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The Effect of Open- Versus Closed-Kinetic-Chain Exercises on Anterior Tibial Laxity, Strength, and Function Following Anterior Cruciate Ligament Reconstruction: A Systematic Review and Meta-analysis

Rupture of the anterior cruciate ligament (ACL) is one of the most common musculoskeletal injuries,[32] with a prevalence of 30 cases per 100 000 people in Australia[25] and up to 60 cases per 100 000 people in the United States[28] per year. The ACL provides significant mechanical stabilization to the knee joint by preventing excessive hyperextension, as well as tibial rotation and anterior tibial translation while in flexion.[24]

BACKGROUND: There is controversy surrounding the early use of open-kinetic-chain (OKC) quadriceps-strengthening exercises following anterior cruciate ligament reconstruction (ACLR) due to the belief that increased strain on the graft could cause damage.

OBJECTIVES: To determine whether OKC quadriceps exercises result in differences in anterior tibial laxity, strength, function, quality of life, or adverse events in the ACLR population, when compared to closed-kinetic-chain (CKC) quadriceps exercises.

METHODS: Seven electronic databases (MEDLINE, Embase, AMED, CINAHL, SPORTDiscus, PEDro, and the Cochrane Central Register of Controlled Trials) were searched through April 2017. A systematic review with meta-analysis was conducted on randomized controlled trials comparing OKC versus CKC exercises following ACLR. Outcomes of interest were tibial laxity, strength, and function. A methodological quality assessment of the included studies was completed, and the results were synthesized using meta-analysis and the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach.

RESULTS: Ten studies were included in the review. The meta-analysis demonstrated low- to moderate-quality evidence of no between-group differences in anterior tibial laxity, strength, or patient-reported function at any time point. Meta-analysis was unable to be performed for functional outcomes.

CONCLUSION: There was limited to moderate-quality evidence of no difference in anterior tibial laxity, strength, patient-reported function, or physical function with early or late introduction of OKC exercises in the ACLR population, when compared to CKC exercises, at all follow-up time points.

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The surgical management of an ACL rupture involves replacing the ruptured ligament with a graft.[22] Consideration of graft healing is required when designing anterior cruciate ligament reconstruction (ACLR) rehabilitation programs. During the first 6 to 12 weeks post ACLR, the graft can be vulnerable to fixation loosening and overstretching from excessive tensile loading due to early necrosis and graft-bone interface healing.[1,5,7,10,30,36] Hence, care should be taken with early tensile loading to prevent possible increased knee laxity, which may lead to knee functional instability.

Since the 1980s, the use of closed-kinetic-chain (CKC) over open-kinetic-chain (OKC) quadriceps exercises has been advocated in the early stages post ACLR.[17] The term *open kinetic chain* describes an exercise in which the foot is not in contact with a solid surface, whereas *closed kinetic chain* describes an exercise in which the

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foot is in contact with a solid surface.[11] Closed-kinetic-chain quadriceps exercises are considered less likely to overstrain ACL grafts due to biomechanical and in vivo studies indicating that they increase tibiofemoral joint compressive forces, activate hamstrings cocontraction, and reduce anterior tibial displacement, which occurs with an isolated OKC quadriceps contraction.[11] However, the proposed detrimental effects of OKC quadriceps-strengthening exercises have been called into question, as in vivo experimental data have shown that all but high-resistance knee extension results in similar levels of anterior-bundle ACL strain.[11,26] Clinical trials comparing OKC to CKC exercises would provide greater clarity regarding the safety of OKC quadriceps exercises.

Of particular interest is the outcome of knee laxity, as greater laxity has been associated with an increased rerupture rate and knee osteoarthritis post ACLR.[34] Clinical trials on this topic were investigated in 2 systematic reviews. One review reported on results where OKC quadriceps exercises were introduced at 6 to 12 weeks,[2] while the other was unclear regarding when the exercises were introduced.[25] Both reviews found no differences between OKC and CKC quadriceps exercise groups for the outcomes of laxity, pain, and function.[2,25] These conclusions conflict with recent guidelines, which recommend delaying OKC quadriceps exercises until 4 weeks post ACLR.[38] This inconsistency is confusing for a clinician looking for guidance, and may be in part due to previous systematic reviews[2,25] not adhering to current Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines[23] with regard to methods, data synthesis, and reporting of results.[13] Clearly, a systematic review using the PRISMA guidelines is required to synthesize current evidence comparing OKC and CKC quadriceps exercise prescription post ACLR.

The primary aim of this review was to determine whether OKC quadriceps exercises result in differences in anterior laxity, when compared to CKC exercises, at any time point following ACLR. The secondary aim was to determine whether there are differences in strength, function, quality of life, and adverse events with OKC quadriceps exercises when compared to CKC exercises at any time point.

METHODS

Protocol and Registration

This review was completed according to a predefined protocol, which was registered with the PROSPERO international prospective register of systematic reviews (registration number CRD42016033100).

Information Sources and Search Strategy

A systematic search of the following electronic databases was conducted on April 12, 2017: MEDLINE (via Ovid, from 1948), Embase (via Ovid, from 1947), AMED (via Ovid, from 1985), CINAHL (via EBSCO, from 1981), SPORTDiscus (via EBSCO, from 1985), PEDro, and the Cochrane Central Register of Controlled Trials.

Search terms used were based on 2 concepts: (1) ACLR and (2) OKC or CKC exercise. Synonyms within each concept were mapped to MeSH headings, where possible, or searched under title or abstract and combined with the "OR" Boolean operator. Concept 1 and 2 searches were combined with the "AND" Boolean operator. Searches were limited to English. There were no limits on publication period. See **APPENDIX A** (available at www.jospt.org) for the full strategy.

Eligibility Criteria

Studies were included if they were randomized controlled trials and fulfilled the following eligibility criteria: (1) participants who had ACLR; (2) interventions that compared OKC and CKC quadriceps exercises; and (3) outcomes that included anterior tibial laxity, lower-limb strength, function, or quality of life. Outcomes could be assessed at any time following surgery and the intervention.

Laxity was selected as the primary outcome measure. Arthrometry provides a measurement of the degree of anterior tibial displacement due to anteriorly directed force on the tibia on a fixed femur. It is valid as a dichotomous diagnostic test for laxity (2 mm of displacement when compared to the other side is the threshold).[3] This review limited measures of laxity to arthrometry.

Secondary outcome measures included quadriceps strength, function, and quality of life. Physical function is typically assessed using a battery of single-leg hop tests or self-report questionnaires. Hop tests replicate an at-risk activity for ACL rupture and include the single-leg hop and triple crossover hop.[35]

Patient-reported measures of function were limited to the Lysholm score and Hughston Clinic Questionnaire. Both have been validated in persons who have had ACLR.[4,20] The Lysholm score is scored out of 100,[4] and the Hughston Clinic Questionnaire is scored as a percentage.[31] In both, a higher score indicates better function.

Study Selection

Search results were imported into EndNote X7 reference management software (Clarivate Analytics, Philadelphia, PA). After removal of duplicates, titles and abstracts were independently screened for eligibility. Full texts of the remaining articles were then sourced and independently evaluated for inclusion. The screening process was performed by 2 reviewers (A.P. and E.L.). Any disagreements were resolved through discussion, or by a third reviewer (A.S.) making the final decision.

Data Extraction

Data were extracted using a predesigned Excel spreadsheet by 1 reviewer and checked by a second reviewer. Data extracted included study authors, year, design, participants, setting, location, inclusion criteria, exclusion criteria, interventions, outcome measures, and results. Means, SDs, and sample sizes were extracted to calculate effect sizes. When insufficient information was provided, attempts were made to contact authors.

Risk-of-Bias (Quality) Assessment in Included Studies

A risk-of-bias assessment of the included studies was completed by 2 reviewers (A.P. and E.L.) independently using the PEDro scale.[27] Discrepancies were settled either via consensus or by a third reviewer (A.S.) making the final decision. Risk of bias was considered when evaluating the quality of the body of evidence (see description below).

Data Synthesis

Data were grouped according to outcome and follow-up times for both early (less than 6 weeks) and late (more than 6 weeks) introduction of OKC exercises. Follow-up times were short term (less than 12 weeks), medium term (3 to 6 months), long term (6 to 12 months), and very long term (greater than 12 months).

Laxity was calculated as mean difference and reported in millimeters. Secondary outcomes of strength and function were reported as standardized mean difference (SMD), with SMD values of 0.2, 0.5, and 0.8 representing small, moderate, and large effect sizes, respectively.[8] Where sufficient data were available for 2 or more studies within each outcome, data were pooled in a meta-analysis (random-effects model) using Review Manager Version 5.3 software (The Nordic Cochrane Centre, Copenhagen, Denmark). Subgroup analyses were performed for graft type (patellar and hamstrings). Statistical heterogeneity was assessed using the I^2 statistic, where 25%, 50%, and 75% indicated low, moderate, and high levels of heterogeneity, respectively.[18] Where meta-analysis was not possible, a narrative description of the results was completed.

As an additional analysis of clinically meaningful differences between groups, the number of participants who would be considered clinically lax (having laxity of greater than 2 mm on the side of the ACLR compared to opposite side)[3,12] in each exercise group was estimated using *z* scores and reported as mean ± SD number of participants.[39] Risk ratio and 95% confidence interval (CI) were calculated for each relevant study to determine whether OKC groups were more at risk of being clinically lax than the CKC groups. Where risk ratios could be determined from 2 homogeneous studies, data were combined in a meta-analysis with a random-effects model.

Strength of the body of evidence for all meta-analyses was assessed using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach.[13] Each meta-analysis was graded using the following predefined criteria: (1) risk of bias (downgraded if PEDro scale score was less than 6), (2) inconsistency (downgraded if I^2 score was 25% or more), (3) precision (downgraded if the CIs crossed the clinical-decision threshold between recommending and not recommending an intervention).[15] The clinical-decision threshold for function and strength outcomes was a moderate effect (0.5) for function or strength outcomes. For anterior laxity, the clinical-decision threshold was set at 2 mm, which has been previously used as an indication of a clinically important effect.[3,12] For risk ratios, a 2-fold change in risk (an increase of greater than 2 units or a decrease of less than 0.5 units) indicated clinically meaningful difference between groups; and (4) directness (downgraded if different outcome measures were used across studies). All studies commenced with a score of 4, as all were randomized controlled studies. Overall evidence quality was graded as high, moderate, low, or very low. Quality of evidence was described as "limited" when only 1 study was available.

RESULTS

THE INITIAL SEARCH FOUND 1442 articles (**FIGURE 1**). After removing duplicates and screening the titles and abstracts, 31 full-text articles were reviewed for eligibility. Ten studies were eligible for the review.[6,9,12,16,19,21,29,30,33,37] One study[30] had insufficient data to be included in the meta-analysis.

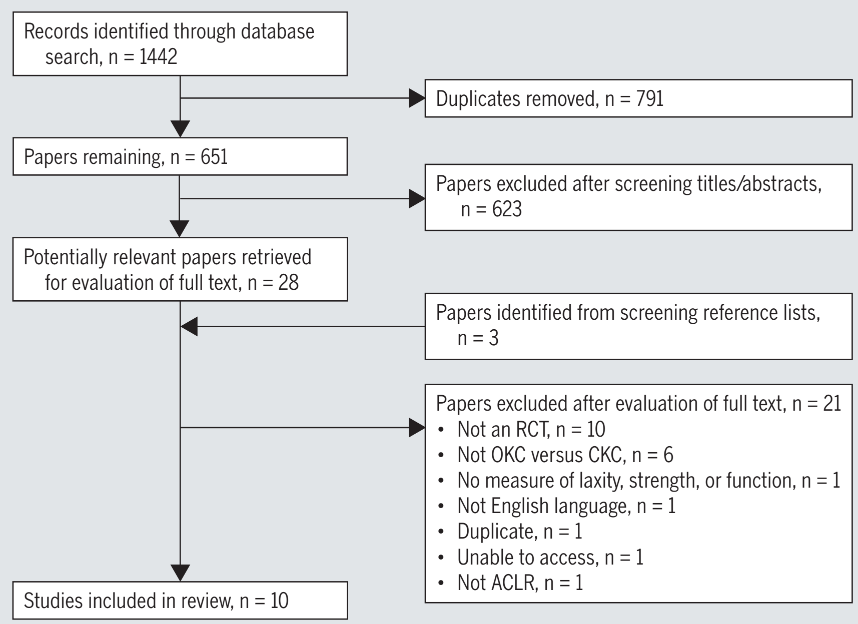


FIGURE 1. Flow of studies through the review. Abbreviations: ACLR, anterior cruciate ligament reconstruction; CKC, closed kinetic chain; OKC, open kinetic chain; RCT, randomized controlled trial.

Study Characteristics

A total of 485 participants were included in the review (**TABLE 1**). Mean age ranged from 24 to 33 years, and most participants were men (74%). There were 5 patellar graft studies[6,9,19,29,30] and 2 hamstrings graft studies.[12,37] Two studies[16,33] included both graft types and 1[21] did not specify.

The exercise protocols that made up the interventions varied between studies (**APPENDIX B**, available at www.jospt.org). Studies either compared CKC exercises solely to OKC exercises (7 studies[6,9,19,21,30,33,37]) or to a combination of OKC and CKC exercises (3 studies[12,16,29]). In 6 studies, OKC exercises or combined OKC and CKC exercises were introduced early, at less than 6 weeks following ACLR.[6,12,16,19,30,37] In 4 studies, they were introduced later, at more than 6 weeks following ACLR.[9,21,29,33]

Risk of Bias

Risk-of-bias assessment found PEDro scale scores ranging from 3 to 8, with a mean score of 5.5 (**TABLE 2**). Most common limitations were lack of therapist and participant blinding (all studies), lack of assessor blinding (5 studies), and omission of intention-to-treat analysis (8 studies).

Laxity

Side-to-side differences between anterior tibial laxity in the healthy leg and that in the ACLR leg were measured in millimeters using arthrometry, with different measurement tools and variable forces

TABLE 1 Study Characteristics, Outcome Measures, and Results

Study	Population	Outcome Measures and Follow-up Time Points	Results
Bynum et al[6]	OKC: n = 47 (45 men); mean age, 26 y CKC: n = 43 (43 men); mean age, 27 y Patellar graft OKC exercises commenced at 3 wk	Laxity: KT-1000 arthrometer (20 lb and maximum) Function: Lysholm score Follow-up: 3, 6, 9, and 12 mo Results only reported at 12 mo	Laxity KT-1000 (20 lb): MD, 1.10 mm; *P* = .057 favoring CKC KT-1000 (maximum): MD, 1.7 mm; *P* = .018 favoring CKC Function Lysholm score: MD, –2.00; *P* = .55 favoring CKC
Donatelli et al[9]	OKC: n = 11 (4 men); mean age, 31.2 y CKC (isokinetic machine): n = 11 (5 men); mean age, 32.6 y Patellar graft OKC exercises commenced at 6 to 24 mo	Strength: knee extension using MERAC isokinetic device (joint moved through 90% of range to determine torque) Function: single-leg hop for distance, triple crossover hop for distance Follow-up: 6 wk	Quadriceps strength Knee extension: MD, 21.63 Nm (95% CI: –10.55, 53.81 Nm); *P* = .19 favoring OKC Function Triple crossover hop: MD, 5.24 cm (95% CI: –18.79, 29.27 cm); *P* = .67 favoring OKC Single-leg hop for distance: MD, –4.67 cm (95% CI: –14.87, 5.53 cm); *P* = .37 favoring CKC
Fukuda et al[12]	Early OKC: n = 23 (16 men); mean age, 26.5 y Late OKC: n = 22 (13 men); mean age, 23.9 y Hamstrings graft OKC exercises started at 4 wk (early start) and 12 wk (late start)	Laxity: Rolimeter device, with the knee in 25° of flexion Function: single-leg hop test, triple crossover hop, Lysholm score Strength: isometric quadriceps Follow-up: 12 wk, 19 wk, 25 wk, 17 mo	Laxity 12 wk: MD, 0.10 mm (95% CI: –1.13, 1.33 mm); *P* = .87 favoring CKC 19 wk: MD, 0.20 mm (95% CI: –0.91, 1.31 mm); *P* = .72 favoring CKC 25 wk: MD, 0.00 mm (95% CI: –1.06, 1.06 mm); *P* = 1.00 17 mo: MD, –0.80 mm (95% CI: –1.87, 0.27 mm); *P* = .14 favoring OKC Function Lysholm score 12 wk: MD, –1.00 (95% CI: –6.53, 4.53); *P* = .72 favoring CKC 19 wk: MD, 0.60 (95% CI: –2.61, 3.81); *P* = .71 favoring OKC 25 wk: MD, 1.50 (95% CI: –4.81, 7.81); *P* = .64 favoring OKC 17 mo: MD, –2.50 (95% CI: –5.65, 0.65); *P* = .12 favoring CKC Triple crossover hop 12 wk: MD, 2.60 cm (95% CI: –5.85, 11.05 cm); *P* = .55 favoring OKC 19 wk: MD, 3.40 cm (95% CI: –3.25, 10.05 cm); *P* = .32 favoring OKC 25 wk: MD, 1.50 cm (95% CI: –3.17, 6.17 cm); *P* = .53 favoring OKC 17 mo: MD, 2.60 cm (95% CI: –2.40, 7.60 cm); *P* = .31 favoring OKC Single-leg hop 12 wk: MD, 3.10 cm (95% CI: –6.69, 12.89 cm); *P* = .53 favoring OKC 19 wk: MD, 0.60 cm (95% CI: –5.49, 6.69 cm); *P* = .85 favoring OKC 25 wk: MD, –2.60 cm (95% CI: –7.51, 2.31 cm); *P* = .30 favoring CKC 17 mo: MD, 1.60 cm (95% CI: –3.21, 6.41 cm); *P* = .51 favoring CKC Quadriceps strength* 12 wk: MD, –0.40 (95% CI: –10.23, 9.43); *P* = .94 favoring CKC 19 wk: MD, 4.80 (95% CI: –3.65, 13.25); *P* = .27 favoring OKC 25 wk: MD, 4.60 (95% CI: –2.92, 12.12); *P* = .23 favoring OKC 17 mo: MD, 4.60 (95% CI: –1.92, 11.12); *P* = .17 favoring OKC

Table continues on page 556.

TABLE 1 Study Characteristics, Outcome Measures, and Results (continued)

Study	Population	Outcome Measures and Follow-up Time Points	Results
Heijne and Werner[16]	Early OKC (patellar graft): n = 19 (11 men); mean age, 31 y Late OKC (patellar graft): n = 15 (11 men); mean age, 27 y Early OKC (hamstrings graft): n = 17 (7 men); mean age, 30 y Late OKC (hamstrings graft): n = 17 (7 men); mean age, 31 y OKC exercises started at 4 wk (early start) and 12 wk (late start)	Laxity: KT-1000 arthrometer, with the knee in 20° of flexion Strength: Kin-Com dynamometer (quadriceps muscle torque) Follow-up: 3, 5, and 7 mo	Laxity Hamstrings graft 3 mo: MD, 1.40 mm (95% CI: 0.34, 2.46 mm); *P* = .01 favoring CKC 5 mo: MD, 1.20 mm (95% CI: 0.11, 2.29 mm); *P* = .03 favoring CKC 7 mo: MD, 1.10 mm (95% CI: –0.06, 2.26 mm); *P* = .06 favoring CKC Patellar graft 3 mo: MD, –0.10 mm (95% CI: –1.09, 0.89 mm); *P* = .84 favoring OKC 5 mo: MD, 0.30 mm (95% CI: –0.82, 1.42 mm); *P* = .60 favoring CKC 7 mo: MD, 0.00 mm (95% CI: –1.06, 1.06 mm); *P* = 1.00 Quadriceps strength Hamstrings graft 3 mo: MD, –0.06 Nm (95% CI: –0.17, 0.05 Nm); *P* = .3 favoring CKC 5 mo: MD, 0.02 Nm (95% CI: –0.08, 0.12 Nm); *P* = .71 favoring OKC 7 mo: MD, 0.04 Nm (95% CI: –0.08, 0.16 Nm); *P* = .50 favoring OKC Patellar graft 3 mo: MD, –0.08 Nm (95% CI: –0.19, 0.03 Nm); *P* = .17 favoring CKC 5 mo: MD, –0.06 Nm (95% CI: –0.17, 0.05 Nm); *P* = .28 favoring CKC 7 mo: MD, –0.03 Nm (95% CI; –0.13, 0.07 Nm); *P* = .57 favoring CKC
Hooper et al[19]	OKC: n = 19 (16 men); mean age not reported CKC: n = 18 (13 men); mean age not reported Patellar graft OKC exercises commenced after 12-19 d	Function: Hughston Clinic Questionnaire Follow-up: 6 wk post surgery, 4 wk after commencing exercise programs	Patient-reported function Hughston Clinic Questionnaire: MD, 0.00 (95% CI: –0.64, 0.64); *P* = 1.00
Kang et al[21]	OKC: n = 18 (12 men); mean age, 29.9 y CKC: n = 18 (12 men); mean age, 29.0 y Unreported graft type OKC exercises commenced at 12 wk	Strength: isokinetic quadriceps: the knee joint moved from 0° to 90° at a speed of 60°/s in 4 forced repetitions to obtain peak torque Follow-up: 12 wk (24 wk post surgery)	Quadriceps strength MD, 20.70 Nm (95% CI: 2.32, 39.08 Nm); *P* = .03 favoring OKC
Mikkelsen et al[29]	OKC: n = 22 (17 men); mean age, 25.4 y CKC: n = 22 (17 men); mean age, 25.7 y Patellar graft OKC exercises commenced at 6 wk	Laxity: KT-1000 arthrometer, with the knee in 30° of flexion Strength: Kin-Com dynamometer (quadriceps muscle torque) Follow-up: 6 and 30 mo	Laxity 6 mo: MD, –0.50 mm (95% CI: –1.97, 0.97 mm); *P* = .5 favoring OKC Quadriceps strength 6 mo: MD, –10.10 Nm (95% CI: –37.71, 17.51 Nm); *P* = .47 favoring CKC
Morrissey et al[30]	OKC: n = 18 (17 men); mean age, 28 y CKC: n = 18 (12 men); mean age, 31 y Patellar graft OKC exercises commenced at 2 wk	Laxity: Knee Signature System arthrometer, with the knee in 25° of flexion (178 N) Follow-up: 4 wk	Laxity Injured-leg anterior drawer test OKC, 9.98 mm; CKC, 10.25 mm; *P* = .68 No further data supplied
Perry et al[33]	OKC: n = 24 (17 men); mean age, 33 y CKC: n = 25 (20 men); mean age, 33 y Hamstrings and patellar grafts OKC exercises commenced at 8 wk	Laxity: Knee Signature System arthrometer, with the knee in 25° of flexion (178 N) Function: Hughston Clinic Questionnaire, single-leg hop for distance, triple crossover hop test Follow-up: 14 wk	Laxity MD, 0.00 mm (95% CI: –1.58, 1.58 mm); *P* = 1.00 Function Hughston Clinic Questionnaire: MD, –3.00 (95% CI: –10.28, 4.28); *P* = .42 favoring CKC Triple crossover hop (percent of opposite side): MD, –0.02% (95% CI: –0.23%, 0.19%); *P* = .85 favoring CKC Single-leg horizontal jump (percent of opposite side): MD, 0.03% (95% CI: –0.09%, 0.15%); *P* = .62 favoring OKC
Uçar et al[37]	OKC: n = 28 (23 men); mean age, 28.1 y CKC: n = 30 (24 men); mean age, 27.4 y Hamstrings graft OKC exercises commenced on day 3	Function: Lysholm score Follow-up: 3 and 6 mo	Function Lysholm score: MD, –9.80 (95% CI: –14.34, –5.26); *P*≤.001 favoring CKC

Abbreviations: CI, confidence interval; CKC, closed kinetic chain; MD, mean difference; OKC, open kinetic chain.
**Units of measurement not reported.*

(ranging from 9 kg[6] to maximal manual force[6,16,29,30]).

Early Addition of OKC Exercises Three studies,[6,12,16] with a total sample of 203 participants (75% men), measured the effect on laxity of OKC exercises introduced earlier than 6 weeks post ACLR. Participants were predominantly men, except for the hamstrings graft arm of Heijne and Werner,[16] which included 59% women. One study[30] did not provide a measure of variability (SD or CI) for the effect estimate, so an effect size could not be calculated.

FIGURE 2 shows the between-group differences in laxity for each of the time points. Overall, calculated effect sizes show slight increased laxity in the OKC groups, particularly for the hamstrings graft. At each of the time points, the pooled difference was not statistically significant ($P>.05$). For all subgroups, the between-group differences and 95% CIs for pooled data across all time points were less than the 2-mm clinical laxity threshold.

Using the GRADE approach (**TABLE 3**), we found low- to moderate-quality evidence in 3 studies that suggested no between-group differences in laxity at any time point with early introduction of OKC exercises compared to CKC exercises.

The risk ratio of having clinically meaningful laxity was calculated at all time points (**FIGURE 3**). The meta-analysis demonstrates low- to moderate-quality evidence of no increase in the risk of having clinically meaningful laxity, regardless of the intervention, across all time points. Subgroup analyses identified no increased risk within graft types and no differences between subgroups.

Late Addition of OKC Exercises There was limited evidence of no between-group difference in laxity at medium- and long-term follow-up with the later introduction of OKC quadriceps exercises. Two studies[29,33] (n = 93, 76% men) measured the effect on laxity when OKC exercises were introduced after 6 weeks. Meta-analysis was not performed due to heterogeneity, as these studies measured follow-up at different time points. At medium-term follow-up, Perry et al[33] reported no difference between groups ($P>.05$) (**TABLE 1**). At long-term follow-up, Mikkelsen et al[29] reported no difference between groups ($P>.05$). The risk ratio of greater than 2-mm laxity between sides was 1.04 (95% CI: 0.60, 1.83) and 0.80 (95% CI: 0.39, 1.64) at medium- and long-term follow-up, respectively.

Strength

Quadriceps strength was measured using a dynamometer (isometric strength)[12,16,29] or isokinetic system.[9,21] Studies reported deficits in strength in terms of percent of the contralateral limb.

Early Addition of OKC Exercises Two studies,[12,16] with a total sample of 113 participants (58% men), measured the effect on strength with the early introduction of OKC exercises, prior to 6 weeks post ACLR. There was low- to moderate-quality evidence from 2 studies that demonstrated no between-group differences in strength outcomes at any time point after early introduction of OKC exercises compared to CKC exercises (**FIGURE 4**) ($P>.05$). This was consistent for each graft type.

Late Addition of OKC Exercises Three studies[9,21,29] (n = 102, 66% men) measured the effect on quadriceps strength when OKC exercises were introduced after 6 weeks. Graft type was not reported in 1 study,[21] and the remaining participants had a patellar graft.[9,29] Meta-analysis was not performed, as studies measured follow-up at different time points. There was limited evidence of no between-group difference at short-term follow-up (SMD, −0.21; 95% CI: −0.81, 0.38; $P>.05$)[29] or long-term follow-up (SMD, 0.54; 95% CI: −0.31, 1.39; $P>.05$)[9] (**TABLE 1**). At medium-term follow-up, Kang et al[21] reported statistically significant increased strength with OKC exercises (SMD, 0.72; 95% CI: 0.04, 1.40).

Patient-Reported Function

Five studies assessed patient-reported function using patient-completed questionnaires (Hughston Clinic Questionnaire[19,33] and Lysholm score[6,12,37]).

Early Addition of OKC Exercises Four studies,[6,12,19,37] with a total sample of 230 participants (84% men), measured the effect on patient-reported function when OKC exercises were introduced prior to 6 weeks. Three studies used the Lysholm

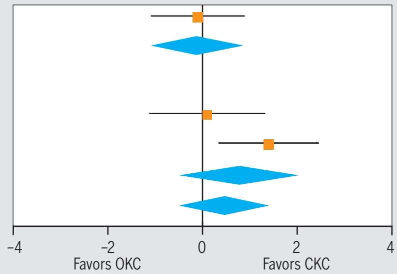
TABLE 2 Risk of Bias: PEDro Scale Score

	Item*										
Study	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Total†**
Bynum et al[6]	Y	Y	Y	N	N	Y	Y	N	Y	N	6
Fukuda et al[12]	Y	Y	Y	N	N	Y	Y	Y	Y	Y	8
Donatelli et al[9]	Y	N	Y	N	N	N	N	N	Y	Y	4
Heijne and Werner[16]	Y	Y	Y	N	N	Y	Y	N	Y	Y	7
Hooper et al[19]	Y	Y	Y	N	N	N	N	N	Y	Y	5
Kang et al[21]	Y	N	N	N	N	N	N	N	Y	Y	3
Mikkelsen et al[29]	Y	N	Y	N	N	N	Y	N	Y	Y	5
Morrissey et al[30]	Y	N	Y	N	N	Y	N	N	Y	N	4
Perry et al[33]	Y	N	Y	N	N	Y	Y	Y	Y	Y	7
Uçar et al[37]	Y	Y	Y	N	N	N	Y	N	Y	Y	6

Abbreviations: N, no; PEDro, Physiotherapy Evidence Database; Y, yes.
**1, Eligibility criteria; 2, Random allocation; 3, Concealed allocation; 4, Baseline comparability; 5, Blinding subjects; 6, Blinding therapists; 7, Blinding assessors; 8, Outcome data greater than 85%; 9, Intention to treat; 10, Between-group results; 11, Point measures/measures of variability.*
†The total 10-point PEDro scale score is the sum of items 2 through 11.

Laxity: Short Term

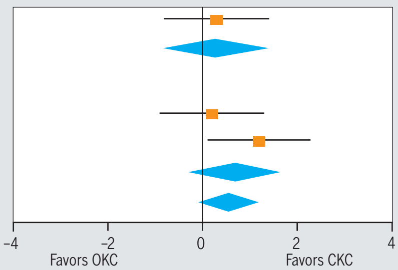
Subgroup/Study	OKC Mean ± SD	OKC Total, n	CKC Mean ± SD	CKC Total, n	Weight	MD IV, Random (95% CI)
Patellar graft						
Heijne and Werner[16]	1.1 ± 1.48	18	1.2 ± 1.42	15	36.1%	−0.10 (−1.09, 0.89)
Subtotal*		18		15	36.1%	−0.10 (−1.09, 0.89)
Hamstrings graft						
Fukuda et al[12]	2.7 ± 1.8	18	2.6 ± 1.9	17	29.8%	0.10 (−1.13, 1.33)
Heijne and Werner[16]	2.3 ± 1.41	17	0.9 ± 1.73	17	34.1%	1.40 (0.34, 2.46)
Subtotal†		35		34	63.9%	0.79 (−0.48, 2.06)
Total‡		53		49	100.0%	0.47 (−0.48, 1.42)



Abbreviations: CI, confidence interval; CKC, closed kinetic chain; IV, independent variable; MD, mean difference; OKC, open kinetic chain.
**Heterogeneity: not applicable. Test for overall effect: z = 0.20 (P = .84).*
†Heterogeneity: τ^2 = 0.50, χ^2 = 2.47, df = 1 (P = .12), I^2 = 59%. Test for overall effect: z = 1.21 (P = .22).
‡Heterogeneity: τ^2 = 0.40, χ^2 = 4.57, df = 2 (P = .10), I^2 = 56%. Test for overall effect: z = 0.97 (P = .33). Test for subgroup differences: χ^2 = 1.17, df = 1 (P = .28), I^2 = 14.2%.

Laxity: Medium Term

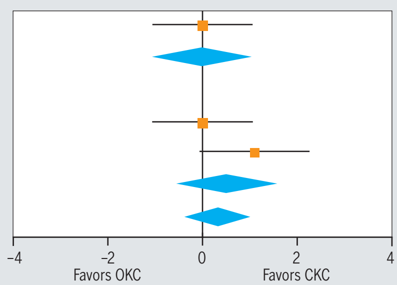
Subgroup/Study	OKC Mean ± SD	OKC Total, n	CKC Mean ± SD	CKC Total, n	Weight	MD IV, Random (95% CI)
Patellar graft						
Heijne and Werner[16]	1.6 ± 1.57	16	1.3 ± 1.43	12	32.7%	0.30 (−0.82, 1.42)
Subtotal*		16		12	32.7%	0.30 (−0.82, 1.42)
Hamstrings graft						
Fukuda et al[12]	2.9 ± 1.4	18	2.7 ± 1.9	17	33.1%	0.20 (−0.91, 1.31)
Heijne and Werner[16]	2.5 ± 1.35	14	1.3 ± 1.59	14	34.2%	1.20 (0.11, 2.29)
Subtotal†		32		31	67.3%	0.71 (−0.27, 1.69)
Total‡		48		43	100.0%	0.57 (−0.06, 1.21)



Abbreviations: CI, confidence interval; CKC, closed kinetic chain; IV, independent variable; MD, mean difference; OKC, open kinetic chain.
**Heterogeneity: not applicable. Test for overall effect: z = 0.53 (P = .60).*
†Heterogeneity: τ^2 = 0.18, χ^2 = 1.58, df = 1 (P = .21), I^2 = 37%. Test for overall effect: z = 1.41 (P = .16).
‡Heterogeneity: τ^2 = 0.00, χ^2 = 1.93, df = 2 (P = .38), I^2 = 0%. Test for overall effect: z = 1.76 (P = .08). Test for subgroup differences: χ^2 = 0.29, df = 1 (P = .59), I^2 = 0%.

Laxity: Long Term

Subgroup/Study	OKC Mean ± SD	OKC Total, n	CKC Mean ± SD	CKC Total, n	Weight	MD IV, Random (95% CI)
Patellar graft						
Heijne and Werner[16]	1.3 ± 1.57	16	1.3 ± 1.39	14	35.1%	0.00 (−1.06, 1.06)
Subtotal*		16		14	35.1%	0.00 (−1.06, 1.06)
Hamstrings graft						
Fukuda et al[12]	3.0 ± 1.5	18	3.0 ± 1.7	17	34.8%	0.00 (−1.06, 1.06)
Heijne and Werner[16]	2.3 ± 1.35	13	1.2 ± 1.66	13	30.1%	1.10 (−0.06, 2.26)
Subtotal†		31		30	64.9%	0.52 (−0.55, 1.60)
Total‡		47		44	100.0%	0.33 (−0.36, 1.03)



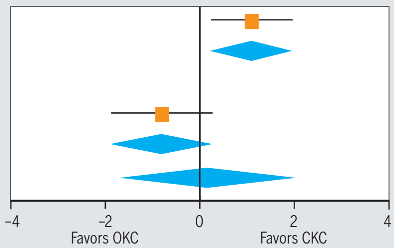
Abbreviations: CI, confidence interval; CKC, closed kinetic chain; IV, independent variable; MD, mean difference; OKC, open kinetic chain.
**Heterogeneity: not applicable. Test for overall effect: z = 0.00 (P = 1.00).*
†Heterogeneity: τ^2 = 0.28, χ^2 = 1.87, df = 1 (P = .17), I^2 = 47%. Test for overall effect: z = 0.95 (P = .34).
‡Heterogeneity: τ^2 = 0.07, χ^2 = 2.43, df = 2 (P = .30), I^2 = 18%. Test for overall effect: z = 0.93 (P = .35). Test for subgroup differences: χ^2 = 0.46, df = 1 (P = .50), I^2 = 0%.

Figure continues on page 559.

FIGURE 2. Forest plots for between-group differences: laxity.

Laxity: Very Long Term

Subgroup/Study	OKC Mean ± SD	OKC Total, n	CKC Mean ± SD	CKC Total, n	Weight	MD IV, Random (95% CI)
Patellar graft						
Bynum et al[6]	2.2 ± 2.17	47	1.1 ± 2.17	50	51.5%	1.10 (0.24, 1.96)
Subtotal*		47		50	51.5%	1.10 (0.24, 1.96)
Hamstrings graft						
Fukuda et al[12]	2.7 ± 1.4	18	3.5 ± 1.8	17	48.5%	−0.80 (−1.87, 0.27)
Subtotal†		18		17	48.5%	−0.80 (−1.87, 0.27)
Total‡		65		67	100.0%	0.18 (−1.68, 2.04)



Abbreviations: CI, confidence interval; CKC, closed kinetic chain; IV, independent variable; MD, mean difference; OKC, open kinetic chain.
**Heterogeneity: not applicable. Test for overall effect: z = 2.50 (P = .01).*
†Heterogeneity: not applicable. Test for overall effect: z = 1.46 (P = .14).
‡Heterogeneity: τ^2 = 1.56, χ^2 = 7.31, df = 1 (P = .007), I^2 = 86%. Test for overall effect: z = 0.19 (P = .85). Test for subgroup differences: χ^2 = 7.31, df = 1 (P = .007), I^2 = 86.3%.

FIGURE 2 (CONTINUED). Forest plots for between-group differences: laxity.

score[6,12,37] and 1 used the Hughston Clinic Questionnaire.[19] **FIGURE 5** shows between-group differences in patient-reported function for each time point. There was low- to moderate-quality evidence from 4 studies, suggesting no between-group differences (*P*>.05) in patient-reported functional outcomes at short-, medium-, and very long–term follow-up.

Late Addition of OKC Exercises There was limited evidence from 1 study[33] (n = 49, 76% men) that found no between-group differences in patient-reported functional outcomes (Hughston Clinic Questionnaire) at medium-term follow-up when OKC exercises were introduced after 6 weeks (SMD, −0.23; 95% CI: −0.79, 0.33) (**TABLE 1**).

Physical Function

Three studies assessed physical function (n = 116, 62% men) using the triple crossover hop[9,12,33] and the single-leg hop for distance.[9,12] No studies were pooled in a meta-analysis due to heterogeneity in tests, time points, or intervention (eg, early or late introduction).

Early Addition of OKC Exercises One study[12] (n = 45, 64% men) measured the effect on the triple crossover hop of introducing OKC exercises prior to 6 weeks post ACLR. Based on this limited evidence, there was no between-group difference in triple crossover hop performance at any of the 4 follow-up time points (SMD, 0.20; 95% CI: −0.47, 0.86; SMD, 0.33; 95% CI: −0.33, 1.00; SMD, 0.21; 95% CI: −0.46, 0.87; SMD, 0.34; 95% CI: −0.33, 1.01) (**TABLE 1**). The same study[12] reported single-leg hop for distance outcomes, with no significant difference at any time point (SMD, 0.20; 95% CI: −0.46, 0.87; SMD, 0.06; 95% CI: −0.60, 0.73; SMD, −0.34; 95% CI: −1.01, 0.33; SMD, 0.22; 95% CI: −0.45, 0.88) (**TABLE 1**).

Late Addition of OKC Exercises Two studies[9,33] (n = 71, 63% men) measured the effect on triple crossover hop performance when OKC exercises were introduced after 6 weeks. A meta-analysis was not performed, as these studies measured follow-up at different time points. There was no between-group difference at short-term (SMD, 0.18; 95% CI: −0.66, 1.01)[9] or medium-term (SMD, −0.09; 95% CI: −1.04, 0.86)[33] follow-up. The same 2 studies reported on single-leg hop for distance, with no significant difference between groups at short-term (SMD, −0.37; 95% CI: −1.21, 0.48)[9] or medium-term (SMD, 0.18; 95% CI: −0.55, 0.91)[33] follow-up.

Quality of Life

No studies used quality-of-life outcomes.

Adverse Events

Four studies reported on adverse events. One study[33] reported no adverse events. One study[6] reported 2 graft failures in the early OKC exercise group, and 1 study[12] reported 2 graft failures in each group. One study[16] reported the requirement for 2 follow-up arthroscopies, but it was not clear in which of the groups these adverse events occurred.

DISCUSSION

The primary aim of this review was to determine whether OKC exercises resulted in increased anterior laxity in the ACLR population, when compared to CKC exercises. Overall, results were drawn from 10 studies (485 participants) that measured differences in knee laxity, quadriceps strength, and function. Data from 5 of these 10 studies were able to be combined in a meta-analysis. When considering all graft types, there was low- to moderate-quality evidence from 3 studies suggesting that there were no between-group differences in laxity at any time point when OKC exercises were introduced earlier than 6 weeks post ACLR, compared to CKC exercises. There was limited evidence of no between-group differences in laxity at short-, medium-, and long-term follow-up

TABLE 3 QUALITY OF BODY OF EVIDENCE*

Outcome	Risk of Bias†	Consistency‡	Precision§	Directness‖	Total¶	Score
Laxity						
OKC before 6 wk						
Both graft types						
Short term	0	–1	0	–1	2	Low
Medium term	0	0	0	–1	3	Moderate
Long term	0	0	0	–1	3	Moderate
Very long term	0	–1	0	–1	2	Low
Hamstrings graft						
Short term	0	–1	–1	–1	1	Very low
Medium term	0	–1	0	–1	2	Low
Long term	0	–1	0	–1	2	Low
Laxity: risk ratio						
OKC before 6 wk						
Both graft types						
Short term	0	–1	–1	–1	1	Very low
Medium term	0	0	0	–1	3	Moderate
Long term	0	0	–1	–1	2	Low
Very long term	0	–1	–1	–1	1	Very low
Hamstrings graft						
Short term	0	–1	–1	–1	1	Very low
Medium term	0	0	0	–1	3	Moderate
Long term	0	–1	0	–1	2	Low
Strength						
OKC before 6 wk						
Both graft types						
Short term	0	0	–1	–1	2	Low
Medium term	0	0	0	–1	3	Moderate
Long term	0	0	–1	–1	2	Low
Hamstrings graft						
Short term	0	0	–1	–1	2	Low
Medium term	0	0	–1	–1	2	Low
Long term	0	0	–1	–1	2	Low
Patient-reported function						
OKC before 6 wk						
Both graft types						
Short term	0	0	0	–1	3	Moderate
Medium term	0	–1	–1	0	2	Low
Very long term	0	0	–1	0	3	Moderate
Hamstrings graft						
Short term	0	0	–1	0	3	Moderate
Medium term	0	–1	–1	0	2	Low

Abbreviations: OKC, open kinetic chain; PEDro, Physiotherapy Evidence Database.
**Using the Grading of Recommendations Assessment, Development and Evaluation approach.*
†Risk of bias was downgraded if the PEDro scale score was less than 6.
‡Consistency was downgraded if the I^2 statistic was 0.25 or greater.
§Precision was downgraded if the confidence intervals crossed the clinical-decision threshold between recommending and not recommending an intervention.
‖Directness was downgraded if different outcome measures were used.
¶All commenced with a score of 4, as all studies were randomized controlled studies.

with the introduction of OKC exercises after 6 weeks.

These pooled results do not mean that any OKC quadriceps exercises can be used in patients following ACLR, regardless of graft type. These studies adhered to specific exercise protocols, and there seemed to be a different response to the protocols depending on the graft type. Patellar grafts appeared to be less vulnerable to the early introduction of OKC quadriceps-strengthening exercises. Three trials, in which the ACLRs were completed using patellar grafts,[6,16,30] introduced OKC exercises before 6 weeks post surgery. These trials varied in training protocol, introducing OKC exercises at 2 weeks,[30] 3 weeks,[6] or 4 weeks.[16] The rate of progression to full extension and dosage used also varied among these trials. Regardless of these differences in protocols, no differences in laxity were found. This was consistent with 2 other studies, which commenced OKC exercises between 6 and 12 weeks and found no increases in laxity for the OKC exercise group.[29,33] In contrast, results were inconsistent in studies that used hamstrings grafts for ACLR.[12,16,33,37] Heijne and Werner[16] found significantly greater laxity ($P<.05$) in OKC compared to CKC exercises, whereas Fukuda et al[12] found no such difference.

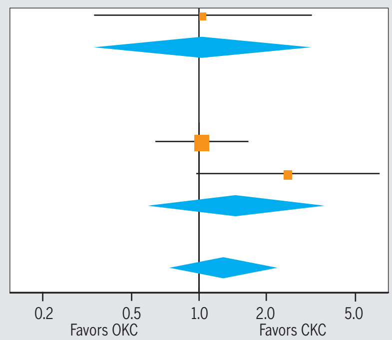
This apparent inconsistency between trials may be explained by the different protocols used. Fukuda et al[12] used a supervised OKC exercise program, commencing at 4 weeks post ACLR. In that trial,[12] the knee was mechanically locked in 45° to 90° of knee flexion until the 12-week postsurgery mark. Heijne and Werner[16] also began OKC exercises at 4 weeks; however, there was a quicker progression of knee extension range used during the exercises, with full knee extension started at 6 weeks. It is possible that this earlier increase in OKC quadriceps exercise range of extension might have contributed to the increased laxity of the ACL. These results suggest that there may be a specific range in which the OKC exercises are performed that is potentially safer for hamstrings grafts. This is consistent with basic science research, which demonstrates that ACL strain is minimal (0.0% peak strain) when OKC quadriceps contractions are performed at 60° to 90° of knee flexion.[11,26]

When considering the differences between studies, it should be kept in mind that Heijne and Werner[16] found that the average difference in laxity was 1.4 mm (CI: 0.34, 2.46 mm), which is below the clinically meaningful threshold of 2 mm that has been associated with increased ACLR graft rerupture.[34] The higher CI (2.46 mm) exceeded the 2-mm threshold, which is indicative of low precision; hence, further research is required before making firm conclusions about the relative safety of the 2 hamstrings graft protocols.

This review's secondary aim was to determine whether there was a difference in strength and function between OKC and CKC exercises. Outcomes for quadriceps strength, patient-reported function, and specific physical function provided limited to moderate-quality evidence demonstrating no between-group differences at any time point with the introduction of OKC exercises before 6 weeks, when

Laxity Risk Ratio: Short Term

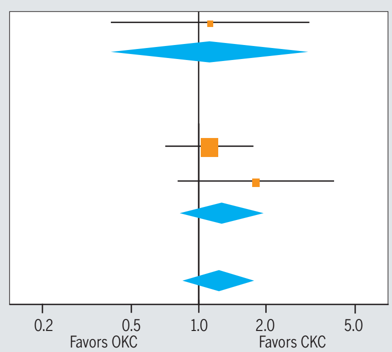
	OKC		CKC			
Subgroup/Study	**Events, n**	**Total, n**	**Events, n**	**Total, n**	**Weight**	**Risk Ratio M-H, Random (95% CI)**
Patellar graft						
Heijne and Werner[16]	5	18	4	15	19.6%	1.04 (0.34, 3.20)
Subtotal*		18		15	19.6%	1.04 (0.34, 3.20)
Total events	5		4			
Hamstrings graft						
Fukuda et al[12]	12	18	11	17	55.1%	1.03 (0.64, 1.66)
Heijne and Werner[16]	10	17	4	17	25.4%	2.50 (0.97, 6.43)
Subtotal†		35		34	80.4%	1.47 (0.59, 3.67)
Total events	22		15			
Total‡		53		49	100.0%	1.29 (0.74, 2.26)
Total events	27		19			



Abbreviations: CI, confidence interval; CKC, closed kinetic chain; M-H, Mantel-Haenszel; OKC, open kinetic chain.
**Heterogeneity: not applicable. Test for overall effect: z = 0.07 (P = .94).*
†*Heterogeneity:* $\tau^2 = 0.30$, $\chi^2 = 3.07$, *df* = 1 (*P* = .08), $I^2 = 67\%$. *Test for overall effect: z = 0.83 (P = .40).*
‡*Heterogeneity:* $\tau^2 = 0.09$, $\chi^2 = 2.99$, *df* = 2 (*P* = .22), $I^2 = 33\%$. *Test for overall effect: z = 0.90 (P = .37). Test for subgroup differences:* $\chi^2 = 0.22$, *df* = 1 (*P* = .64), $I^2 = 0\%$.

Laxity Risk Ratio: Medium Term

	OKC		CKC			
Subgroup/Study	**Events, n**	**Total, n**	**Events, n**	**Total, n**	**Weight**	**Risk Ratio M-H, Random (95% CI)**
Patellar graft						
Heijne and Werner[16]	6	16	4	12	13.0%	1.13 (0.41, 3.12)
Subtotal*		16		12	13.0%	1.13 (0.41, 3.12)
Total events	6		4			
Hamstrings graft						
Fukuda et al[12]	13	18	11	17	66.0%	1.12 (0.71, 1.76)
Heijne and Werner[16]	9	14	5	14	21.0%	1.80 (0.81, 4.02)
Subtotal†		32		31	87.0%	1.27 (0.82, 1.95)
Total events	22		16			
Total‡		48		43	100.0%	1.24 (0.85, 1.78)
Total events	28		20			



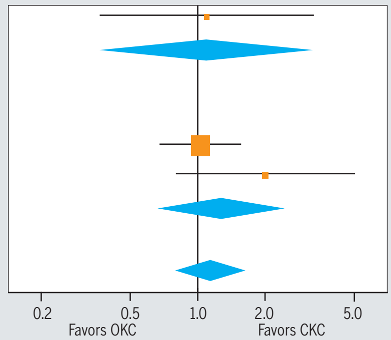
Abbreviations: CI, confidence interval; CKC, closed kinetic chain; M-H, Mantel-Haenszel; OKC, open kinetic chain.
**Heterogeneity: not applicable. Test for overall effect: z = 0.23 (P = .82).*
†*Heterogeneity:* $\tau^2 = 0.01$, $\chi^2 = 1.11$, *df* = 1 (*P* = .29), $I^2 = 10\%$. *Test for overall effect: z = 1.08 (P = .28).*
‡*Heterogeneity:* $\tau^2 = 0.00$, $\chi^2 = 1.11$, *df* = 2 (*P* = .58), $I^2 = 0\%$. *Test for overall effect: z = 1.12 (P = .26). Test for subgroup differences:* $\chi^2 = 0.04$, *df* = 1 (*P* = .83), $I^2 = 0\%$.

Figure continues on page 562.

FIGURE 3. Forest plots for between-group differences: laxity risk ratio. A risk ratio of less than 1 indicates a lower risk of clinically meaningful laxity in the OKC group; a risk ratio of greater than 1 indicates a lower risk of clinically meaningful laxity in the CKC group. Abbreviations: CKC, closed kinetic chain; OKC, open kinetic chain.

Laxity Risk Ratio: Long Term

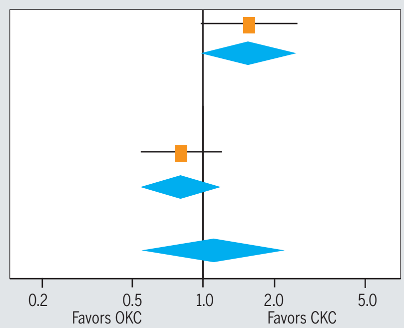
Subgroup/Study	OKC Events, n	OKC Total, n	CKC Events, n	CKC Total, n	Weight	Risk Ratio M-H, Random (95% CI)
Patellar graft						
Heijne and Werner[16]	5	16	4	14	10.7%	1.09 (0.36, 3.29)
Subtotal*		16		14	10.7%	1.09 (0.36, 3.29)
Total events	5		4			
Hamstrings graft						
Fukuda et al[12]	13	18	12	17	73.9%	1.02 (0.67, 1.56)
Heijne and Werner[16]	8	13	4	13	15.3%	2.00 (0.80, 5.03)
Subtotal†		31		30	89.3%	1.28 (0.66, 2.47)
Total events	21		16			
Total‡		47		44	100.0%	1.14 (0.80, 1.64)
Total events	26		20			



Abbreviations: CI, confidence interval; CKC, closed kinetic chain; M-H, Mantel-Haenszel; OKC, open kinetic chain.
**Heterogeneity: not applicable. Test for overall effect: z = 0.16 (P = .87).*
†Heterogeneity: τ^2 = 0.12, χ^2 = 1.92, df = 1 (P = .17), I^2 = 48%. Test for overall effect: z = 0.72 (P = .47).
‡Heterogeneity: τ^2 = 0.00, χ^2 = 1.84, df = 2 (P = .40), I^2 = 0%. Test for overall effect: z = 0.72 (P = .47). Test for subgroup differences: χ^2 = 0.06, df = 1 (P = .81), I^2 = 0%.

Laxity Risk Ratio: Very Long Term

Subgroup/Study	OKC Events, n	OKC Total, n	CKC Events, n	CKC Total, n	Weight	Risk Ratio M-H, Random (95% CI)
Patellar graft						
Bynum et al[6]	25	47	17	50	48.3%	1.56 (0.98, 2.50)
Subtotal*		47		50	48.3%	1.56 (0.98, 2.50)
Total events	25		17			
Hamstrings graft						
Fukuda et al[12]	12	18	14	17	51.7%	0.81 (0.55, 1.20)
Subtotal†		18		17	51.7%	0.81 (0.55, 1.20)
Total events	12		14			
Total‡		65		67	100.0%	1.11 (0.55, 2.23)
Total events	37		31			



Abbreviations: CI, confidence interval; CKC, closed kinetic chain; M-H, Mantel-Haenszel; OKC, open kinetic chain.
**Heterogeneity: not applicable. Test for overall effect: z = 1.87 (P = .06).*
†Heterogeneity: not applicable. Test for overall effect: z = 1.05 (P = .29).
‡Heterogeneity: τ^2 = 0.20, χ^2 = 5.17, df = 1 (P = .02), I^2 = 81%. Test for overall effect: z = 0.30 (P = .76). Test for subgroup differences: χ^2 = 4.43, df = 1 (P = .04), I^2 = 77.4%.

FIGURE 3 (CONTINUED). Forest plots for between-group differences: laxity risk ratio. A risk ratio of less than 1 indicates a lower risk of clinically meaningful laxity in the OKC group; a risk ratio of greater than 1 indicates a lower risk of clinically meaningful laxity in the CKC group. Abbreviations: CKC, closed kinetic chain; OKC, open kinetic chain.

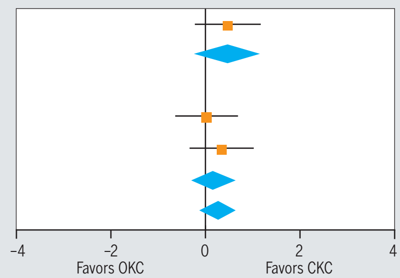
compared to CKC exercises. There was limited evidence (no meta-analysis) of no between-group differences in quadriceps strength, patient-reported function, and physical function outcomes with the late introduction of OKC exercises, compared to CKC exercises, at various time points.

The early introduction of OKC quadriceps exercises did not appear to offer additional significant benefits in function and strength for the average patient post ACLR; therefore, this early introduction is questionable, especially in patients with a hamstrings graft. However, there are individual situations in which the early introduction of OKC quadriceps exercises may be justified, as muscle strengthening should be functional and task specific.[11] Patient populations and functional testing from the included studies were not sport specific. It is possible that the potential benefits of early introduction of OKC exercises might, therefore, have been missed within specific sporting subgroups (eg, kicking in football).

This review should be viewed in light of its strengths and limitations. This was the first review to comprehensively compare OKC and CKC exercises in individuals who have had ACLR by consolidating the results of multiple independent studies in a meta-analysis for a range of outcomes. No previous review has included a meta-analysis that rated studies in terms of quality of evidence using a modified

Strength: Short Term

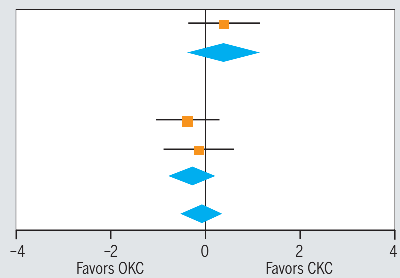
Subgroup/Study	OKC Mean ± SD	OKC Total, n	CKC Mean ± SD	CKC Total, n	Weight	SMD IV, Random (95% CI)
Patellar graft						
Heijne and Werner[16]	−0.55 ± 0.16	18	−0.63 ± 0.17	15	31.7%	0.47 (−0.22, 1.17)
Subtotal*		18		15	31.7%	0.47 (−0.22, 1.17)
Hamstrings graft						
Fukuda et al[12]	−81.2 ± 11	18	−81.60 ± 17.7	17	34.9%	0.03 (−0.64, 0.69)
Heijne and Werner[16]	−0.72 ± 0.17	17	−0.78 ± 0.17	17	33.4%	0.34 (−0.33, 1.02)
Subtotal†		35		34	68.3%	0.18 (−0.29, 0.66)
Total‡		53		49	100.0%	0.27 (−0.12, 0.67)



Abbreviations: CI, confidence interval; CKC, closed kinetic chain; IV, independent variable; OKC, open kinetic chain; SMD, standardized mean difference.
**Heterogeneity: not applicable. Test for overall effect: z = 1.34 (P = .18).*
†Heterogeneity: τ^2 = 0.00, χ^2 = 0.43, df = 1 (P = .51), I^2 = 0%. Test for overall effect: z = 0.75 (P = .45).
‡Heterogeneity: τ^2 = 0.00, χ^2 = 0.89, df = 2 (P = .64), I^2 = 0%. Test for overall effect: z = 1.37 (P = .17). Test for subgroup differences: χ^2 = 0.46, df = 1 (P = .50), I^2 = 0%.

Strength: Medium Term

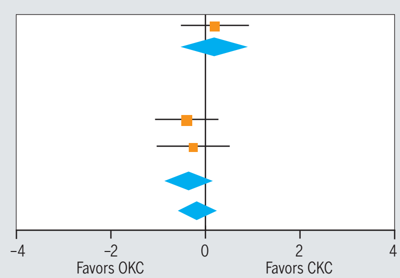
Subgroup/Study	OKC Mean ± SD	OKC Total, n	CKC Mean ± SD	CKC Total, n	Weight	SMD IV, Random (95% CI)
Patellar graft						
Heijne and Werner[16]	−0.64 ± 0.15	16	−0.70 ± 0.14	12	30.5%	0.40 (−0.36, 1.16)
Subtotal*		16		12	30.5%	0.40 (−0.36, 1.16)
Hamstrings graft						
Fukuda et al[12]	−91.80 ± 11.90	18	−87.00 ± 13.50	17	37.9%	−0.37 (−1.04, 0.30)
Heijne and Werner[16]	−0.82 ± 0.14	14	−0.80 ± 0.14	14	31.6%	−0.14 (−0.88, 0.60)
Subtotal†		32		31	69.5%	−0.27 (−0.76, 0.23)
Total‡		48		43	100.0%	−0.06 (−0.51, 0.38)



Abbreviations: CI, confidence interval; CKC, closed kinetic chain; IV, independent variable; OKC, open kinetic chain; SMD, standardized mean difference.
**Heterogeneity: not applicable. Test for overall effect: z = 1.03 (P = .30).*
†Heterogeneity: τ^2 = 0.00, χ^2 = 0.20, df = 1 (P = .65), I^2 = 0%. Test for overall effect: z = 1.05 (P = .29).
‡Heterogeneity: τ^2 = 0.02, χ^2 = 2.28, df = 2 (P = .32), I^2 = 12%. Test for overall effect: z = 0.27 (P = .78). Test for subgroup differences: χ^2 = 2.07, df = 1 (P = .15), I^2 = 51.8%.

Strength: Long Term

Subgroup/Study	OKC Mean ± SD	OKC Total, n	CKC Mean ± SD	CKC Total, n	Weight	SMD IV, Random (95% CI)
Patellar graft						
Heijne and Werner[16]	−0.75 ± 0.15	16	−0.78 ± 0.14	14	33.1%	0.20 (−0.52, 0.92)
Subtotal*		16		14	33.1%	0.20 (−0.52, 0.92)
Hamstrings graft						
Fukuda et al[12]	−94.10 ± 12.00	18	−89.50 ± 10.70	17	38.2%	−0.39 (−1.06, 0.28)
Heijne and Werner[16]	−0.84 ± 0.15	13	−0.80 ± 0.15	13	28.7%	−0.26 (−1.03, 0.51)
Subtotal†		31		30	66.9%	−0.34 (−0.84, 0.17)
Total‡		47		44	100.0%	−0.16 (−0.57, 0.26)

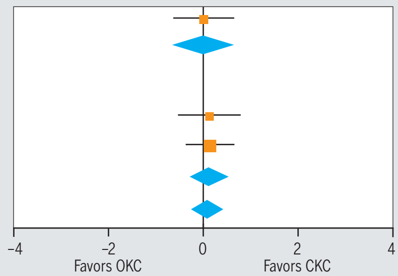


Abbreviations: CI, confidence interval; CKC, closed kinetic chain; IV, independent variable; OKC, open kinetic chain; SMD, standardized mean difference.
**Heterogeneity: not applicable. Test for overall effect: z = 0.55 (P = .58).*
†Heterogeneity: τ^2 = 0.00, χ^2 = 0.07, df = 1 (P = .79), I^2 = 0%. Test for overall effect: z = 1.30 (P = .19).
‡Heterogeneity: τ^2 = 0.00, χ^2 = 1.50, df = 2 (P = .47), I^2 = 0%. Test for overall effect: z = 0.75 (P = .45). Test for subgroup differences: χ^2 = 1.43, df = 1 (P = .23), I^2 = 30.1%.

FIGURE 4. Forest plots for between-group differences: quadriceps strength.

Patient-Reported Function: Short Term

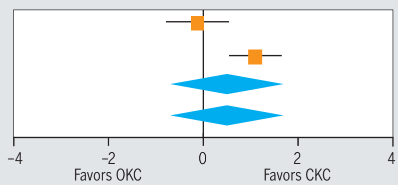
Subgroup/Study	OKC Mean ± SD	OKC Total, n	CKC Mean ± SD	CKC Total, n	Weight	SMD IV, Random (95% CI)
Patellar graft						
Hooper et al[19]	−61 ± 15	19	−61 ± 14	18	28.5%	0.00 (−0.64, 0.64)
Subtotal*		19		18	28.5%	0.00 (−0.64, 0.64)
Hamstrings graft						
Fukuda et al[12]	−88.3 ± 7.6	18	−89.3 ± 9.0	17	26.9%	0.12 (−0.55, 0.78)
Uçar et al[37]	−78.5 ± 14.5	28	−80.8 ± 19.1	30	44.6%	0.13 (−0.38, 0.65)
Subtotal†		46		47	71.5%	0.13 (−0.28, 0.53)
Total‡		65		65	100.0%	0.09 (−0.25, 0.44)



Abbreviations: CI, confidence interval; CKC, closed kinetic chain; IV, independent variable; OKC, open kinetic chain; SMD, standardized mean difference.
**Heterogeneity: not applicable. Test for overall effect: z = 0.00 (P = 1.00).*
†Heterogeneity: τ^2 = 0.00, χ^2 = 0.00, df = 1 (P = .97), I^2 = 0%. Test for overall effect: z = 0.61 (P = .54).
‡Heterogeneity: τ^2 = 0.00, χ^2 = 0.11, df = 2 (P = .95), I^2 = 0%. Test for overall effect: z = 0.52 (P = .60). Test for subgroup differences: χ^2 = 0.11, df = 1 (P = .74), I^2 = 0%.

Patient-Reported Function: Medium Term

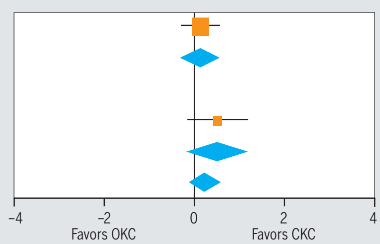
Subgroup/Study	OKC Mean ± SD	OKC Total, n	CKC Mean ± SD	CKC Total, n	Weight	SMD IV, Random (95% CI)
Hamstrings graft						
Fukuda et al[12]	−95.5 ± 5.1	18	−94.9 ± 4.6	17	48.8%	−0.12 (−0.78, 0.54)
Uçar et al[37]	−84.3 ± 9.1	28	−94.1 ± 8.5	30	51.2%	1.10 (0.54, 1.65)
Subtotal*		46		47	100.0%	0.50 (−0.69, 1.70)
Total†		46		47	100.0%	0.50 (−0.69, 1.70)



Abbreviations: CI, confidence interval; CKC, closed kinetic chain; IV, independent variable; OKC, open kinetic chain; SMD, standardized mean difference.
**Heterogeneity: τ^2 = 0.65, χ^2 = 7.64, df = 1 (P = .006), I^2 = 87%. Test for overall effect: z = 0.83 (P = .41).*
†Heterogeneity: τ^2 = 0.65, χ^2 = 7.64, df = 1 (P = .006), I^2 = 87%. Test for overall effect: z = 0.83 (P = .41). Test for subgroup differences: not applicable.

Patient-Reported Function: Very Long Term

Subgroup/Study	OKC Mean ± SD	OKC Total, n	CKC Mean ± SD	CKC Total, n	Weight	SMD IV, Random (95% CI)
Patellar graft						
Bynum et al[6]	−86 ± 15.35	41	−88 ± 15.35	41	70.8%	0.13 (−0.30, 0.56)
Subtotal*		41		41	70.8%	0.13 (−0.30, 0.56)
Hamstrings graft						
Fukuda et al[12]	−96.5 ± 4.7	18	−99 ± 4.8	17	29.2%	0.51 (−0.16, 1.19)
Subtotal†		18		17	29.2%	0.51 (−0.16, 1.19)
Total‡		59		58	100.0%	0.24 (−0.12, 0.61)



Abbreviations: CI, confidence interval; CKC, closed kinetic chain; IV, independent variable; OKC, open kinetic chain; SMD, standardized mean difference.
**Heterogeneity: not applicable. Test for overall effect: z = 0.58 (P = .56).*
†Heterogeneity: not applicable. Test for overall effect: z = 1.49 (P = .14).
‡Heterogeneity: τ^2 = 0.00, χ^2 = 0.89, df = 1 (P = .35), I^2 = 0%. Test for overall effect: z = 1.30 (P = .19). Test for subgroup differences: χ^2 = 0.89, df = 1 (P = .35), I^2 = 0%.

FIGURE 5. Forest plots for between-group differences: patient-reported function.

GRADE approach and considered statistical and clinical heterogeneity, CI width, and risk of bias across studies.

Despite these strengths, there are also limitations to consider. Overall, there were a small number of trials, with small sample sizes, that addressed this important question. These trials were heterogeneous in graft type, interventions, and outcomes assessed, which limited the ability to complete meta-analyses. This was particularly the case for functional outcomes such as hopping. Three studies evaluated the triple crossover hop and single-leg hop for distance[9,12,33]; however, the participants completed the test at 3 different times postoperatively, so a meta-analysis was not performed. Adverse events were poorly reported. Because the safety of early implementation of OKC exercises has been questioned, this is important information for clinicians. While laxity was used as a surrogate adverse outcome, rerupture rate and instability episodes are more meaningful for clinicians and their patients.

All the trials included in this review were of mixed populations; thus, the individual response of each sex to exercise type is uncertain. Most studies included a greater proportion of men; therefore, extrapolating these findings to women may not be valid. Women have been found to have increased knee laxity when hamstrings grafts are used post ACLR[14]; hence, there is a possibility of increased vulnerability to laxity with the early use of OKC exercises.

Further research is required in the form of high-quality, larger-scale randomized controlled trials comparing CKC and OKC quadriceps exercises immediately post ACLR. Research focusing on populations in whom hamstrings grafts are used is of particular interest, given the inconsistent findings from such studies in this review. Long-term physical functional outcomes and proper reporting of adverse events are required. In addition, the influence of sex, graft type, and exercise variables requires consideration when designing and reporting these trials. The optimum manipulation of exercise dosage and intensity to maximize strength gains should also be considered when designing interventions in future research.

CONCLUSION

There was limited to moderate evidence of no significant difference in clinically important anterior tibial laxity, strength, patient-reported function, or physical function with the early introduction of OKC exercises in the ACLR population, when compared to CKC exercises, at all follow-up time points. The hamstrings graft may potentially be more vulnerable to laxity than the patellar graft, but this conclusion is based on limited evidence.

KEY POINTS

FINDINGS: There was no significant difference in anterior tibial laxity, strength, patient-reported function, or physical function with the early or late introduction of open-kinetic-chain exercises in those who have had anterior cruciate ligament reconstruction, when compared to closed-kinetic-chain exercises, at all follow-up time points.

IMPLICATIONS: Due to the limited nature of the current evidence, a cautious approach is recommended with respect to the introduction of open-kinetic-chain quadriceps exercises in the first 12 weeks following anterior cruciate ligament reconstruction.

CAUTION: These findings were based on limited to moderate evidence, and further high-quality research is required before research can guide clinical practice.

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APPENDIX A

SEARCH STRATEGY

Ovid (MEDLINE, Embase, and AMED)

1. Anterior Cruciate Ligament.ab,kf,ti.
2. Anterior Cruciate Ligament/
3. acl.ab,kf,ti.
4. Knee/ or Knee Joint/ or Knee Injuries/ or knee.mp.
5. 1 OR 2 OR 3 OR 4
6. open chain.ab,kf,ti.
7. open kinetic chain.ab,kf,ti.
8. closed chain.ab,kf,ti.
9. closed kinetic chain.ab,kf,ti.
10. distal fixat$.ab,kf,ti.
11. foot fix$.ab,kf,ti.
12. 6 OR 7 OR 8 OR 9 OR 10 OR 11
13. 5 AND 12
14. Limit 13 to English language

EBSCO (CINAHL and SPORTDiscus)

1. (MH "Anterior Cruciate Ligament")
2. anterior cruciate ligament OR acl
3. (MH "Knee") OR "knee" OR (MH "Knee Injuries") OR (MH "Knee Surgery")
4. 1 OR 2 OR 3
5. open chain OR open kinetic chain OR closed chain OR closed kinetic chain OR distal fixat$ OR foot fix$
6. 4 AND 5

Limiter: Language—English

PEDro and Cochrane Central Register of Controlled Trials

1. Anterior cruciate ligament

APPENDIX B

INTERVENTION PROTOCOLS FOR INTERVENTION AND COMPARISON GROUPS

Study	Intervention Group	Comparison Group	Both Groups
Bynum et al[6]	0-3 wk: cocontraction isometrics, hamstrings concentric and eccentric isotonics 3 wk: SLR at 30° of flexion 6 wk: quadriceps isotonics (low weights), stationary bike (low resistance), proprioceptive training 8 wk: isokinetic hamstrings 12 wk: unrestricted quadriceps eccentric and concentric isotonics 16 wk: treadmill jogging, forward and backward running, SL squats 24 wk: isokinetic quadriceps; unrestricted resistance training 7-8 mo: progressive running and sport-specific tasks	0-8 wk: bilateral squats, seated leg presses, hamstrings curls 6 wk: stationary bike, proprioceptive training 8 wk: SL squat, forward/backward walking with cord resistance, slow jogging 12 wk: slow deep side-to-side jumping with cord resistance 16 wk: free-weight leg press and squat, sport-specific exercise with Thera-Band 24 wk: progressive running and sport-specific training	Postop surgery – discharge HKB, 0°-90° CPM, 0°-60° PROM, AAROM, AROM in brace 9 mo: noncutting, jumping, and pivoting sports 12 mo: unrestricted sports
Donatelli et al[9]	Group A (OKC) 90% maximum effort MERAC isokinetic device in NWB or OKC position Hip flexors and extensors, knee flexors and extensors, ankle dorsiflexors and plantar flexors	Group B (machine) 90% maximum effort Fitnet concentric device Hip extensors, knee extensors, ankle plantar flexors	6-wk duration 3 sessions per week
Fukuda et al[12]	Early OKC group OKC exercises commenced at 4 wk: seated knee extension with NMES (isokinetic, 45°-90°; isometric, 60°)	Late OKC See Both Groups column OKC exercises Commenced at 12 wk: seated knee extension with NMES (isokinetic, 0°-90°)	25-wk duration 3 sessions per week; approximately 70 sessions PWB at 2 wk post surgery, with 2 crutches Isometric CKC exercises for hip and knee strengthening started at the second postoperative week, followed by dynamic CKC exercises at the sixth postoperative week 1 wk: PROM extension/flexion, patellar mobilizations 2 wk: bike core, strength (hip, calf, squat), leg press, balance 3 wk: FWB without aid; AROM flexion 5-7 wk: increase ROM in leg press, bridges, step-ups/-downs, SL sit-to-stand, trampoline 8-9 wk: SL HR, increase ROM in leg press, hamstrings curl 10-11 wk: straight-line running, hip strength with Thera-Band, SL trampoline, DL jumping 4 mo: SL squats, SL jumping, lateral shuttle runs, seated knee extension 5-6 mo: continued plyometric and agility training, pivoting, sport-specific training
Heijne and Werner[16]	Patellar and hamstrings grafts OKC 4-wk group (hamstrings, n = 4; patellar, n = 4) 4 wk: knee extension, 90°-40° 5 wk: knee extension, 90°-20° 6 wk: knee extension, 90°-0° 7 wk: knee extension with resistance	Patellar tendon and hamstrings grafts OKC at 12 wk (hamstrings, n = 12; patellar, n = 12) Immediately commence 0°-90° OKC exercises. No resistance for the first week See Both Groups column	All groups 0-2 wk: patellar mobilizations, PROM extension, AROM flexion/extension, gait, squats, HR 2-5 wk: bike, leg press and curl in machine 6-8 wk: AROM knee extension from 30° to 0°, step-ups/-downs, SL HR and sit-to-stand, lunges, DL trampoline 9-11 wk: jumping, SL trampoline, straight-line running 3-4 mo: OKC quadriceps full ROM, continue balance and plyometric drills 4-6 mo: running and cutting, acceleration/deceleration, sport-specific training

Table continues on page B3.

APPENDIX B

Study	Intervention Group	Comparison Group	Both Groups
Hooper et al[19]	OKC group Knee and hip extensor training with either ankle weights or machines designed for isolated resistance of this muscle group	CKC group Unilateral hip and knee extensor training with leg-press machine	4-wk duration 3 sessions per week, 3 sets of 20 repetitions (maximum) in each session Training ROM of hip and knee, 90°-0° Additional exercises not controlled Included hip adduction/hip abduction/knee flexors and stationary bike
Kang et al[21]	OKC group SLR, leg extension, leg curl	CKC group Squat, leg press, lunge	12-wk duration 30-min sessions, 3 sessions per week All exercises: 5 sets of 12 repetitions at 70% intensity of 1RM Stationary bike warm-up/cool-down
Mikkelsen et al[29]	OKC group (from week 6) 6 wk: isokinetic concentric/eccentric quadriceps within 90° to 40° of knee flexion, which over 6 wk was gradually increased to 90° to 10° of knee flexion. Continued these exercises throughout the rehabilitation period	See Both Groups column	0-2 wk: PROM extension, AROM flexion 2-6 wk: patellar mobilization, gait, CKC quadriceps/hamstrings, proprioception and balance, isokinetic hamstrings, bike 6-12 wk: stairs, skipping, slide-board skating 3-4 mo: straight-line jogging 4-6 mo: jogging and running on uneven surfaces, turns, cutting, acceleration/deceleration, sport-specific training
Morrissey et al[30]	Unilateral hip and knee extensor training in open chain, using either ankle weights or machines	Unilateral training of hip and knee extensors on a leg-press machine	4-wk duration 3 sessions per week Stationary bike, hip abductor and adductor strength, knee flexor strength
Perry et al[33]	Unilateral OKC knee extension with ankle weights or machine Hip extension with ankle weights Dosage: 1-3 wk, 3 × 20; 4-6 wk, 3 × 6; increase load when pain is less than 5	Unilateral hip/knee extension on leg press Dosage: 1-3 wk, 3 × 20; 4-6 wk, 3 × 6; increase load when pain is less than 5	Bike for 10 min; stretch hamstrings, quadriceps, iliotibial band, and calves; lunges; patellar, tibiofemoral, and soft tissue mobilization; proprioception, balance, and agility training; isotonic and ballistic hamstrings strength; step-ups; calf raises; interferential current; ice
Uçar et al[37]	Isometric quadriceps, flexor/extensor bench, isotonic quadriceps, long leg press on/off, knee flexion/extension stretching	Squatting lunges, standing weight shift, wall sits, 1-leg quadriceps dips, lateral step-ups	Jones bandage, elevation, and cold pack 24 h post surgery: standing and WBAT with crutches Days 3-7: ankle pumps, isometric quadriceps, SLR Days 7-15: knee PROM with CPM from 0° to 90°, ambulation with crutches (FWB) Days 15-30: if knee flexion is greater than 110°, then okay to walk quickly, run on smooth surface, ascend/descend stairs

Abbreviations: 1RM, 1-repetition maximum; AAROM, active assisted range of movement; AROM, active range of movement; CKC, closed kinetic chain; CPM, continuous passive motion; DL, double leg; FWB, full weight bearing; HKB, hinge knee brace; HR, heel raise; NMES, neuromuscular electrical stimulation; NWB, non–weight bearing; OKC, open kinetic chain; PROM, passive range of movement; PWB, partial weight bearing; ROM, range of movement; SL, single leg; SLR, straight leg raise; WBAT, weight bearing as tolerated.