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Knee biomechanics during rehabilitation exercise in individuals with and without anterior cruciate ligament reconstruction: A systematic review

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ABSTRACT

Background: Post-traumatic osteoarthritis rates are similar in individuals with anterior cruciate ligament injury who receive surgical reconstruction and those who opt for non-surgical management, indicating continuing changes in knee biomechanics post-surgery. There is no gold standard rehabilitation strategy for the post-reconstruction patient, however investigating the biomechanics of the knee during rehabilitation exercises will drive the development of more efficacious rehabilitation paradigms. This systematic review aimed to synthesise biomechanical data from healthy participants and participants with anterior cruciate ligament reconstruction during rehabilitation exercises to provide insights into knee biomechanical changes induced by injury and surgery.

Methods: A systematic literature search was conducted in Web of Science, MEDLINE, EMBASE, PubMed, CINAHL and Scopus, using key terms relating to anterior cruciate ligament reconstruction, lower limb rehabilitation exercises, and knee biomechanics. 34 articles matching the inclusion criteria were identified following abstract and full text screening.

Findings: The included studies reported data on 607 healthy participants and 175 participants with an anterior cruciate ligament reconstruction across five different exercises. Peak knee flexion angle was the most reported variable, whereas tibial anterior translation and adduction biomechanics were reported infrequently, despite their relevance to the ligament injury status.

Interpretation: There is limited biomechanical data of rehabilitation exercise in the knee, with the exception of knee flexion angles. Furthermore, variations in data collection and reporting methods across studies cause difficulties in systematic analysis of results and demonstrate inconsistent kinematic results between articles.

1. Introduction

Injuries to the anterior cruciate ligament (ACL) are common in young, active individuals, and surgical intervention is increasing in incidence in adolescent and adult populations (Mall et al., 2014; Sanders et al., 2016). For those returning to sport, ACL reconstruction (ACLR) is the standard treatment to restore knee stability and function (Diermeier et al., 2020).The definition of successful ACLR is debated (Ma, 2022), however in most cases the ability of a patient to return to sport and performance is the primary measure of success, with over 80 % of athletes and active individuals receiving ACLR returning to some level of performance, whether at their prior level or below (Lai et al., 2018).

Despite the success of surgical intervention in restoring knee function, individuals opting for ACLR are at a similar, if not increased, risk of developing post-traumatic knee osteoarthritis (PTOA) to those who opt to remain ACL deficient, with one systematic review reporting an osteoarthritis prevalence of 41 % in ACLR patients, compared to 35 % in patients with non-surgical treatment with similar pre-injury activity levels (Harris et al., 2017). This could be due to the fact that changes in knee biomechanics, such as alterations to tibial rotation and knee adduction moment (Scanlan et al., 2010; Wellsandt et al., 2016), which are induced following ACL injury, persist following surgery and thus

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may alter the native loading patterns of the tibiofemoral joint, leading to progressive degeneration (Carbone and Rodeo, 2017; Dare and Rodeo, 2014).

Rehabilitation programs following ACLR aim to restore knee kinematics through strengthening the musculature about the knee joint, however there is limited evidence regarding the effect of rehabilitation on the prevention or delay of PTOA (Holm et al., 2023). Previous research has demonstrated a narrowing of the tibiofemoral joint space width in the time immediately following ACLR, a variable which is associated with articular cartilage change preceding osteoarthritis diagnosis (Tourville et al., 2013; Tourville et al., 2014). The observed narrowing in joint space width is increased in individuals with greater deficits in quadriceps strength (Tourville et al., 2013; Tourville et al., 2014), which may indicate that development of rehabilitation protocols for more effective maintenance and improvement of quadriceps strength could improve outcomes related to osteoarthritis development. Unfortunately, there is currently no gold standard rehabilitation protocol for ACLR (van Grinsven et al., 2010) and rehabilitation outcomes may differ largely between clinical sites. Generally, clinicians agree on the importance of strength training as a component of rehabilitation (Vlok et al., 2022), however the time of initiation, type of exercises included, and length and progression of rehabilitation is debated (van Grinsven et al., 2010). For example, there is continued caution surrounding the use of open kinetic chain exercises, which involve motions where the foot is free to move such as during leg extensions, despite evidence that open kinetic chain exercises improve strength at similar rates to closed kinetic chain exercises and do not compromise the laxity of an ACL graft (Forelli et al., 2023). While the maintenance of the immature ACL graft is prioritised during rehabilitation protocol development, the effect of exercise on the mechanics of the tibiofemoral joint post-ACLR is less studied.

The tibiofemoral joint moves in six degrees-of-freedom, comprising three axes of rotation and three of translation. The paucity of data surrounding changes in translation following ACLR may relate to the methods of three-dimensional motion capture employed by researchers. Marker-based motion capture methods are common but present accuracy issues relating to soft-tissue artefact when millimetre precision is required for translational motion (Hume et al., 2018), whereas image-matching methods involving fluoroscopy or radiography and MRI techniques allow for determination of translation but have limits relating to the data volume available to capture. The shortcomings in each technique may both limit the biomechanical data present across all six degrees-of-freedom of the knee and provide a level of variability to the results reported.

Previous systematic reviews have investigated the alterations in kinematics and kinetics that are exhibited post-ACLR during gait (Slater et al., 2017), activities of daily living such as stair ambulation and balance (Moore et al., 2020), and return to sport assessments (Kotsifaki et al., 2020; Petersen et al., 2014). These reviews have observed alterations in peak knee rotation angles and moments with ACLR, however fail to consider changes in tibiofemoral translation despite the ACL's role in preventing anterior translation. One systematic review observed the rotational and translational kinematics of the knee during squat and lunge exercises (Galvin et al., 2018), however only healthy participants were considered. As far as we are aware, there are currently no systematic reviews which consider the biomechanics of different rehabilitation exercises in participants with ACLR. These data could be useful in the development of rehabilitation protocols which consider the safety and effectiveness of specific exercises after ACLR, as in a recent study which used kinetic data related to patellar tendon loading during common rehabilitation exercises to advise on exercise progression during the rehabilitative process (Scattone Silva et al., 2024).

The aim of this systematic review was to synthesise published kinematic and kinetic data describing knee biomechanics during commonly prescribed resistance-based lower-limb rehabilitation exercises in both healthy participants and participants with ACLR. These data should provide insights on the biomechanical changes observed in the knee during early strengthening rehabilitation post-surgery.

2. Methods

The present review was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Page et al., 2021).

2.1. Search strategy

A systematic literature search of Web of Science, MEDLINE (Ovid), EMBASE (Ovid), PubMed, CINAHL, and Scopus was conducted ranging from the date of inception of the database to 22nd May 2024. Search terms relating to surgical state, rehabilitation exercise, and knee mechanics were carefully selected and can be found in Supplementary Table 1.

2.2. Inclusion and exclusion criteria

Title and abstract screening were performed by two authors (ZNM and MMA) independently to determine articles suitable for full-text retrieval. All identified articles were subsequently retrieved where possible and screened for inclusion by the primary author. Full details of the exclusion protocol are listed in the PRISMA diagram (Fig. 1).

Articles were included in the review if they reported three-dimensional knee kinematics and/or kinetics during bodyweight lower limb rehabilitation exercise in individuals with healthy or ACLR knees. All relevant healthy control data was included, however data from other injury states, e.g. ACL deficiency or patellofemoral pain syndrome, were excluded. Reported mean age of participants was restricted to 18–50 to control for the potential onset of idiopathic osteoarthritis and to assess the key population at risk of ACL injury. Studies reporting data collected with experimental rehabilitation methods such as shoe orthoses, knee bracing, or electrical muscle stimulation were excluded. Studies were also excluded where data was reported as a mean value across the range of motion of the exercise due to the inability to extract range of motion specific results. Finally, case reports, systematic reviews, and articles not published in English were excluded.

2.3. Quality and bias assessment

Quality assessment was conducted independently by two authors (ZNM and FZ) using a quality assessment tool based on the Strengthening the Reporting of Observational Studies in Epidemiology guidelines (STROBE) (von Elm et al., 2007). The checklist was modified for relevance as has been reported in similar systematic reviews in the field of biomechanics (Koussou et al., 2021; Lempereur et al., 2014; Moissenet et al., 2017). All questions used can be found in Supplementary Table 2. Studies were scored either 1 (fully reported), 0.5 (partial/limited reporting), or 0 (not reported), resulting in studies being scored out of 16. Discrepancies in scoring were resolved by reassessing each paper and discussion reaching a consensus between authors. A third author was not needed to resolve discrepancies.

2.4. Data extraction

Study information including sample size, demographics, methods of data collection and reported outcome measures were extracted by the primary author. Kinematic data extracted included flexion/extension angle, internal/external rotation angle, and abduction/adduction angle. In terms of kinetic data, compressive and anterior-posterior shear forces were extracted, as well as flexion/extension moment, internal/external rotation moment and abduction/adduction moment. For these data, discrete values such as peak angles were extracted. Where data were reported in graphs, OriginPro was used to digitise and extract values. The decision was made to not include a meta-analysis in the present

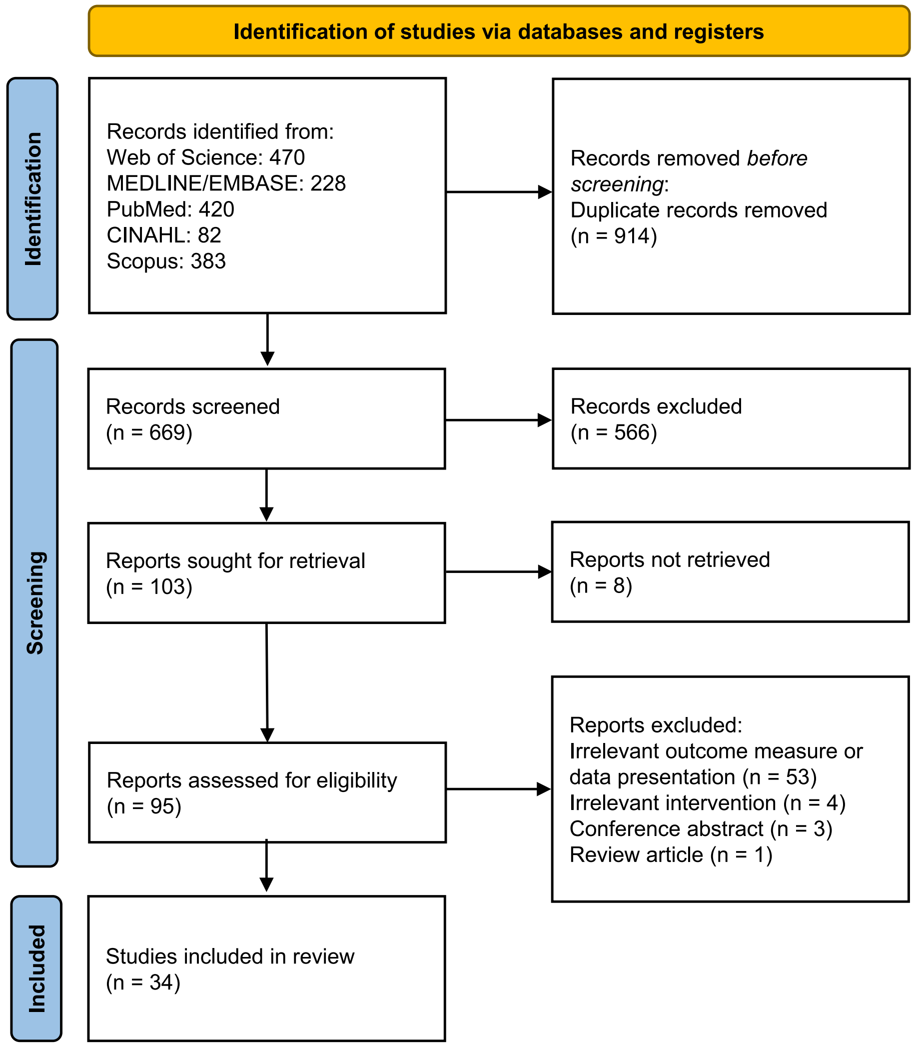

Fig. 1. PRISMA diagram of study selection.

review due to the disparate nature of many reported variables and as most of the included studies used an observational study design.

3. Results

3.1. Study characteristics

34 studies were included in the final analysis, 8 of which included participants with ACLR and 30 which included healthy participants, comprising 607 healthy participants (age 27.7 + 7.9 years) and 175 with ACLR (age 28.3 + 8.3 years). One study (Khuu and Lewis, 2019) included data reported in a previous study (Khuu et al., 2016), and therefore the duplicated data was excluded from the current review. Exercises measured in the selected studies included single-leg squat ($n =$ 16), forward lunge ($n = 8$), squat ($n = 7$) and forward or lateral step down ($n = 4$). Data for ACLR patients was reported for all exercises except step down. Further study details are listed in Table 1.

3.2. Study methodological quality

Results of the study quality assessment are summarised in Supplementary Table 3. All studies reported adequately on methods of data collection, statistical methods, quantitative results, and discussion of main results. Conversely, study settings and study size of the results had limited reporting. While limitations and interpretations in reference to wider literature were discussed by the majority of included studies, an analysis of external validity and generalisability was only partially reported or absent from most papers (68 %). The highest scoring study (Carvalho et al., 2022) achieved a quality score of 97 %. Only one study scored below 60 % (Han et al., 2014). 29 of the 34 included studies scored a methodological quality of 75 % or above.

3.3. Single-leg squat

3.3.1. Kinematics

Two studies (Bell et al., 2014; Scarneo-Miller et al., 2022) reported the kinematics of ACLR subjects during single-leg squat and 16 studies (Barker-Davies et al., 2019; Bell et al., 2014; Carvalho et al., 2022; Carvalho et al., 2024; Glaviano et al., 2019; Graci et al., 2012; Houston et al., 2021; Khuu et al., 2016; Khuu and Lewis, 2019; Lewis et al., 2015; Martins et al., 2022; Mauntel et al., 2018; Scarneo-Miller et al., 2022; Weeks et al., 2012; Willson and Davis, 2008; Zawadka et al., 2020) reported the kinematics of healthy participants or control subjects. The most commonly reported variable was peak knee flexion, which was reported for 12 studies (Barker-Davies et al., 2019; Bell et al., 2014; Glaviano et al., 2019; Graci et al., 2012; Khuu et al., 2016; Khuu and Lewis, 2019; Lewis et al., 2015; Martins et al., 2022; Mauntel et al., 2018; Scarneo-Miller et al., 2022; Weeks et al., 2012; Zawadka et al., 2020). Peak knee flexion in ACLR subjects ranged from 60.39° (Scarneo-Miller et al., 2022) to 75.33° (Bell et al., 2014), and from 60.95°

Table 1
Details of included studies.

Study	Country	Healthy/Control N (M/F)	Healthy/Control Age, mean (SD)	ACLR N (M/F)	ACLR Age, mean (SD)	ACLR N with meniscal pathology or surgery	Testing time points	Exercise(s) assessed	Variation(s)	Data collection method	Biomechanical variables reported
Alkjaer 2020 (Alkjaer et al., 2020)	Denmark	28 (17/11)	27.0 (6.9)	28 (17/11)	29.8 (9.1)	Not stated	10.7 months post-ACLR	Forward lunge		Vicon 3D motion capture; Kinematics: 100 Hz, Kinetics: 1000 Hz	FE rotation, FE moment
Almosnino 2013 (Almosnino et al., 2013)	Canada	28 (17/11)	M: 23 (4) F: 24 (6)					Squat	Neutral stance and foot position, feet turned out to 30°, stance at 140 % shoulder width, wide stance and turned feet	3D motion capture; Kinematics; Optotrak: 100 Hz, Kinetics; AMTI: 1000 Hz	FE moment, AA moment, IE moment
Barker-Davies 2019 (Barker-Davies et al., 2019)	United Kingdom	22 (22/0)	34.0 (6.5)					Single-leg squat		3D motion capture; Kinematics; Vicon: 120 Hz, Kinetics; AMTI: 1200 Hz	FE rotation, AA rotation, FE moment, IE moment, AA moment
Bell 2014 (Bell et al., 2014)	United States	51 (7/44)	19.8 (1.4)	BPTB: 34 (5/29), ISGA: 21 (0/21)	BPTB: 19.3 (1.9), ISGA: 19.1 (1.7)	Not stated	34 (19)/37 (21) months post-ACLR	Single-leg squat		Electromagnetic 3D tracking; Kinematics: 144 Hz, Kinetics: 1440 Hz	FE rotation, AA rotation, IE rotation
Carvalho 2022 (Carvalho et al., 2022)	Brazil	10 (5/5)	47.8 (5.5)					Single-leg squat	Descent and ascent considered separately	Vicon 3D motion capture; Kinematics: 90 Hz	FE rotation, AA rotation
Carvalho 2024 (Carvalho et al., 2024)	Brazil	8 (4/4)	46.4 (5.1)					Single-leg squat	Descent and ascent considered separately	Vicon 3D motion capture; Kinematics: 90 Hz	FE rotation, AA rotation
Chen 2021 (Chen et al., 2021)	China			ACLR: 8 (4/4), ACLR+ALSA: 8 (5/3)	ACLR: 30.3 (4), ACLR+: 31.3 (5.1)	ACLR: 2 (APM), ACLR+: 2 (repair), 2 (APM)	12 months post-ACLR	Forward lunge		SOMATOM Definition dual fluoroscopy	AP translation, IE rotation, ML translation, AA rotation
Farrokhi 2008 (Farrokhi et al., 2008)	United States	10 (5/5)	26.7 (3.2)					Forward lunge	Forward leaning trunk, neutral trunk, backward stretched trunk	3D motion capture; Kinematics; Vicon: 60 Hz, Kinetics; AMTI: 1560 Hz	FE rotation
Gao 2023 (Gao et al., 2023)	China	15 (15/0)	22.5 (1.6)					Forward lunge	Before and after a fatiguing protocol of 400 m running and 20 lunges	3D motion capture; Kinematics; Vicon: 200 Hz, Kinetics; Kistler: 1000 Hz	FE rotation, IE rotation, FE moment, IE moment
Glaviano 2019 (Glaviano et al., 2019)	United States	9 (0/9)	20.8 (1.4)					Single-leg squat		Vicon 3D motion capture; Kinematics: 250 Hz	FE rotation, AA rotation
Graci 2012 (Graci et al., 2012)	United States	19 (10/9)	M: 28.7 (6.05) F: 26.9 (5.77)					Single-leg squat		Vicon 3D motion capture; Kinematics: 120 Hz	FE rotation, AA rotation, IE rotation
Han 2014 (Han et al., 2014)	China	16 (8/8)	22.2 (2.4)					Squat	Neutral knees, valgus/inward knees, varus/outward knees	Optotrak 3D motion capture; Kinematics: 100 Hz	FE rotation, AA rotation, IE rotation
Han 2013 (Han et al., 2013)	China	15 (6/9)	21.4 (2.0)					Squat		Optotrak 3D motion capture; Kinematics: 100 Hz	FE rotation, AA rotation, IE rotation, FE moment, AA moment, IE moment, compressive force, shear force
Houston 2021 (Houston et al., 2021)	United Kingdom	22 (22/0)	34.0 (6.5)					Single-leg squat		3D motion capture; Kinematics; Vicon: 120 Hz Kinetics; AMTI: 1200 Hz	AA rotation

(continued on next page)

Table 1 (*continued*)

		Healthy/Control		ACLR							
Study	Country	N (M/F)	Age, mean (SD)	N (M/F)	Age, mean (SD)	N with meniscal pathology or surgery	Testing time points	Exercise(s) assessed	Variation(s)	Data collection method	Biomechanical variables reported
Khuu 2016 (Khuu et al., 2016)	United States	16 (0/16)	23.1 (1.9)					Single-leg squat	Non-stance leg in front of the body, beneath the hip, or behind the body	3D motion capture; Kinematics; Vicon: 100 Hz, Kinetics; Bertec: 1000 Hz	FE rotation, AA rotation, IE rotation, FE moment, AA moment, IE moment
Khuu 2019 (Khuu and Lewis, 2019)	United States	32 (16/16)	M: 22.2 (3.7), F: as above					Single-leg squat	Non-stance leg in front of the body, beneath the hip, or behind the body	3D motion capture; Kinematics; Vicon: 100 Hz, Kinetics; Bertec: 1000 Hz	FE rotation, AA rotation, FE moment, AA moment
Lewis 2015 (Lewis et al., 2015)	United States	14 (10/4)	23.9 (2.0)					Single-leg squat, step down		Vicon 3D motion capture; Kinematics: 100 Hz	FE rotation, AA rotation, IE rotation
Martins 2022 (Martins et al., 2022)	Brazil	13 (not stated)	28 (7)					Single-leg squat		3D motion capture; Kinematics; Vicon: 100 Hz, Kinetics; AMTI: 1000 Hz	FE rotation, AA rotation, IE rotation
Mauntel 2018 (Mauntel et al., 2018)	United States	40 (20/20)	20.3 (1.6)					Single-leg squat		Electromagnetic motion capture; Kinematics; Motion Star: 100 Hz, Kinetics; Bertec: 1000 Hz	FE rotation, IE rotation, VV rotation
Murakami 2016 (Murakami et al., 2016)	Japan	5 (5/0)	34 (32–36)					Squat		Image matching of X-ray and CT	FE rotation, IE rotation, AP translation
Nicolas 2015 (Nicolas et al., 2015)	Canada	11 (3/8)	25.9 (7.5)					Step down		Vicon 3D motion capture; Kinematics: 120 Hz	FE rotation, AA rotation, IE rotation
Papannagari 2006 (Papannagari et al., 2006)	United States			7 (not stated)	19–38	1 with tear, 4 with partial meniscectomy	6.5 (11.6) months post-injury	Forward lunge		Dual-orthogonal fluoroscopy	AP translation, IE rotation
Qi 2013 (Qi et al., 2013)	United States	7 (5/2)	23–49					Forward lunge		Dual fluoroscopy	AP translation, ML translation, IE rotation, AA rotation
Sanford 2016 (Sanford et al., 2016)	United States	8 (3/5)	25 (4)	8 (3/5)	28 (7)	Not stated	86.4 (75.6) months post-ACLR	Squat		Qualisys 3D motion capture; Kinematics: 100 Hz, Kinetics: 1000 Hz	AP translation
Scarneo-Miller 2022 (Scarneo-Miller et al., 2022)	United States	23 (14/9)	21 (3)	23 (14/9)	21 (3)	Not stated	55.7 (37.4) months post-ACLR	Single-leg squat		Electromagnetic motion capture; Kinematics; Trackstar: 150 Hz, Kinetics; Bertec: 1500 Hz	FE rotation
Scheys 2013 (Scheys et al., 2013)	Belgium	25 (13/12)	32.9 (9.8)					Squat, forward lunge	Partial and full depth squat	Vicon 3D motion capture; Kinematics: 100 Hz	FE rotation, AA rotation, IE rotation
Sigward 2018 (Sigward et al., 2018)	United States			11 (4/7)	22.9 (9.5)	6 with meniscal tear, no surgical intervention	3 and 5 months post-ACLR	Squat		3D motion capture; Kinematics; Qualisys: 250 Hz, Kinetics; AMTI: 1500 Hz	FE rotation, FE moment
Stensdotter 2024 (Stensdotter et al., 2024)	Sweden	31 (21/10)	46.7 (4.9)	27 (16/11)	46.0 (4.1)	Not stated	<20 years post-ACLR	Squat		Qualisys 3D motion capture; Kinematics: 240 Hz	FE rotation, AA rotation, IE rotation
Thomas 2023 (Thomas et al., 2023)	United States	19 (9/10)	22.1 (1.6)					Lateral step down		Polhemus electromagnetic motion sensor	FE rotation, AA rotation, IE rotation

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Table 1 (*continued*)

Study	Country	Healthy/Control N (M/F)	Healthy/Control Age, mean (SD)	ACLR N (M/F)	ACLR Age, mean (SD)	N with meniscal pathology or surgery	Testing time points	Exercise(s) assessed	Variation(s)	Data collection method	Biomechanical variables reported
Varadarajan 2009 (Varadarajan et al., 2009)	United States	24 (12/12)	M: 33.0 (7.3) F: 29.0 (10.5)					Forward lunge		Dual-orthogonal fluoroscopy	AP translation, ML translation, IE rotation, AA rotation
Weeks 2012 (Weeks et al., 2012)	Australia	22 (13/9)	23.8 (3.1)					Single-leg squat		Vicon 3D motion capture; Kinematics: 200 Hz	FE rotation
Werner 2021 (Werner et al., 2021)	United States	30 (12/18)	23.2 (1.4)					Step down, lateral step down		Vicon 3D motion capture; Kinematics: 150 Hz	FE rotation, AA rotation, IE rotation
Willson 2008 (Willson and Davis, 2008)	United States	20 (0/20)	23.7 (3.6)					Single-leg squat		3D motion capture; Kinematics; Vicon: 120 Hz, Kinetics; Bertec: 1080 Hz	FE moment, IE rotation
Zawadka 2020 (Zawadka et al., 2020)	Poland	58 (35/23)	M: 21.0 (1.2) F: 20.3 (0.5)					Single-leg squat		Vicon 3D motion capture; Kinematics: 100 Hz	FE rotation, AA rotation, IE rotation

(Zawadka et al., 2020) to 87.5° (Khuu and Lewis, 2019) in healthy subjects (Table 2). Peak knee extension ranged from 7.1 ± 2.1° (Barker-Davies et al., 2019) to 12.5 ± 7.2° (Zawadka et al., 2020) in healthy participants (Table 2).

Peak values for knee abduction (Barker-Davies et al., 2019; Glaviano et al., 2019;Mauntel et al., 2018; Zawadka et al., 2020), adduction (Barker-Davies et al., 2019; Zawadka et al., 2020), internal rotation (Mauntel et al., 2018; Zawadka et al., 2020) and external rotation (Zawadka et al., 2020) were also reported for the single-leg squat (Table 2), however none of these studies reported on participants with ACLR. By contrast, knee adduction and rotation at specific knee flexion values were reported for both healthy and ACLR knees (Table 3); knee rotation at peak knee flexion was reported in three studies (Bell et al., 2014; Khuu et al., 2016; Martins et al., 2022), at 45° flexion in one study (Willson and Davis, 2008) and at 60° flexion in one study (Khuu et al., 2016) (Supplementary Fig. 1). Knee rotation broadly remained in internal rotation through the range of motion in both healthy and ACLR knees, with knee rotation at 60° of flexion reaching 6.2 ± 9.3° internal rotation in healthy female participants (Khuu et al., 2016) (Supplementary Fig. 1) and peak internal-external rotations ranging from 18.4 ± 8.9° to −3.4 ± 11.2° in healthy participants (Zawadka et al., 2020).

6 studies (Bell et al., 2014; Graci et al., 2012; Khuu et al., 2016; Khuu and Lewis, 2019; Lewis et al., 2015; Martins et al., 2022) reported adduction at peak knee flexion, two (Carvalho et al., 2022; Carvalho et al., 2024) reported adduction at 30° knee flexion, three (Carvalho et al., 2022; Carvalho et al., 2024; Graci et al., 2012) reported adduction at 45° flexion and four (Carvalho et al., 2022; Carvalho et al., 2024; Khuu et al., 2016; Khuu and Lewis, 2019) reported adduction at 60° flexion (Supplementary Fig. 2). Adduction angle demonstrated a pattern of increasing abduction up to 60° knee flexion, before moving towards adduction at peak knee flexion in healthy participants (Supplementary Fig. 2). Knee abduction peaked at −24.1 ± 7.5° at 60° knee flexion during squat descent in healthy knees (Carvalho et al., 2024), whereas adduction peaked at 7.0 ± 4.1° at peak knee flexion in healthy males (Graci et al., 2012).

3.3.2. *Kinetics*

No studies reported the single-leg squat kinetics of ACLR participants. One study of healthy participants (Barker-Davies et al., 2019) reported peak kinetic data for the single-leg squat exercise, reporting a mean peak extension moment of 1.3 ± 0.10 $Nm.kg^{-1}$, mean peak adduction moment of −0.15 ± 0.04 $Nm.kg^{-1}$ and mean peak internal rotation moment of 0.03 ± 0.02 $Nm.kg^{-1}$. Furthermore, three studies (Khuu et al., 2016; Khuu and Lewis, 2019; Willson and Davis, 2008) reported kinetics in relation to knee flexion angle, with two studies reporting flexion and adduction moment at peak knee flexion and 60° flexion, one study (Khuu et al., 2016) reporting internal rotation moments at peak flexion and 60° flexion, and Willson et al. (Willson and Davis, 2008) reporting flexion moment at 45° knee flexion.

Khuu et al. (Khuu et al., 2016; Khuu and Lewis, 2019) compared the kinetics of differing non-stance leg positions in females and males, with extensor moment at 60° knee flexion ranging from 1.20 ± 0.25 $Nm.kg^{-1}$ in females to 1.32 ± 0.18 $Nm.kg^{-1}$ in males with the non-stance leg in a neutral position. At peak flexion, knee extensor moment increased to 1.51 ± 0.30 $Nm.kg^{-1}$ in females and 1.78 ± 0.25 $Nm.kg^{-1}$ in males (Khuu et al., 2016; Khuu and Lewis, 2019). Conversely, knee adduction moment was lower in males, at 0.02 ± 0.18 $Nm.kg^{-1}$ and 0.19 ± 0.25 $Nm.kg^{-1}$ in males at 60° and peak knee flexion respectively, compared to 0.14 ± 0.20 $Nm.kg^{-1}$ and 0.28 ± 0.24 $Nm.kg^{-1}$ in females at the same flexion points with a neutral non-stance leg (Khuu et al., 2016; Khuu and Lewis, 2019). At 45° knee flexion, the knee extensor moment in healthy females was reported as approximately 0.98 ± 0.08 $Nm.kg^{-1}$ (Willson and Davis, 2008).

3.4. Forward lunge

3.4.1. Kinematics

Three studies compared the kinematics of ACLR knees to either healthy controls (Alkjaer et al., 2020) or the uninjured contralateral knee of ACLR participants (Chen et al., 2021; Papannagari et al., 2006) during forward lunge. Five studies reported the data on healthy participants only (Farrokhi et al., 2008; Gao et al., 2023; Qi et al., 2013; Scheys et al., 2013; Varadarajan et al., 2009). For this exercise, peak values were reported for knee flexion in 6 studies (Alkjaer et al., 2020; Chen et al., 2021; Farrokhi et al., 2008; Gao et al., 2023;Qi et al., 2013; Scheys et al., 2013), knee extension in two studies (Gao et al., 2023; Qi et al., 2013), abduction and adduction in two studies (Qi et al., 2013; Scheys et al., 2013), internal rotation in five studies (Gao et al., 2023; Papannagari et al., 2006; Qi et al., 2013; Scheys et al., 2013; Varadarajan et al., 2009) and external rotation in four studies (Gao et al., 2023; Papannagari et al., 2006; Qi et al., 2013; Varadarajan et al., 2009) (Table 4). Tibial rotations at specific knee angles were reported in graphs in four studies (Collins et al., 2009; Krosshaug et al., 2007; Tagesson et al., 2015; Thomas et al., 2023) and extracted values are plotted in Supplementary Fig. 3. Similarly, adduction angles were reported in graphs by Qi et al. (Qi et al., 2013) and Varadarajan et al. (Varadarajan et al., 2009) (Supplementary Fig. 4).

Tibial translation was reported in four studies (Chen et al., 2021; Papannagari et al., 2006; Qi et al., 2013; Varadarajan et al., 2009), all of which reported using the method of dual fluoroscopy during motion capture. The studies reported creating perpendicular anteroposterior and mediolateral axes on the tibial plateau and a transepicondylar axis though the centre points of the femoral condyles to define femoral position in relation to the tibial coordinate system (Papannagari et al., 2006). This axis system was used to define anterior or posterior motion of the midpoint of the transepicondylar femoral line to calculate tibial translation (Papannagari et al., 2006).

Peak anterior and posterior translation was reported by Chen et al. (Chen et al., 2021), Papannagari et al. (Papannagari et al., 2006), Qi et al. (Qi et al., 2013) and Varadarajan et al. (Varadarajan et al., 2009) Peak medial and lateral translations were also reported by Chen et al. (Chen et al., 2021), Qi et al. (Qi et al., 2013) and Varadarajan et al. (Varadarajan et al., 2009). Peak medial translation ranged from 3.7 $\pm$ 2.5 mm in healthy individuals as reported by Qi et al. (Qi et al., 2013), to 4.8 $\pm$ 1.3 mm in healthy females (Varadarajan et al., 2009). Qi et al. (Qi et al., 2013) reported a peak lateral translation of 8.1 $\pm$ 4.3 mm and Varadarajan et al. (Varadarajan et al., 2009) found a peak lateral translation of 7.0 $\pm$ 2.7 mm in females and 5.6 $\pm$ 1.9 mm in males. For participants with ACLR, tibial anterior-posterior translation during the forward lunge motion ranged from 13.9 $\pm$ 3.7 mm to -1.2 ± 1.6 mm (Papannagari et al., 2006), where a positive value denotes anterior tibial position (Supplementary Fig. 5). In healthy participants, the peak anterior translation ranged from 25.1 $\pm$ 3.3 mm (Qi et al., 2013) to 19.0 $\pm$ 2.0 mm (Varadarajan et al., 2009), at peak knee angles of 145° and 120° respectively. Peak posterior translation ranged from 1.4 $\pm$ 3.1 mm (Qi et al., 2013) to -0.4 ± 3.6 mm (Varadarajan et al., 2009) in healthy participants. Papannagari et al. (Papannagari et al., 2006) reported translation values in the uninjured knee of individuals with ACLR, finding anterior-posterior translation ranging from 13.9 $\pm$ 4.4 mm to -4.1 ± 1.5 mm (Supplementary Fig. 5).

3.4.2. Kinetics

Two studies reported knee kinetics during a forward lunge (Alkjaer et al., 2020; Gao et al., 2023). In ACLR participants, a peak flexion moment of 0.6 $\pm$ 0.20 Nm.kg^{-1} was reported by Alkjaer et al. (Alkjaer et al., 2020), compared to a reported peak flexion moment of 0.8 $\pm$ 0.20 Nm.kg^{-1} in healthy participants. Gao et al. (Gao et al., 2023) reported kinetics following a fatiguing protocol of running and repetitions of the lunge exercise. A pre-fatigue peak flexion moment of 1.54 $\pm$ 0.68 Nm.kg^{-1} was reported compared to a post-fatigue moment of 1.3 $\pm$ 0.30 Nm.kg^{-1} (Gao et al., 2023). Further, Gao et al. (Gao et al., 2023) reported peak internal rotation moments of -10.98 ± 1.38 Nm.kg^{-1} pre-

Table 2
Peak knee rotation angles during single-leg squat exercise.

Study	Peak knee flexion (°)	Peak knee extension (°)	Peak knee abduction (°)	Peak knee adduction (°)	Peak internal rotation (°)	Peak external rotation (°)
Barker-Davies 2019	64.6 (8.3)	7.1 (2.1)*	−8.4 (1.7)*	−2.0 (1.3)*		
Bell 2014 (ACLR; BPTB)	75.33 (9.73)					
Bell 2014 (ACLR; ISGA)	72.96 (6.67)					
Bell 2014 (Healthy)	81.54 (11.62)					
Glaviano 2019 (females)	65.9 (3.2)		−6.6 (1.8)			
Graci 2012 (males)	76.43 (10.15)					
Graci 2012 (females)	69.77 (7.27)					
Khuu 2016 (females; forward leg)	82.0 (7.0)					
Khuu 2016 (females; neutral leg)	79.2 (8.7)					
Khuu 2016 (females; backward leg)	75.1 (6.1)					
Khuu 2019 (males; forward leg)	87.5 (13.2)					
Khuu 2019 (males; neutral leg)	84.0 (9.3)					
Khuu 2019 (males; backward leg)	81.9 (7.5)					
Lewis 2015	84.4 (7.3)					
Martins 2022	59.6 (2.8)*					
Mauntel 2018	62.04 (60.47, 63.61)		−9.59 (−11.53, −7.65)		2.58 (0.03, 5.13)	
Scarneo-Miller 2019 (healthy)	69.76 (10.48)					
Scarneo-Miller 2019 (ACLR)	60.39 (12.82)					
Weeks 2012 (all participants)	79.9 (12.3)					
Weeks 2012 (males)	86.2 (13.0)					
Weeks 2012 (females)	71.5 (7.3)					
Zawadka 2020 (males)	64.92 (11.76)	9.92 (4.86)	2.69 (5.85)	13.40 (8.77)	18.42 (8.88)	−2.44 (8.06)
Zawadka 2020 (females)	60.95 (9.57)	12.48 (7.21)	−3.43 (7.18)	4.93 (8.24)	16.73 (12.7)	−3.35 (11.22)

Data reported as mean (standard deviation) or mean (+ − 95 % confidence interval).
* Derived from graph digitisation.

Table 3
Knee rotation angles at specified knee flexion angles during single-leg squat exercise.

Study	Knee adduction at peak flexion (°)	Knee adduction at 30° flexion (°)	Knee adduction at 45° flexion (°)	Knee adduction at 60° flexion (°)	Knee rotation at peak flexion (°)	Knee rotation at 45° flexion (°)	Knee rotation at 60° flexion (°)
Bell 2014 (ACLR; BPTB)	5.87 (12.12)				4.68 (10.74)		
Bell 2014 (ACLR; ISGA)	2.35 (14.3)				3.38 (8.89)		
Bell 2014 (Healthy)	1.68 (17.87)				1.40 (10.33)		
Carvalho 2022 (descent)		−10.6 (5.81)	−17.46 (9.02)	−21.46 (9.73)			
Carvalho 2022 (ascent)		−9.03 (6.45)	−15.4 (8.81)	−19.24 (8.76)			
Carvalho 2024 (descent)		−12.5 (4.25)	−19.96 (6.99)	−24.08 (7.46)			
Carvalho 2024 (ascent)		−11.12 (4.96)	−17.94 (7.16)	−21.89 (6.15)			
Graci 2012 (males)	7.00 (4.11)		3.34 (2.14)				
Graci 2012 (females)	−1.25 (4.77)		−0.89 (3.95)				
Khuu 2016 (females; forward leg)	−9.9 (7.8)			−8.6 (7.2)	3.1 (10.1)		6.4 (9.5)
Khuu 2016 (females; neutral leg)	−8.8 (7.9)			−8.4 (7.0)	3.1 (8.8)		6.2 (9.3)
Khuu 2016 (females; backward leg)	−7.4 (7.9)			−8.0 (6.8)	2.7 (9.5)		5.5 (9.7)
Khuu 2019 (males; forward leg)	−6.7 (7.1)			−7.1 (6.0)			
Khuu 2019 (males; neutral leg)	−5.2 (6.5)			−6.0 (5.8)			
Khuu 2019 (males; backward leg)	−2.9 (6.5)			−5.0 (6.0)			
Lewis 2015	−4.7 (4.1)			−4.8 (4.9)			
Martins 2022	1.6 (3.3)*				−13.6 (3.9)*		
Willson 2008					−6.4 (1.7)*		

Data reported as mean (standard deviation).
* Derived from graph digitisation.

fatigue and -11.48 ± 2.15 Nm.kg^{-1} post-fatigue.

3.5. Squat

3.5.1. Kinematics

Three studies reported ACLR kinematics during a squat; two compared the ACLR participants to controls (Sanford et al., 2016; Stensdotter et al., 2024) and one compared the ACLR knee to the contralateral knee (Sigward et al., 2018) (Table 5). Peak knee flexion during a squat in participants with ACLR was reported at $104.3 \pm 14.8°$, compared with $106.7 \pm 15°$ in their contralateral uninjured knee (Sigward et al., 2018). Four additional studies reported squat kinematics

Table 4
Peak knee rotation angles during forward lunge exercise.

Study	Peak knee flexion (°)	Peak knee extension (°)	Peak knee abduction (°)	Peak knee adduction (°)	Peak internal rotation (°)	Peak external rotation (°)
Alkjaer 2020 (ACLR)	104.2 (9.7)					
Alkjaer 2020 (Healthy)	109.2 (7.9)					
Chen 2021 (ACLR)	109.4 (11.2)					
Chen 2021 (ACLR with ALSA)	114.8 (10.3)					
Chen 2021 (Contralateral)	105.2 (9.9)					
Chen 2021 (ALSA Contralateral)	115.7 (9.4)					
Farrokhi 2008 (upright torso)	110.3 (5.9)					
Farrokhi 2008 (backward lean)	113.4 (7.4)					
Farrokhi 2008 (forward lean)	104.3 (11.1)					
Gao 2023 (pre-fatigue)	120.5 (10.45)	20.9 (8.21)			13.4 (11.46)	−12.2 (8.42)
Gao 2023 (post-fatigue)	124.4 (8.34)	19.1 (7.11)			25.4 (5.07)	−10.5 (5.15)
Papannagari 2006 (ACLR)					6.0 (4.0)*	−2.7 (5.9)
Papannagari 2006 (Contralateral)					8.7 (4.2)*	−5.4 (7.6)
Qi 2013	145.3 (5.7)	−2.9 (7.0)	−1.3 (1.2)*	4.4 (4.1)*	−0.9 (6.3)*	−12.9 (7.9)*
Scheys 2013	101.7 (5.5)				16.3 (3.2)	
Varadarajan 2009 (males)			0.1 (3.5)*	2.7 (3.0)*	8.4 (3.7)*	−1.3 (4.6)*
Varadarajan 2009 (females)			−0.2 (2.8)*	3.7 (4.3)*	11.7 (6.5)*	−5.5 (3.5)*

Data reported as mean (standard deviation).
* Derived from graph digitisation.

in healthy participants (Han et al., 2013; Han et al., 2014; Murakami et al., 2016; Scheys et al., 2013). Peak values for knee flexion (Han et al., 2013; Han et al., 2014; Sanford et al., 2016; Scheys et al., 2013; Sigward et al., 2018) and internal rotation (Han et al., 2013; Han et al., 2014; Murakami et al., 2016; Scheys et al., 2013; Stensdotter et al., 2024) were reported by five studies respectively, external rotation by four studies (Han et al., 2013; Han et al., 2014; Murakami et al., 2016; Stensdotter et al., 2024), abduction and adduction by three studies (Han et al., 2013; Han et al., 2014; Stensdotter et al., 2024) and knee extension was reported by two studies (Han et al., 2013; Han et al., 2014) (Table 5).

Peak flexion-extension angles ranged from 145.3 ± 11.5° to 2.9 ± 5.5° (Han et al., 2014). Peak internal rotation demonstrated a high degree of variation, ranging from 1.1 ± 5.6° (Han et al., 2013) to 24.3 ± 4.7° (Scheys et al., 2013) (Table 5), with external rotation ranging from approximately −6.4° in ACLR participants (Stensdotter et al., 2024) to 3.1 ± 5.6° in a healthy cohort (Murakami et al., 2016). Comparably, the range of peak knee abduction-adduction was smaller, from −2.2 ± 4.17° (Han et al., 2013) to 7.2 ± 4.7° (Han et al., 2014) in healthy participants and from approximately 0.4° to 7.9° in ACLR knees (Stensdotter et al., 2024). Further, one study (Murakami et al., 2016) reported anterior translation, with a peak value of approximately 21.5 ± 2.5 mm extracted from graphs by the primary author (ZNM).

3.5.2. Kinetics

Two studies (Sigward et al., 2018; Stensdotter et al., 2024) reported knee kinetics in ACLR participants, with the latter reporting flexion moment graphically and the former reporting mean peak flexion moments for ACLR knees and the contralateral knee (Table 6). Peak compressive and shear knee force was reported by Han et al. (Han et al., 2013) in a cohort of healthy participants, with compressive force ranging from 2.99 ± 0.89 to 3.32 ± 0.62 times bodyweight (Table 6). Peak flexion moment was reported by 4 studies (Almosnino et al., 2013; Han et al., 2013; Sigward et al., 2018; Stensdotter et al., 2024), with the peak value in individuals with ACLR reported as 0.78 ± 0.22 $Nm.kg^{-1}$ (Sigward et al., 2018) compared to 1.59 ± 0.32 $Nm.kg^{-1}$ in healthy individuals with out-turned feet (Almosnino et al., 2013) (Table 6). Minimum flexion moment was reported by Almosnino et al. (Almosnino et al., 2013), Han et al. (Han et al., 2013) and Stensdotter et al. (Stensdotter et al., 2024). Additionally, peak abduction and adduction and peak internal rotation and external rotation moments were reported for healthy participants by two studies (Almosnino et al., 2013; Han et al., 2013). Abduction-adduction moments ranged from −0.28 ± 0.15 $Nm.kg^{-1}$ (Almosnino et al., 2013) to 0.15 ± 0.07 $Nm.kg^{-1}$ (Han et al., 2013). Internal-external rotation moments ranged from 0.33 ± 0.11 $Nm.kg^{-1}$ (Almosnino et al., 2013) to −0.12 ± 0.06 $Nm.kg^{-1}$ (Han et al., 2013).

3.6. Step down

Four studies reported on variations of a step down exercise; three on a forward step down (Lewis et al., 2015;Nicolas et al., 2015; Werner et al., 2021), and two on a lateral step down (Thomas et al., 2023; Werner et al., 2021). All of these studies reported data from healthy participants only. These studies reported peak knee flexion (Table 7), which ranged from 56.0 ± 5.5° in a lateral step down (Werner et al., 2021) to 86.9 ± 8.3° in a forward step down from a 24 cm high box (Lewis et al., 2015). Two studies reported mean peak knee abduction, adduction, and internal rotation (Nicolas et al., 2015; Werner et al., 2021). Furthermore, Nicolas et al. (Nicolas et al., 2015) reported peak knee extension (10.9 ± 1.3°) and peak external knee rotation (−19.7 ± 3.0°) for the forward step down exercise only. Knee kinetics were not reported for any of these studies.

4. Discussion

Knee biomechanics following ACL injury and reconstruction (ACLR) may influence an individual's risk of developing post-traumatic knee osteoarthritis (PTOA). The kinematics and kinetics exhibited during rehabilitation exercise may provide important information regarding the suitability and safe progression of exercises following ACLR to reduce PTOA risk. The present systematic review aimed to synthesise kinematic and kinetic data during commonly prescribed lower limb rehabilitation exercises in people who have received an ACLR and healthy participants. We found that biomechanical data was reported across six-degrees-of-freedom of knee motion for ACLR and healthy knees during four different rehabilitation exercises. However, the data spread was inconsistent, with few studies reporting frontal and transverse plane rotation or tibial translation. In terms of kinetics, tibiofemoral force data was reported for the squat exercise only, with most studies reporting on the kinetics of knee rotation.

Alterations in knee biomechanics were reported for individuals post-ACLR compared to their contralateral knee or healthy controls in eight studies included in the present review. During the single-leg squat, forward lunge, and squat exercise, reduced peak flexion angles were reported in the injured knee of post-surgery participants (Bell et al., 2014; Chen et al., 2021; Sanford et al., 2016; Scarneo-Miller et al., 2022; Sigward et al., 2018). This may suggest that following surgery the loading stimulus of the knee will change as patients adopt compensatory

Table 5
Peak knee rotation angles during squat exercise.

Study	Peak knee flexion (°)	Peak knee extension (°)	Peak knee abduction (°)	Peak knee adduction (°)	Peak internal rotation (°)	Peak external rotation (°)
Han 2013 (neutral stance)	94.70 (10.58)	6.80 (5.10)	−2.2 (4.17)	0.3 (3.73)	1.1 (5.60)	−1.0 (7.26)
Han 2013 (valgus stance)	88.90 (12.95)	8.99 (7.39)	−2.0 (4.56)	−0.4 (4.66)	1.9 (6.06)	−3.6 (8.38)
Han 2013 (varus stance)	91.90 (14.15)	4.20 (5.21)	−2.2 (4.06)	1.8 (3.89)	3.9 (5.46)	2.3 (3.57)
Han 2014	145.30 (11.5)	2.90 (5.5)	1.0 (1.8)	7.2 (4.7)	7.6 (4.7)	2.5 (1.0)
Murakami 2016					15.7 (1.52)*	3.1 (5.6)*
Sanford 2016 (ACLR)	83 (17)					
Sanford 2016 (Healthy)	99 (13)					
Sigward 2018 (ACLR 3 months)	101.5 (12.9)					
Sigward 2018 (ACLR 5 months)	104.3 (14.8)					
Sigward 2018 (Contralateral 3 months)	103.7 (12.6)					
Sigward 2018 (Contralateral 5 months)	106.7 (15.0)					
Scheys 2013 (partial)	80.1 (6.6)				18.7 (3.4)	
Scheys 2013 (deep)	111.0 (5.9)				24.3 (4.7)	
Stensdotter 2024 (Healthy)			0.3*	4.8*	2.3*	−3.3*
Stensdotter 2024 (ACLR)			0.4*	7.9*	1.1*	−6.4*

Data reported as mean (standard deviation).
* Derived from graph digitisation.

strategies which may need to be controlled by clinicians during supervised rehabilitation. Similarly, Bell et al. reported that reduced peak flexion in ACLR patients during the single-leg squat was associated with increased trunk flexion, which again may alter knee loading (Bell et al., 2014). Interestingly, this study also reported increased knee adduction and internal rotation in the ACLR participants at peak knee flexion compared to healthy control participants, suggesting the compensatory strategies protect the knee by attempting to counteract the mechanical changes by shifting the torso laterally away from knee collapse caused by muscular weakness (Bell et al., 2014). The increasing knee rotations may suggest alterations in joint contact position following surgery, and as they occur at reduced flexion angles, this may indicate the need to provide flexion regressions for exercises during strength-based rehabilitation until the quadriceps can adequately control adduction and rotation.

However, during forward lunge, a reduced range of tibial rotation was reported in ACLR patients across the same flexion range of motion (Papannagari et al., 2006), and while these results also indicate minor alterations in joint contact following surgery, they perhaps also suggest overconstraint of the joint in the months immediately post-surgery. As the time frame of these studies (Bell et al., 2014; Papannagari et al., 2006) ranged from 6 months post-surgery to around 3 years post-surgery, it is feasible that knee kinematics differ between participants both due to maturity and recovery of the graft and progressive knee strengthening following rehabilitation and return to activity. Future research of knee biomechanics during these rehabilitation exercises may wish to place additional focus on kinematic changes throughout the duration of rehabilitation and in the years following return to sport to provide additional support for exercise selection and progressions. Another study assessing forward lunge found slower increases in internal tibial rotation before reaching the same internal rotation angle at peak knee flexion in the ACLR knee compared to the healthy contralateral knee 1 year post-surgery, suggesting that while some biomechanics may seem to be recovered if peak angles are examined, changes in the biomechanics throughout the motion persist after rehabilitation (Chen et al., 2021). Compensatory strategies are also indicated in the bipedal squat via reduced ground reaction forces and flexion moments in the injured limb compared to the contralateral limb (Sanford et al., 2016; Sigward et al., 2018), which are apparent up to 7 years post-surgery, as well as 5–7 months post-surgery. For clinicians, these results may reinforce the importance of single-leg exercises to avoid overcompensation of the healthy limb – with respect to adjusting body position compensations as discussed previously.

The ACL primarily acts to prevent excessive anterior translation and the main aim of an ACLR is to restore this native function (Diermeier et al., 2020). Despite this, studies reported tibial translation sparingly compared with rotational kinematics, meaning the restoration of anterior translation constraint during exercise remains uncertain. The ACL is also a secondary restraint to internal-external tibial rotation, however this review found transverse plane rotations reported infrequently in comparison to sagittal plane rotations. These kinematic variables may provide insight into the efficacy of the reconstruction surgery and restoration of knee stability and thus could be used as a primary outcome measure of rehabilitation success. Furthermore, these changes to knee biomechanics are linked to alterations and misalignments in tibiofemoral joint contact, a potential risk factor in PTOA development (Dare and Rodeo, 2014), and reporting these data for rehabilitation exercise could assist researchers on determining appropriate exercise

Table 6
Peak knee forces and moments during squat exercise.

Study	Peak compressive force (BW)	Peak shear force (BW)	Peak flexion moment (Nm/kg)	Minimum flexion moment (Nm/kg)	Peak abduction moment (Nm/kg)	Peak adduction moment (Nm/kg)	Peak internal rotation moment (Nm/kg)	Peak external rotation moment (Nm/kg)
Almosnino 2013 (neutral stance; neutral feet)			1.38 (0.28)*	0.09 (0.05)*	−0.16 (0.13)*	0.09 (0.09)*	0.29 (0.11)*	0.05 (0.03)*
Almosnino 2013 (neutral stance; outturned feet)			1.59 (0.32)*	0.09 (0.08)*	−0.21 (0.16)*	0.05 (0.07)*	0.29 (0.10)*	0.05 (0.03)*
Almosnino 2013 (wide stance; neutral feet)			1.38 (0.31)*	0.09 (0.07)*	−0.21 (0.12)*	0.14 (0.10)*	0.33 (0.11)*	0.05 (0.03)*
Almosnino 2013 (wide stance; outturned feet)			1.44 (0.26)*	0.12 (0.07)*	−0.28 (0.15)*	0.12 (0.10)*	0.28 (0.09)*	0.05 (0.03)*
Han 2013 (neutral stance)	3.32 (0.62)	0.92 (0.29)	0.95 (0.32)	0.07 (0.1)	−0.2 (0.11)	0.08 (0.10)	0.03 (0.03)	−0.08 (0.04)
Han 2013 (valgus stance)	2.99 (0.89)	0.73 (0.2)	0.77 (0.31)	0.08 (0.09)	−0.3 (0.02)	0.02 (0.07)	0.03 (0.02)	−0.12 (0.06)
Han 2013 (varus stance)	3.12 (0.74)	1.04 (0.21)	0.82 (0.33)	0.03 (0.06)	−0.1 (0.07)	0.15 (0.07)	0.02 (0.03)	−0.07 (0.05)
Sigward 2018 (ACLR 3 months)			0.67 (0.24)**					
Sigward 2018 (ACLR 5 months)			0.78 (0.22)**					
Sigward 2018 (Contralateral 3 months)			1.08 (0.18)**					
Sigward 2018 (Contralateral 5 months)			1.11 (0.25)**					
Stensdotter 2024 (Healthy)			1.4*	−0.3*				
Stensdotter 2024 (ACLR)			1.4*	−0.2*				

Data reported as mean (standard deviation).
Moments from Han et al. (2013) converted from %BW.Ht.
* Derived from graph digitisation.
** Reported as knee extensor moment.

Table 7
Peak knee rotation angles during step-down exercise.

Study	Peak knee flexion (°)	Peak knee extension (°)	Peak knee abduction (°)	Peak knee adduction (°)	Peak internal rotation (°)	Peak external rotation (°)
Lewis 2015 (16 cm step)	72.8 (5.3)					
Lewis 2015 (24 cm step)	86.9 (8.3)					
Nicolas 2015	74.3 (1.4)	10.9 (1.3)	0.7 (2.1)	8.5 (2.0)	−7.6 (3.2)	−19.7 (3.0)
Thomas 2023 (lateral; left)	67.5 (5.9)					
Thomas 2023 (lateral; right)	62.9 (6.7)					
Werner 2021 (lateral)	56.0 (5.5)		−6.0 (5.2)	2.0 (3.3)	8.8 (6.6)	
Werner 2021 (forward)	63.1 (4.8)		−6.1 (5.1)	2.0 (3.7)	9.1 (6.4)	

Data reported as mean (standard deviation).

progression and the healing process of the patient.

Non-contact ACL injury typically occurs during single-leg landings, where a valgus collapse of the knee joint is observed (Krosshaug et al., 2007). The risk of ACL injury and reinjury therefore may be considered by researchers via the reporting of knee adduction data during exercise. During rehabilitation, single-leg squats and landings are often used to train athletes into low-risk landing strategies, however female athletes, who are at increased risk of ACL injury compared to males, show greater knee valgus during single-leg activities (Khuu and Lewis, 2019; Krosshaug et al., 2007). In the present systematic review, frontal plane knee rotations were reported more frequently during the single-leg squat exercise than transverse plane rotations, likely due to the link between knee adduction and ACL injury. This, however, does not explain the disparity in reporting knee adduction kinetics. The knee adduction moment is associated with the development, diagnosis, and severity of knee osteoarthritis (D'Souza et al., 2022), therefore reporting this measure during rehabilitation exercise for healthy individuals could provide normative values for ACLR patients to achieve to be at a lower PTOA risk.

The single-leg squat exercise was the only exercise in this review in which frontal and transverse plane kinematics were frequently reported relative to specific knee flexion angles (Table 3). These data may be of particular interest when designing rehabilitation protocols as they allow the ability to monitor changes in adduction and rotation at the knee during different stages of the squat cycle and guide appropriate limits to squat depth during rehabilitation. Therefore, providing this information for other exercises could be beneficial. The data was however variable with respect to both the magnitude and polarity of frontal and transverse plane values during single-leg squat. This may be related to the use of marker-based motion capture and its limited precision for small rotation angles, indicating the shortcomings in this data collection method for accurate measurements and consistency between clinical sites. Tibial translation was reported most frequently in the forward lunge, measured via dual-orthogonal fluoroscopy. Only one study (Sanford et al., 2016) chose to report tibial translation measured with marker-based methods. Marker-based motion capture is typically not used for translation measurement as large errors, potentially over 10 mm (Hume et al., 2018), are produced via skin movement artefact. While motion capture is typically more accessible than fluoroscopy or radiography techniques, the latter may be capable of providing more accurate estimations of knee kinematics. A previous review (Galvin et al., 2018) explored knee kinematics during squat and lunge motions in healthy participants and chose to exclude data derived from marker-based motion capture methods. While this previously published systematic review did find similar patterns of femoral posterior translation and tibial internal rotation occurring in deep flexion between exercises, they also reported contradictions and variations in results for the same exercise and kinematic variables, as well as a paucity of evidence in certain axes such as medial-lateral translation (Galvin et al., 2018). This may indicate, along with the results in the present review, that differences in kinematic and kinetic results are not only produced by differing motion capture techniques, but by inconsistencies in analysis techniques including anatomical reference frames (Galvin et al., 2018; Peters et al., 2010), differing marker sets (Collins et al., 2009), and analysis software differences (Hume et al., 2018). When motion capture and analysis techniques are compared, the lowest errors tend to be seen in flexion/extension angle (Collins et al., 2009; Hume et al., 2018), which may explain the reliance on flexion angle as a primary outcome measure in many studies.

Previous research has shown a change in anterior tibial translation exhibited in ACL-reconstructed patients during early-stage (< 6 weeks post-surgery) rehabilitation exercise compared to their uninjured limb (Tagesson et al., 2010), with the authors using their results to advocate for the progressive introduction of knee extension exercises post-ACLR. Further work by the same research group however found that improvements in anterior tibial translation during gait from 5.7 ± 1.7 mm pre-surgery to 4.8 ± 1.6 mm 5 weeks post-surgery, were reversed by 5 years post-surgery as translation in the reconstructed knee increased to 5.5 ± 1.4 mm in the ACLR knee, significantly higher than the uninjured leg (Tagesson et al., 2015). Future research should make a concerted effort to build on these results and report translations in the ACLR in later stage rehabilitation exercise (3–12 months post-surgery) and throughout the rehabilitation timeline to help develop appropriate exercise progression guidelines. In addition, excessive anterior tibial translation may pose an issue for the post-ACLR patient by placing additional pressure on the medial meniscus to prevent translation (Lorbach et al., 2015) which may increase the risk of meniscal tears. If medial meniscus tears do occur, they can potentially trigger a mechanical and inflammatory pipeline to osteoarthritis development (Edd et al., 2015). On the other hand, timely ACLR, e.g. within 3 months of injury, is associated with lower meniscal tear risk (Korpershoek et al., 2020). This may be influential in demonstrating which ACLR patients are at greater risk of PTOA development, creating additional considerations for rehabilitation progression and for monitoring translation and tibial rotation kinematics during the rehabilitation process.

There are limitations of the present systematic review. The review reported data solely from bodyweight exercises. While this may address variations between studies in loading conditions and participant ability, this may not accurately reflect the nature of rehabilitation and further investigation of biomechanical alterations caused by progressive loading of exercise is needed. Further, the review was limited to closed kinetic chain exercises due to data availability. As discussed in the introduction, open kinetic chain exercises are often avoided in early ACLR rehabilitation due to lasting misconceptions around graft safety, and a balance of closed kinetic chain and open kinetic chain exercises should be prescribed in rehabilitation to enhance strengthening. However, given the reliance on force plates in many biomechanical studies, data detailing the kinematics and kinetics of open kinetic chain exercise is limited. Due to the variability of reporting and the quantity of observational studies, the decision was taken to not conduct meta-analyses. While this limits the ability to conclude biomechanical differences, small sample meta-analyses may introduce bias into conclusions and reduce the ability to interpret results without a large amount of caution. Notably, only 8 studies reported in this review included ACLR data and not all these studies reported data from healthy control subjects or the uninjured knees of their ACLR participants (Table 1). This lack of comparative data, paired with inconsistent reporting of biomechanical markers outside of knee flexion angle demonstrates the limitations regarding data synthesis, as well as the gap in information regarding the biomechanics of rehabilitation. Further, the inclusion criteria of the review are limited to English language studies, potentially excluding some relevant studies. In some cases, data was digitised from graphs due to values and standard deviations not being given in the text, introducing error into the reported values. Data in ACL deficient patients was excluded, although it may be useful for future reviews to consider the recovery of exercise kinematics pre- to post-surgery, as has been explored for gait kinematics.

5. Conclusion

In conclusion, current data reporting knee biomechanics during common rehabilitation exercise is highly variable in terms of data collection methods, variables reported, and magnitude and polarity of results. This highlights the need for future research to consider consistency and reproducibility in their reporting of kinematics and kinetics. The present review has also demonstrated a paucity in tibial translation and rotation data during rehabilitation exercise, despite the primary aim of ACLR to restore these kinematics. Knee adduction kinetics, which are associated with osteoarthritis development and progression, are similarly poorly reported. Additionally, the current available biomechanical data for individuals with ACLR overall is sparse for the exercises considered in this review. If gold standard rehabilitation protocols are to be developed, they should consider the kinematics and kinetics of the knee in the post-surgery patient, therefore further observational studies of individuals with ACLR performing rehabilitation exercise are needed.

CRediT authorship contribution statement

Zhané N. Murrell-Smith: Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Meernah Mohammed Alabdullah:** Writing – review & editing, Validation, Formal analysis, Data curation. **Fengtao Zhang:** Writing – review & editing, Validation, Formal analysis, Data curation. **Louise M. Jennings:** Writing – review & editing, Supervision, Conceptualization. **Sarah L. Astill:** Writing – review & editing, Supervision, Conceptualization. **Aiqin Liu:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clinbiomech.2025.106559.

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