	8
Dai et al. (2012)	1	-	1	1	-	-	1	1	-	1	1	7
Mantashloo i et al. (2019)	1	1	1	1	-	-	1	1	-	1	1	8
Earl et al. (2007)	1	1	1	1	-	-	-	1	-	1	1	7
Arhos et al. (2021)	1	1	1	1	-	-	1	1	-	1	1	8
Nagelli et al. (2020)	1	-	1	1	-	1	-	1	-	1	1	7
King et al (2019)	1	-	1	1	-	1	1	1	-	1	1	8
Renner et al. (2018)	1	-	1	1	-	1	-	1	-	1	1	7
Mueske et al. (2018)	1	-	1	1	-	1	1	1	-	1	1	8
Orishimo et al. (2010)	1	-	1	1	-	-	1	1	-	1	1	7
Butler et al. (2016)	1	1	1	1	-	1	1	1	-	1	1	9
Paterno et al. (2010)	1	-	1	1	-	1	-	1	-	1	1	7
Curran et al. (2018)	1	-	1	1	1	-	1	1	-	1	1	8
Sharafoddin-Shirazi et al. (2020)	1	-	1	1	1	1	1	1	1	1	1	10
Curran et al. (2020)	1	1	1	1	-	1	1	1	-	1	1	9
Królikowska et al. (2018)	1	-	1	1	-	1	1	1	-	1	1	8
Paterno et al. (2007)	1	-	1	1	-	-	1	1	-	1	1	7

*>1 key outcome was obtained for more than 85% of subjects initially allocated to groups. ** Received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome was analysed by 'intention to treat'. *** Results of between-group statistical comparisons are reported for at least one key outcome. **** The study provides both point measures and measures of variability for at least one key outcome.

ing that the majority of articles were RCTs (Table 1). The following information was extracted from the reviewed studies: study design, sample size, study objectives, asymmetry of biomechanical variables between injured and uninjured limbs in the time elapsed after ACLR considering the type of autograft, primary outcome measures, and inclusion/exclusion criteria. The data extracted from the reviewed studies are summarized in Table 2.

Kinetic and kinematic parameters: Knee (K), Ankle (A) hip (H), Rotation (R), Peak Knee Flexion (PKF), vertical Ground Reaction Force (vGRF) and posterior Ground Reaction Force (pGRF), Peak vertical Ground Reaction Force (PvGRF), and Peak pGRF (PpGRF), Range of Motion (ROM), Peak Knee Extensor Moment (PKEM), Knee Extensor Moment (KEM), Abduction Moment (AbdM), Flexion Angle (F°), Flexion Moment (FM), Peak Extension Moment (PEM), peak Power (pP), Extensor Moment (EM), Hip Internal Rotation (HIR), Knee Flexion Angle (KF°), Knee Abduction Angle (KAbd°), Knee Internal Rotation Angle (KIR°), Hip Adduction Angle (HAdd°), as well as Hip Internal Rotation Angle (HIR°)

Functional tasks that were evaluated included the following: Stop-Jumps (SJ), Stop Jump Landing (SJL), Drop Jump Landing (DJL), Drop Vertical Jump (DVJ), Single-leg Forward Hop (SLH), Triple Hop (TH), Crossover Hop (CH), Single-leg Vertical Hop (SLVH), Double- and Single-leg Vertical Hops (D-S LVH), and Single-leg Drop (SLD)

Hamstring (HT), Bone-Patellar (PT), Quadriceps (QT), Tendon Graft (TG), and Allograft Tissue (AT)

Control group (C), Return-to-Sport (RTS)

Results

Having analyzed the relevant literature, 18 articles were ranked according to 3 overlapping groups, respectively mentioned in Table 1.

- The biomechanical evaluation of the lower limb to 6 months after ACLR (6 studies)
- The biomechanical evaluation of the lower limb to 12 months after ACLR (7 studies)
- The biomechanical evaluation of the lower limb for more than 24 months after ACLR (5 studies)

Study designs varied among these papers (retrospective, 2; case-control, 2; cross-sectional, 3; longitudinal, 2; controlled laboratory, 5; descriptive laboratory, 1; re-

peated-measures, 1; prognosis, 1). In total, 252 participants were examined (734 ACLR & 121 healthy individuals) to demonstrate the research purposes. Accordingly, the examined subjects reported a sports background (n=248) [3, 6, 8, 18, 22, 28, 34]. Furthermore, most articles were analyzed to comparatively evaluate the involved and non-involved limbs as well as healthy limbs; except one article which compared patients with post-operative physiotherapy supervision <6 months and those with postoperative physiotherapy supervision ≥6 months, and control group [18]. Some articles compared the limbs in athletes who encountered a second ACL injury [8]. Furthermore, two articles compared biomechanics, as landing, between limbs with Hamstring Tendon (HT) autograft, Patellar Tendon (PT) autograft, Quadriceps Tendon (QT) autograft, and uncontrolled individuals following ACLR [16, 21]. Most functional task evaluations were specifically conducted as mainly focusing on landing and jumping tasks [3, 6, 8, 22, 27, 28, 33]. Besides, some papers were explored hop tasks [3, 7, 18, 24, 30, 31, 32, 43], gait cycles [17, 34], and side-cutting tasks [9].

Study characteristics

Biomechanical changes of ACLR limb up to 6 months

By evaluating the movement patterns between the thigh, knee, and ankle when landing a single-leg hop for distance, Gokeler et al. demonstrated the maximum asymmetry between the limbs in the ROM of the knee and ankle during take-off; thus, the involved limbs, as rising, significantly reduced knee flexion and improved, accordingly. Specifically, the involved limbs significantly reduced knee flexion during the take-off and increased plantarflexion at initial contact. Furthermore, the knee extension moment was significantly lower in the involved limb. In the control group, earlier contraction onset times were significantly found for the semitendinosus, vastus lateralis, and medial gastrocnemius of the non-dominant side, compared with the dominant side. Muscle onset times were earlier and movement patterns are altered in the involved limb 6 months after ACLR [32]. There was a statistically significant difference between limbs respecting all kinetic and kinematic variables of the knee, especially knee flexion angle during initial contact and peak knee flexion in ACL gait patterns between involved and non-involved limbs. Besides, a clinically significant asymmetry was also identified in the hip in this group [31]. During a 35 side-cutting task, patients' surgical limb demonstrated a significant decrease in peak impact vGRF [2.55 Body Weight (BW) vs. 2.8 BW; P=0.01], peak propulsion vGRF (2.15 BW vs. 2.3

Table 2. Evaluating the kinetic and kinematic markers of injured and uninjured limbs in individuals with ACLR

Study	Study Design	N (ACLR)	Time After ACLR	Kinetic & Kinematic Variable	Grafts	Functional Tasks	Results (Asymmetries Between Limb)
Gokeler et al. (2010) [32]	Controlled laboratory	9 ACLR & 11 Healthy	6 Month	(v-hGRF) H,K,A EM and ROM	PT	SLH	KROM during take-off: 37.0 vs 25.3 KROM during landing: 42.0 vs 31.3 AROM during take-off: 39.3 vs 28.4 AROM during landing: 5.7 vs 13.3 PKEM during landing: 0.30 vs 0.17 PvGRF: 0.89 vs 0.74
Di Stasi et al. (2013) [31]	Controlled laboratory	42	6 Month	FK° HEM, KEM at PKF	HT	SLH	KF° at initial contact: 7.2 vs 9.4 (Fail) KF° at PKF: 22.6 vs 29.1 (Fail) KEM at PKF: 0.37 vs 0.52 (Fail)
Dai et al. (2012) [9]	Controlled laboratory	23 Adolescent	6 Month	PvGRF PpGRF PKEM KF° PKF velocity	HT	During a 35 side-cutting	PKF° velocity during stance phase: 57.1 vs 682.9 PKF° during stance phase: 43.4 vs 48.5 Peak impact vGRF: 2.55 vs 2.8 PKEM during stance phase: 0.13 vs 0.17
Mantashloo et al. (2019) [17]	Cross-sectional	28 Male 28 Healthy	6 Month	vGRF		Activity in gait cycles	First peak force symmetry: ACL= 5.3 and healthy= 2.6 Second peak force symmetry: ACL= 3.3 and healthy= 2.0
Earl et al. (2007) [33]	Mixed-model, repeated-measures	19 Females & 18 males	6 Month	Rearfoot-eversion° KF° KAbd° KIR° HAdd° HIR°		DVI, step-down	Step-down: rearfoot eversion (12° compared to 8°) (P, .0005), HAdd (16° compared to 1°) (P = .03) Both tasks: females (1.6) had greater KAbd than males (6.0)
Arhos et al. (2021) [34]	Cross-sectional	79 Athletes	7.1±2.0 Months	PKF°, KE IPKEM		Walking gait	Asymmetry index: PKF°: 68%, KE: 83%, IPKEM: 74%; medial compartment contact force: 57%
Nagelli et al. (2020) [3]	Controlled laboratory	18 Athletes	8 Month	PvGRF, HAbd, F, E,R° and M,	HT	SLD	H external rotation M: 0.046 vs 0.035 H abduction°: 11.6 vs 9.6 HF°: 26.5 vs 23.0 HFM: 0.39 vs 0.44

King et al. (2019) [7]	Controlled laboratory	156 Male ACLR & 62 Healthy	9 Month	H-K-FAbD, Add M and ° Kvalgus	a-v-pGRF in three plane	PT HT	D-S DIJ	VGRF: C=1.3; ACL= 2.6 HEM at sagittal: C=4.3; ACL= 7.8 A Plantarflexion M at sagittal: C=1.7; ACL= 3.1 HF° at sagittal: C=2.2; ACL= 3.5 A External rotation M at transverse: C=2.3; ACL= 3.7 K Valgus M at frontal: C=6.1; ACL= 9.2
Renner et al. (2018) [6]	level IV cohort	23 Athletes	4, 5, 6 & 12 Months	PKF PvGRF PpGRF PKEM ROM		HT	SJ	PKF from 4 to 12 months: 70.29 to 74.41 PvGRF: 1.37 to 1.50 PpGRF: 0.47 to 0.60 PKEM: 1.40 to 1.66 Frontal knee ROM: 7.16 to 5.86 Sagittal hip ROM: 18.41 to 14.36 Loading rate: 0.15 to 0.16
Mueske et al. (2018) [16]	Retrospective	61 Adolescents	4 to 12 Months	H, K, A F°, FM, AddM		HT PT QT	DIL	Asymmetry was observed in all autografs. PvGRF: HT=1.7; PT= 1.6; QT=1.7 at C= 1.9 PKF°: HT=100; PT= 92.2; QT=101.3 at C=99.3 1.9 PKA°: HT=26.5; PT= 23.3; QT=24.9 at C=31.4 HFMM: HT=1.1; PT= 1.0; QT=1.1 at C=0.87 Hadd°: HT=4.5; PT= 2.4; QT=26 at C=4.6 HRM: HT=0.15; PT= 0.12; QT=0.17 at C=0.16 KFM: HT=0.75; PT= 55.5; QT=0.664 at C=1.1
Orishimo et al. (2010) [24]	Longitudinal	13	4-12 Months	Pa-vGRF ROM H,K,APEM Pp		PT	SLH (take off and landing)	KM during takeoff: 35.6 vs 48.1 HM during takeoff: 48.1 vs 56.2 KM during landing: 35.7 vs 43.4
Butler et al. (2016) [27]	Case-series	15 Adolescen	6-12 Months	PK, H, A EM and F°	PvGRF	HT	SIL	PvGRF from 6 (1.63 vs 2.09) to 12 months (1.65 vs 1.92) PKEM from 6 (0.109 vs 0.150) to 12 months (0.110 vs 0.136) Initial A plantarf° from 6 (4.0 vs 7.1) to 12 months (0.5 vs 4.1) PA plantar FM from 6 (0.093 vs 0.103) to 12 months (0.097 vs 0.103)

Paterno et al. (2010) [8]	Prognosis	56 Athletes	During 12 Month	valgusM KF° IKEM HRM GRF	25P 27H 4A	DVJ and Bio- dex stability	DVJ: sagittal PKM at initial contact: First ACL Injury: 0.120 vs 0.080 Second ACL injury: 0.090 vs 0.025
Curran et al. (2018) [30]	Descriptive laboratory	20	More than 12 Month	K-joint R KEM In sagittal-plane	PT HT	SLH	Plane Knee-Joint Rotation, KEM at Sagittal: asymmetries of more than 10% were still present more than 12 months post-ACLR
Sharafoddin-Shirazi et al. (2020) [28]	longitudinal	20(ACLR) & 20 Healthy	6, 12, 18 & 24 Month	VGRF a-pGRF PH,K,AFM PKAdM PHAbM knee valgus°	HT	Drop- landing	Asymmetry index from 6 to 24 months for: VGRF: 100% to 6.5%, a-pGRF: 155.5% to 7% PHFM: 74.5% to 17.1%, PKFM: 79.0% to 5.8% PAFM: 59.3% to 5.9%, PHAbM: 67.8% to 5.1%, PKAdM: 55.7% to 14.8%, PKValgus°: 48.7% to 23.5%
Curran et al. (2020) [43]	Cross-sectional	82	9, 12, 18 & 24 Months	PKF	PT HT QT	SLH TH CH SLVH	Asymmetry index PKFFrom 6 to 24 months for: SLH: 86.25 to 92.85 TH: 85.59 to 94.34 CH: 86.87 to 92.63 SLVH: 90.32 to 90.72
Królikowska et al. (2018) [18]	Retrospective	38 Males Athletes	24 Month	VGRF	HT	D-S LVH	Physiotherapy Supervision < 6 to ≥ 6 Months: Double-leg: 84.45 to 99.05; C: 99.34 Single-leg: 94.03 to 99.36; C: 101.44
Paterno et al. (2007) [22]	Case control	14 Female athletes	27 Month	PVGRF	PT	DVJ	PVGRF: Takeoff phase: 1.5 vs 2.5 Landing phase: 1.1 vs 1.3

BW; $P=0.01$), peak knee extension moment (0.13 BW 3 body height vs. 0.17 BW 3 BH; $P=0.01$), and presented knee flexion angle at peak knee flexion velocity ($P=0.01$) [9]. In this regard, vGRF and muscle asymmetry were demonstrated at different stages of the gait cycle [17]. To evaluate gender-wise lower limb movement using drop-vertical jump and step-down task, the step-down produced greater rear-foot eversion (12° vs. 8°) ($P<0.0005$) and hip adduction (16° vs. 1°) ($P=0.03$), compared to the drop-vertical jump. Additionally, females performed greater hip internal rotation in the step-down than in the drop-vertical jump (5° vs. 2°) ($P=0.02$). As averaged across both tasks, females had greater knee abduction, compared with males in both tasks (4° vs. 0°) ($P<0.0005$) [33]. To analyze walking gait using a limb symmetry index (the value of involved limb value/uninvolved limb value $\times 100$), 67% asymmetry in peak knee flexion angle and 74% internal peak knee extension moment were measured [34].

Biomechanical changes of ACLR limb up to 12 months

In a controlled laboratory study, athletes had a greater hip flexion angle (involved: 26.5 & noninvolved: 23.0), hip external rotation moment (involved: 0.046 & noninvolved: 0.035), hip abduction angle (involved: 11.6 & noninvolved: 9.6), and hip flexion moment (involved: 0.39 and noninvolved: 0.44) in single-leg drop tasks [3]. The asymmetry indicated further biomechanical variables 9 months after ACLR in all the jump tests, compared to healthy participants. Additionally, most of the between-group differences concerned the sagittal and frontal planes, including asymmetry between the healthy and ACLR groups during double-legged drop jump, as follows: hip extension moment (healthy: 4.3 & ACL: 7.8), ankle plantarflexion moment (healthy: 1.7 & ACL: 3.1) hip flexion angle (healthy: 2.2 & ACL: 3.5), ankle external rotation moment at transverse (healthy: 2.3 group & ACL: 3.7), knee valgus moment at frontal (healthy: 6.1 & ACL: 9.2), and vGRF (healthy: 1.3 & ACL: 2.6) [7]. As examined during a stop-jump task, the peak vGRF (4, 5, & 6 months $P<0.001$; 12 months $p \frac{1}{4}$ 0.044), peak knee extension moment (5; 4, 5, & 6 months $P<0.001$; 12 months $p \frac{1}{4}$ 0.001) and impulse (4 & 5 months $P<0.001$; 6 months $p \frac{1}{4}$ 0.001; 12 months $p \frac{1}{4}$ 0.015) demonstrated a difference between the involved and uninvolved limbs sides up to 12 months after ACLR. At all the visits, the uninvolved limb impulse was higher than that of the involved limb. The loading rate (4 & 5 months $P<0.001$; 6 months $p \frac{1}{4}$ 0.014) and peak posterior Ground Reaction Force (pGRF) (4 months $p \frac{1}{4}$ 0.002; 5 months $p \frac{1}{4}$ 0.022; 6 months $p \frac{1}{4}$ 0.045) indicated differences up to 6 months after ACLR. Mean-

while, the uninvolved limb loading rate was higher than the involved one at 4, 5, and 6 months. The involved and uninvolved limb pGRF converge at each progressive visit with a statistical difference that was present at the 4, 5, and 6-month visits; however, not manifested at the 12-month visit. Limb stiffness (4-month $p \frac{1}{4}$ 0.002, 5 months $p \frac{1}{4}$ 0.047) demonstrated side-to-side differences up to 5 months after ACLR as the uninvolved limb stiffness reckoned higher than the involved limb. Accordingly, peak knee flexion was only different at the 4-month time visit, and the involved limb peak knee flexion was significantly lower than the uninvolved limb ($p \frac{1}{4}$ 0.038) [6]. In the single-leg hop task, the knee moment was significantly reduced during takeoff on the involved side. Furthermore, peak moments and powers on the involved side were lower at the knee and higher at the ankle and hip, compared with the noninvolved side. However, the peak total extensor moment was not different between legs while a decrease in knee moment and increases in the ankle and hip moments were witnessed. Respecting landing, knee motion was reduced, and peak power absorbed was decreased at the knee and hip, and increased at the ankle on the involved side as compared with it on the noninvolved one [24]. Averagely, asymmetry between the limbs of fifteen adolescent patients (7 males & 8 females, age: 15.9 6 1.3 years) from 6 to 12 months in stop jump task at the ankle plantarflexion angle at initial contact (involved: 4.0 ± 13.0 ; non-involved limb: 7.1 ± 12.2) to (involved: 0.5 ± 11.3 ; non-involved limb: 4.1 ± 13.0), the peak impact vGRF (involved: 1.63 ± 0.44 ; non-involved limb: 2.09 ± 0.57) to (involved: 1.65 ± 0.35 ; non-involved limb: 1.92 ± 0.57) and the peak knee extension moment (involved: 0.109 ± 0.030 ; non-involved limb: 0.150 ± 0.026) to (involved: 0.110 ± 0.024 ; non-involved limb: 0.136 ± 0.033) slightly changed; however, only the peak hip extension moment (involved: 0.170 ± 0.052 ; non-involved limb: 0.208 ± 0.058) to (involved: 0.199 ± 0.066 ; non-involved limb: 0.196 ± 0.069) had reached the symmetrical level at 12 months [27].

Of the 56 athletes who undergone ACLR in a prospective biomechanical screening, 13 suffered ACL injury for the second time, and a greater asymmetry was observed in the involved limb in internal knee extension moment at initial contact as performed the drop vertical jump task of total frontal plane (valgus) movement. At initial contact in the first injury, moreover, the asymmetry between limbs in peak knee moment at sagittal was respectively 0.120 and 0.080 in the involved and the non-involved limbs, while it was respectively deemed 0.090 and 0.025 [8].

Biomechanical changes of the ACLR limb for >24 months

Compared to the healthy group, the asymmetry index from 6- to 24 months decreased in the ACLR group; specifically, peak vGRF decreased from 100% to 6.5%, and anterior-pGRF reduced from 155.5% to 7%. Moreover, the AI decreased for peak hip flexion, peak knee flexion, and peak ankle dorsiflexion moments were respectively recorded from 74.5% to 17.1%, 79.0% to 5.8%, and 59.3% to 5.9%. Furthermore, the AI decreased for peak hip abduction moment was from 67.8% to 5.1%; it was respectively observed from 55.7% to 14.8% and 48.7% to 23.5% for peak knee adduction moment and peak knee valgus angle [28]. From 6 to 24-month asymmetry index for peak, sagittal plane knee flexion angles, triple hop, crossover hop, and single-leg vertical hop were respectively recorded from 92.85% to 86.25%, 94.34% to 85.59%, 92.63% to 86.87%, and 90.72% to 90.32% during single-leg jump [43]. Besides, females who underwent ACLR demonstrated increased vGRF ($P=0.001$) and loading rate ($P<0.001$) on the uninvolved limb during landing, compared with the involved limb and the control group. During takeoff, the involved limb showed significantly less ability to generate force ($P=0.03$), compared to the uninvolved and control limbs [22].

Discussion

Reviewing selected articles relevant to injury-related biomechanical changes in ACLR individuals revealed significant kinetic and kinematic changes between the limbs of injured and healthy individuals as performing functional tasks for months following the injury. In general, the extent of biomechanical changes could be attributed to the type of activity and movement patterns before injury and rehabilitation programs in the first months after injury. Furthermore, the subset factors that will be next referred to delay the time to reach the biomechanical symmetry of the limb.

Frontal plane knee joint collapse (i.e., dynamic knee valgus) and the consequential increased internal knee adductor moments were identified as key biomechanical factors predisposing injury during landing tasks [19]. King et al. stated that athletes at risk of subsequent ACL injury to the uninjured reciprocal limb could be identified using biomechanical testing after ACLR [40]. A group of male athletes who returned to level 1 sports 9 months after surgery were examined. They experienced isokinetic strength testing and 3-dimensional biomechanical analysis. Regarding the Return-To-Play (RTP) process, the study participants were followed up at 2 years or second ACL injury. Results from 993 follow-up

cases demonstrated that 67 of these subjects would undergo a contralateral ACL injury, and 38 of them would suffer from an ipsilateral injury. Male athletes who experienced a contralateral ACL injury experienced lower quadriceps strength and biomechanical differences on the contralateral limb during double- and single-leg drop jump tests, compared with those who did not experience an injury [35]. In this regard, a research report highlighted the importance of the hip and knee joint in controlling potentially dangerous trunk and pelvic kinematics during the sidcut to prevent and rehabilitate ACL injuries [37].

Considering side-to-side differences in neuromuscular control of the knee during dynamic, athletic tasks were theorized to be a potential risk factor for ACL injury in a healthy population. These side-to-side differences in vGRF and loading rate persisted for up to 2 years after ACLR. Besides, related studies revealed that limb asymmetries identified following ACLR are predictive of future ACL injury, specific asymmetries in sagittal plane knee moments. Injuries to the ACL often occur with the knee at low knee flexion angles. Plus, the related data suggested that the contraction of the quadriceps and hamstrings assists in providing up to 80% of the resistance to frontal plane movement at the knee [10, 26]. Therefore, the ability of the knee to symmetrically activate the sagittal plane musculature is critical to assist in frontal plane stability during a bipedal task, when the knee is in a high-risk position of low flexion [8].

Using the Concussion Resolution Index (CRI), a controlled laboratory study measured neurocognitive performance and three-dimensional kinematic and kinetic data of the dominant limbs of 37 athletes performing an unpredictable jump-landing task. One High Performance (HP) group and one Low Performance (LP) group were neurologically screened. The LP group significantly altered neuromuscular performance during the landing phase, as a significant increase in peak vGRF, maximum peak anterior tibial shear force, knee abduction moment, and knee abduction angle, as well as decreased trunk flexion angle were relatively observed. The result was reported that healthy athletes with lower neurocognitive performance develop knee kinematic and kinetic patterns which are associated with ACL injury [18, 25, 36, 38].

King et al. argued that the RTP rate was 81% in the 2-year follow-up stage after surgery [40]; of those who returned, 1.3% of those with patellar tendon grafts and 8.3% of those with hamstring grafts experienced ipsilateral rupture (hazard ratio, 0.17). In other words, the contralateral ACL injury rate was reckoned at 6.6%. Fur-

thermore, the findings demonstrated high overall RTP rates, lower re-injury rates with patellar tendon graft after 2-year follow-up in level 1 athletes, and no influence of time to RTP was observed on second ACL injury [40]. Grindem et al. demonstrated high overall RTP rates, lower re-injury rates with patellar tendon graft after a 2-year follow-up in level 1 athletes, and they reported no influence of time to RTP on second ACL injury [21, 41]. Johnson et al. suggested a symmetry between the lower extremities during functional tasks such as double-leg vertical hop landing in the two years after ACLR; this condition was highly correlated with the duration of postoperative physiotherapy monitoring [18]. Cronström et al. reported that as one of the 7 factors that independently increase the odds of Contra-lateral Anterior Cruciate Ligament (C-ACL) injury retaining, primary ACL reconstruction was performed ≤ 3 months following injury [38]. Additionally, delays in returning to sports for nearly 2 years significantly reduced the incidence of second ACL injuries [11].

In a 5-year follow-up, it was reported that women suffered more anterior cruciate ligament injuries than men after reconstruction and that the knee valgus angle increased concerning kinematic variables during landing jump. Moreover, the knee flexion was observed lower in the injured limb [8, 28, 42]. The incidence of injury to either knee after reconstruction was associated with younger age and higher activity levels, but returning to full activities before 6 months does not postoperatively increase the risk of subsequent injury [42].

In response to the question “can the uninvolved leg be used as a reference regardless of whether it was the dominant leg before the ACL rupture or not?” Van der Harst et al. documented no significant difference between the dominant leg and the opposite leg in healthy individuals. Besides, that the uninvolved leg of ACLR patients can be consequently used as a reference. Furthermore, they used kinetic and kinematic variables as reference values of normal differences and values between legs in healthy subjects [23].

According to the reviewed articles, biomechanical changes last between 18 and over 28 months until normal conditions can be reached in all respects. Therefore, the return-to-sport time of such individuals depends on the biomechanical changes between the limb during functional tasks after injury, and that other factors may also be effective in this delay.

Conclusion

The present systematic review findings indicated that ACLR patients display limb asymmetries in functional tasks after 18 months. It is hoped that, by identifying possible asymmetries in each month after injury, understanding the rapid and safe return to exercises and rehabilitation will be quickly reached and effectively realized.

Ethical Considerations

Compliance with ethical guidelines

Since this is a systematic review, there are no ethical principles to be observed.

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Authors' contributions

All authors equally contributed to preparing this article.

Conflict of interest

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