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STRENGTH, RATE OF FORCE DEVELOPMENT, POWER AND REACTIVE STRENGTH IN ADULT MALE ATHLETIC POPULATIONS POST ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION - A SYSTEMATIC REVIEW AND META-ANALYSIS

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Abstract

Background: Residual deficits in athletic performance are common despite rehabilitation guidelines following anterior cruciate ligament reconstruction including criterion-based progressions to protect healing structures, ensure safe restoration of fundamental physical capacities, and guide appropriate return to sports activities. A synthesis of the available literature is warranted to examine the physical readiness to re-perform of athletic populations in the later stages of rehabilitation in comparison to healthy controls.
Objectives: To determine the level of strength, power, rate of force development, and reactive strength in adult males who are more than six months following anterior cruciate ligament reconstruction.

Methods: A systematic review of the literature was undertaken using the Medline, CINAHL and SPORTDiscus databases and the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. Studies including males only and assessed strength, power, rate of force development and reactive strength comparing performance to healthy controls were included. A meta analysis was also performed to compute standardized mean differences (SMD ± 95% confidence intervals), calculated using Hedge's g, and examine the effect of ACLR on these fundamental physical capacities.

Results: 2023 articles were identified, of which 14 articles with similar level of evidence and methodological quality met the inclusion criteria. The most commonly investigated and impaired physical capacity was quadriceps (g¼_0.89, 95% CI [-1.33,-0.44]) and hamstring strength (g¼_0.44, 95% CI [-0.78, -0.10]). Only one study investigated rate of force development and none measuring reactive strength met our eligibility criteria.

Conclusions: Pooled data showed moderate evidence indicating large and small negative deficits on knee peak extension and flexion, respectively, in male adults at more than 6 months post anterior cruciate ligament reconstruction. The magnitude of these differences are influenced by graft type and can be mitigated by targeted rehabilitation programs. Insufficient evidence is available in male adults following anterior cruciate ligament reconstruction to examine rate of force development and reactive strength.

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1. Introduction

The impact of anterior cruciate ligament (ACL) injuries can include a long absence from sports, lifelong financial, socioeconomic, and emotional burdens, reduced confidence in their knee and perceived self-efficacy, in addition to early development of osteoarthritis, risk of re-injury (graft rupture) and contralateral ACL injury (Ajuied et al., 2014; Culvenor et al., 2015; Czuppon, Racette, Klein, & Harris-Hayes, 2014; Engstrom, Forssblad, Johansson, & Tornkvist, 1990; Kyritsis, Bahr, Landreau, Miladi, & Witvrouw, 2016; Lai, Feller, & Webster, 2018; Larsen, Jensen, & Jensen, 1999; Losciale, Zdeb, Ledbetter, Reiman, & Sell, 2019; O'Connor, King, Richter, Webster, & Falvey, 2019). Significant deficits in muscle function have also commonly been reported following ACL reconstruction (ACLR). Specifically, reductions in quadriceps muscle cross-sectional area (CSA), tissue quality, strength, central activation ratio (CAR), and rate of torque development (RTD), which may persist for years after the completion of rehabilitation and RTS (Birchmeier, Lisee, Geers, & Kuenze, 2019; Curran, Lepley, & Palmieri-Smith, 2018; Garcia et al., 2020; Herrington, Ghulam, & Comfort, 2018; Jordan, Aagaard, & Herzog, 2017; Kline, Morgan, Johnson, Ireland, & Noehren, 2015; Lisee et al., 2019a; Palmieri-Smith & Lepley, 2015; Pua, Mentiplay, Clark, & Ho, 2017; Thomas, Lepley, Wojtys, McLean, & Palmieri-Smith, 2015; Ward et al., 2018). These impairments can have detrimental implications for athletes as the ability to express high power outputs is an important performance indicator (Haff & Stone, 2015), and force must be generated within specific time constraints. However, a synthesis of the literature to determine the magnitude of residual deficits in ACLR cohorts compared to healthy populations is needed. Recent systematic reviews and meta-analysis (Lisee et al., 2019b; Petersen, Taheri, Forkel, & Zantop, 2014) showed persistent strength deficits in the ACLR limb compared to controls. However, large heterogeneity was present in confounding variables such as gender, graft type and level of sports participation. Furthermore, a broader examination of pertinent physical qualities such as rate of force development (RFD) and reactive strength following ACLR is required to more clearly elucidate an athlete's state of readiness to re-perform and inform the content of reconditioning programs with the aim of reducing the risk of secondary injuries.

In athletic populations, research indicates that healthy athletes who can squat 2 x body mass express higher power outputs than their weaker counterparts in vertical and horizontal jumping activities (Haff & Nimphius, 2012). Furthermore, Case et al. (Case, Knudson, & Downey, 2020) showed that male football players displaying 1RM back squat (normalised to body mass) values below 2.2 were at higher risk for lower extremity injuries during the season in comparison to stronger individuals ($g = 0.86$). Specific strength qualities, such as maximal eccentric strength underpin an athlete's reactive-strength ability and allowan efficient storage and reutilisation of elastic energy during stretch-shortening cycle (SSC) activities (Beattie, Carson, Lyons, & Kenny, 2017; Suchomel et al., 2019). Greater eccentric strength, reactive strength, and leg stiffness, significantly correlate with a reduced metabolic cost of running and enhanced change of direction (COD) performance (Li, Newton, Shi, Sutton, & Ding, 2019; Maloney, Richards, Nixon, Harvey, & Fletcher, 2017). Furthermore, eccentric knee extensor and flexor strength exhibit large correlations ($r > -0.603$) with COD performance in female soccer players (Jones & Thomas, 2017) and male athletes ($r=-0.506$ and $r=-0.592$ for normalised isokinetic eccentric extension and flexion strength respectively) (Jones, Bampouras, & Marrin, 2009). That said, pivoting, cutting, landing, and jumping sports (e.g. soccer, basketball or rugby) also expose athletes to a high risk of sustaining an anterior cruciate ligament (ACL) injury (Lindanger, Strand, Molster, Solheim, & Inderhaug, 2019; Moses, Orchard, & Orchard, 2012; Silvers-Granelli, Bizzini, Arundale, Mandelbaum, & Snyder-Mackler, 2017). Thus, it seems prudent to determine an athlete's level of maximal and reactive strength in the later stages of rehabilitation to ensure they possess adequate physical capacity to safely and efficiently execute commonly performed sports skills. Higher knee extension strength limb symmetry indexes (LSI) have been associated with reduced rate of re-injury (Grindem, Snyder-Mackler, Moksnes, Engebretsen, & Risberg, 2016), and thus are commonly considered important RTS criteria. However, Ardern et al. (Ardern, Webster, Taylor, & Feller, 2011) found that these widely used RTS criteria were achieved also in cohorts with a relatively low rate of return to competitive sport, thus not being considered adequate enough to detect relevant factors for RTS success.

Due to observed time constraints in many sporting actions (e.g. COD) which limit the production of maximal force, RFD should also be assessed. Defined as the ability of the neuromuscular system to produce a high rate in the rise of muscle force in the first 30-250 ms (Taber, Bellon, Abbott, & Bingham, 2016), RFD is calculated as ΔForce/ΔTime, which is determined from the slope of the force time curve (generally between 0 and 250 ms) (Maffiuletti et al., 2016; Rodriguez-Rosell, Pareja-Blanco, Aagaard, & Gonzalez-Badillo, 2018). This performance characteristic is central to success in most power-based sporting events (Brazier, Maloney, Bishop, Read, & Turner, 2017). Impaired knee extension RTD has been reported following ACLR (Angelozzi et al., 2012; Pua et al., 2017), and is associated with decreased self-reported knee function (Angelozzi et al., 2012; Davis et al., 2017; Hsieh, Indelicato, Moser, Vandenborne, & Chmielewski, 2015). Normative values in RFD/RTD associated with readiness to RTS would represent a useful additional criteria to assess rehabilitation status and to plan the athletes return to more complex ballistic tasks. In addition, comparisons to healthy controls are warranted to determine the magnitude of observed deficits as an indicator of readiness to reperform.

Current evidence suggests that residual deficits in fundamental athletic qualities such as maximal strength and RFD are present following ACLR; however, a synthesis of the available literature to determine the effects of ACLR on these explosive strength qualities is currently unavailable. The aim of this systematic review and meta-analysis was to investigate the level of physical capacities such as strength, RFD, power and reactive strength in male adult athletic populations during the later stages (>6 months) of rehabilitation following ACLR compared to healthy, non-injured controls.

2. Methods

2.1. Protocol

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines were followed in the preparation, conduct, and reporting of this review (Liberati et al., 2009).

2.2. Eligibility criteria and information sources

The studies were selected according to PICOS framework (Participants, Intervention, Comparison, Outcome, and Study design) (Liberati et al., 2009). Controlled cohort studies investigating strength, RFD or reactive strength in adult males following ACLR were considered. They had to be published in peer-reviewed journals and written using English language between 2010 and April 2020. These dates were chosen after reviewing the conclusions from two systematic reviews (Narducci, Waltz, Gorski, Leppla, & Donaldson, 2011; Thomee et al., 2011) published in 2011, which analysed the clinical utility and predictive validity of functional performance tests after ACLR, and found a paucity of literature with regard to the critical elements that determine readiness to RTS. The examined population was male adults (>18 years) following ACLR with any graft type during the later stages of their rehabilitation (≥6 months post-surgery), with performance compared to matched controls. Studies assessing strength, RFD or reactive strength were considered. The outcome measures were the effect of ACLR on (1) strength; (2) RFD/power; (3) reactive strength.

2.3. Searches

A comprehensive literature search of three electronic databases (MEDLINE, SPORTDiscus and CINHAL) was conducted on April 14, 2020. The reference lists of articles found were also scanned. Two authors (LM and KP) developed a systematic search strategy following the PICOS framework (Liberati et al., 2009). The search strategy used is listed in Appendix 1. The keywords "strength" or "rate of force development" "or power" or "reactive strength" were combined with the Boolean operator "AND" for keywords pertinent to anterior cruciate ligament reconstruction (e.g. "ACLR", "ACL reconstruction").

2.4. Study selection

Two reviewers (LM and KP) independently screened titles and abstracts to identify relevant studies. Title and abstracts investigating ACLR adult male populations (≥18 years) with at least one group ≥6 months, which included the assessment of strength, RFD or reactive strength were considered. Full-text manuscripts of remaining eligible studies were evaluated for inclusion in this review. The additional inclusion criteria were: (1) presence of a control group; (2) patients with any ACLR graft type; (3) assessment of strength, RFD or reactive strength using dynamometers or force platforms.

Studies were excluded for the following reasons: (1) absence of a control group; (2) studies including patients <18 years; (3) patients with revision ACLR or bilateral ACL injury; (4) nonsurgical treatment of ACL injury; (5) inclusion of female patients; (6) no conventional assessment of strength (e.g. manual muscle testing), RFD or reactive strength.

2.5. Data extraction

Two authors (LM and KP) independently extracted data from the included studies. Disagreements with regard to the selection criteria were discussed and resolved by consensus including all four authors (LM, KP, PR and AT). Demographic details including population size, gender, age, graft type, time since surgery and rehabilitation status were recorded from each study. The following variables were extracted: strength, rate of force development/power and reactive strength.

2.6. Assessment of level of evidence, quality, risk of bias in individual studies and across studies

The level of evidence, methodological quality and risk of bias of each individual study was examined independently by two authors (LM and KP). The Oxford Centre for Evidence-Based Medicine (OCEBM) Levels of Evidence tool was used to assess the level of evidence and quality of research design for each included study, where level 1 indicates the highest category, and Level 5 the lowest. Study quality was examined using the modified Downs and Black scale, which is a reliable tool for cohort studies (Downs & Black, 1998). The highest total score for the modified version is 16. A score ≥12 is considered high quality; a score of 10 and 11 are moderate quality; and a score ≥9 is deemed low quality (Losciale et al., 2019). The methodological quality of the selected studies was assessed using the PEDro Scale, which considers the following characteristics: sequence generation, allocation concealment, blinding, incomplete outcome data, and selective outcome reporting.

A risk of bias assessment for each of the selected studies was conducted to identify the presence of any publication bias, selective data reporting, conflict of interest, time lag bias, location bias or funding sources.

2.7. Data synthesis

Due to the different data reporting of the outcomes measured in the included studies, effect sizes (Hedges'g) were calculated as the standardized mean difference (SMD) with mean ± SD and 95% confidence using ReviewManager Software (RevMan 5.3; Cochrane Collaboration, Oxford, UK). Data were analysed using the ACLR limb compared with the dominant limb of the control group when limbs were not matched. The Cohen scale was used to interpret pooled SMD, where 0.2 represents a small effect, 0.5 a moderate effect, and 0.8 a large effect. Heterogeneity between studies was evaluated through I (Ajuied et al., 2014) statistics, the Cochrane Chi square (χ (Ajuied et al., 2014)), and the between-study variance using the tau-square (τ (Ajuied et al., 2014)) at the 95% CI. The categorization to rate the level of heterogeneity was the following: I (Ajuied et al., 2014) = 0%, no heterogeneity; I (Ajuied et al., 2014) = 1-25%, low heterogeneity, not important; I (Ajuied et al., 2014) = 26%-50%, moderate heterogeneity; I (Ajuied et al., 2014) = 51%-75%, high heterogeneity, substantial; I (Ajuied et al., 2014) = 76%-100%, considerable heterogeneity (Higgins, Thompson, Deeks, & Altman, 2003). All studies containing variables eligible for meta-analysis were ordered in forest plots based on effect size. Subgroup analyses on graft types were conducted, where applicable (Schriger, Altman, Vetter, Heafner, & Moher, 2010). Levels of evidence (i.e. “strong”, “moderate”, “limited”, “very limited” or “no evidence”) were based on guidelines reported by van Tulder et al. (van Tulder, Furlan, Bombardier, & Bouter, 2003) and previous reviews with similar included study types (Hart et al., 2016; Kotsifaki, Korakakis, Whiteley, Van Rossom, & Jonkers, 2019), accounting for study quality and statistical homogeneity of the included studies in the data sets. Results are qualitatively and quantitatively synthesized and presented in three subgroups: 1) Strength; 2) Rate of force development and power; and 3) Reactive strength.

3. Results

3.1. Study selection/search results

The electronic search initially identified 2023 articles from the databases (3156 before duplicates were removed); 1808 were excluded after reviewing the titles and abstracts. The full-text versions of the remaining 215 studies were obtained, of which 202 were subsequently excluded. 13 studies fulfilled the eligibility criteria and were included in this systematic review and meta-analysis. One study meeting the inclusion criteria was published after the initial electronic search (Read, Michael Auliffe, Wilson, & Graham-Smith, 2020) and was subsequently included (Fig. 1). 12 of the included studies assessed strength, 2 measured single joint power contribution, 1 analysed RFD, and none evaluated reactive strength.

3.2. Study characteristics

Participants and study characteristics are summarized in Table 1. All studies included were controlled cohort trials. Eight studies analysed strength of knee extensor and flexors using isokinetic dynamometry (Almeida, Santos Silva, Pedrinelli, & Hernandez, 2018; Baltaci, Yilmaz, & Atay, 2012; Królikowska, Reichert, Czamara, & Krzemínska, 2019; Miles & King, 2019; Mohammadi et al., 2013; O’Malley et al., 2018; Welling, Benjaminse, Lemmink, Dingenen, & Gokeler, 2019; Xergia, Pappas, Zampeli, Georgiou, & Georgoulis, 2013). Two studies assessed knee extensor and flexor strength using a stabilized dynamometer (Holsgaard-Larsen, Jensen, Mortensen, & Aagaard, 2014; Norouzi, Esfandiarpour, Mehdizadeh, Yousefzadeh, & Parnianpour, 2019). One study investigated hip flexion strength with an isokinetic dynamometry (Mouzopoulos, Siebold, & Tzurbakis, 2015) and another measured hamstring strength with a custom made device employing uniaxial load cells (Timmins et al., 2016) One study measured single joint power during a CMJ (Castanharo et al., 2011) and the remaining study also assessed power and RFD in a CMJ (Read et al., 2020).

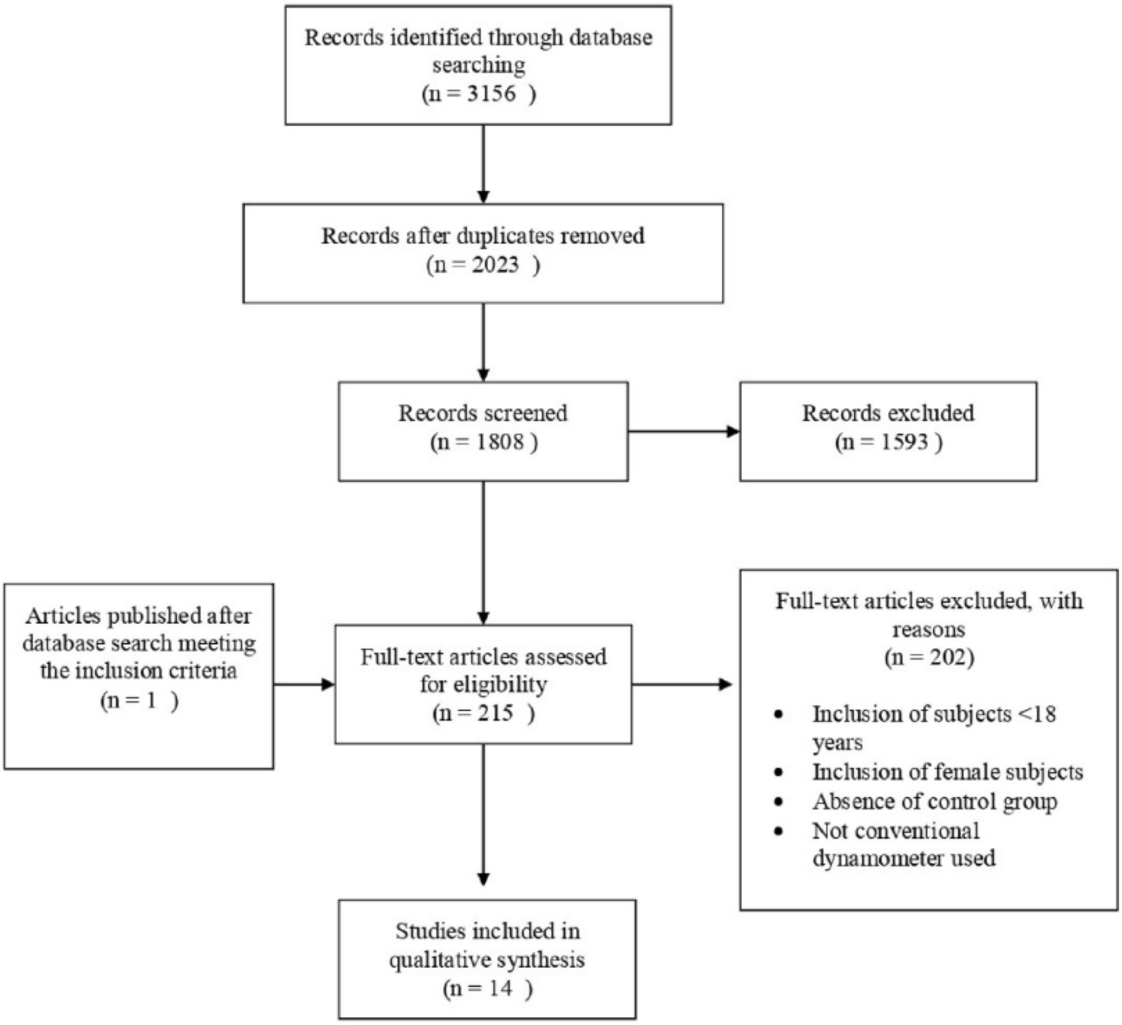

FIGURE 1 FLOW DIAGRAM.

3.3. Level of evidence, study quality, and risk of bias within studies

The OCEBM level, PEDro and modified Downs and Black scores for each study can be found in Tables 2 and 3. All 14 studies (100%) were classified as level 3b (cohort controlled trials). The risk of bias score was 6 (PEDro scale) for all studies (100%). The study quality was high (≥12) in 13 of the included articles, with the remaining study deemed as moderate (i.e. 11). There were no disagreements between the authors on the ratings.

3.4. Risk of bias across studies

Of the 14 studies included, 7 reported to have received some funding in support to their research. All authors reported no conflicts of interest. There was no selective data reporting in

TABLE 1 SUMMARY OF THE INCLUDED STUDIES

Author(s), year and population studies	Participants and age (years)	Interventions	Comparisons	Outcomes	Study design
Xergia et al. (2013) Active population	22 BPTB 28.8 ± 11.2	Isokinetic concentric knee extension and flexion strength (120º/s, 180º/2, and 300º/s)	Contralateral limb Control group	Compared to the control group, the ACLR group had greater isokinetic knee extension torque deficits at all speeds ($p \leq 0.001$)	Controlled cohort study
Mohammedi et al. (2013) Athletes involved in competitive sports	42 = 21 BPTB + 21 STG 25 ± 3	Isokinetic concentric knee extension and flexion strength (60º/s and 180º/s)	Between ACLR groups Contralateral limb Control group	No difference between BPTB and STG for hamstrings peak torque ($p = 0.69$ for 60º/s and $p = 0.63$ for 180º/s) or the limb symmetry index for the single-hop ($p = 0.78$) or 6-m-hop ($p = 0.74$) tests. STG group had greater values for quadriceps peak torque (13% and 17% change, $p = 0.004$) compared to the BPTB group. The ACLR limbs of both groups had lower peak torques ($p = 0.01$) compared to matched controls	Controlled cohort study
Miles and King (2019) Multidirectional sports	44 = 22BPTB + 22STG BPTB 23.4 ± 4.4 STG 26.1 ± 4.4	Isokinetic concentric knee extension and flexion strength (60º/s)	Between ACLR groups Contralateral limb Control group	BPTB had a greater knee extensor strength AAI than STG ($P = 0.002$, ES = 1.17) and controls ($P < 0.001$, ES = 1.40). No difference was found between STG and controls in knee extensor strength AAI ($P = 0.18$)	Controlled cohort study
O'Malley et al. (2018) Multidirectional sports	118 patellar tendon 23.6 ± 5.8	Isokinetic concentric knee extension and flexion strength (60º/s)	Contralateral limb Control group	**Between-limbs differences**: ISO knee-extension peak torque (ES = -1.33), SLCMJ knee power contribution (ES = -0.37), and ISO knee-flexion peak torque (ES = -0.19). **Between-groups differences**: ISO knee-extension LSI (ES = -1.53), LSImodified (ES = 1.28), ISO knee-extension peak torque (ES = -1.20), hip power contribution (ES = 0.61), SLCMJ knee power contribution (ES = -0.40), and ISO knee-flexion peak torque (ES = -0.36)	Controlled cohort study
Castanharo et al. (2011) Recreational sports activities	12 STG 28 ± 8	Knee joint power in CMJ	Contralateral limb Control group	In the ACLR group the peak knee joint power on the operated side was 13% lower than on the non-operated side ($p = 0.02$)	Controlled cohort study
Norouzi et al. (2019) Multidirectional sports (football players)	27 23.8 ± 3.3	Knee extensor strength (using a stabilized dynamometry)	Passed and failed RTS criteria groups Contralateral limb Control group	No significant difference between the 3 groups in terms of the quadriceps strength symmetry index ($p > 0.05$)	Controlled cohort study
Holsgaard-Larsen et al. (2014) Active population	23 STG 27.2 ± 7.5	MVC knee extensors and flexors (using stabilized dynamometry)	Contralateral limb Control group	Asymmetry in hamstring MVC was greater ($p < 0.001$) for ACLR participants than controls (77.4% vs. 101.3%)	Controlled cohort study
Read et al. (2020) Multidirectional sports (elite soccer players)	124 = 69 (6 – 9 months) + 55 (>9 months) 6 – 9 months 23.7 ± 6.7	Eccentric deceleration RFD in CMJ	Between ACLR groups Contralateral limb Control group	Between-limb differences in eccentric deceleration RFD remained significantly greater in players >9 months after ACLR versus matched controls ($p < 0.05$)	Controlled cohort study

Author(s), year and population studies	Participants and age (years)	Interventions	Comparisons	Outcomes	Study design
	>9 months 24.0 ± 5.4				
Welling et al. (2019) Multidirectional sports (amateur soccer players)	38 24.2 ± 4.7	Isokinetic concentric knee extension and flexion strength (60º/s)	Contralateral limb Control group	Soccer players after ACLR had no significant differences in peak quadriceps and hamstring muscle strength in the injured leg at 7 months after ACLR compared to the dominant leg of the control group. Furthermore, 65.8% of soccer players after ACLR passed LSI >90% at 10 months for quadriceps muscle strength	Controlled cohort study
Królikowska et al. (2019) Active people	Group 1 = 77 STG Group 2 = 66 STG	Isokinetic concentric knee extension and flexion strength (60º/s and 180º/s)	Between ACLR groups Contralateral limb Control group	The shift towards extension was noted when comparing the ACL-reconstructed limb to the uninvolved limb (Group I, $p \leq 0.001$; Group II, $p \leq 0.001$) and to Group III ($p \leq 0.001$), but it was not correlated with physiotherapy supervision duration ($r = -0.037$, $p = 0.662$). In ACLR patients, there was a moderate association of supervision duration and knee flexor LSI ($r – 0.587$, $p < 0.001$)	Controlled cohort study
Almeida et al. (2018) Multidirectional sports (elite soccer players)	20 STG Median 21 (18-28)	Isokinetic concentric knee extension and flexion strength (60º/s)	Contralateral limb Control group	At six months post-surgery knee function questionnaires and quadriceps peak torque deficit improved after surgery but were significantly lower compared to controls	Controlled cohort study
Mouzopoulos et al. (2015) Weekend athletes	32 BPTB 36 STG 26.2 ± 5.6	Isokinetic hip flexor contraction at an angular velocity of 120º/seconds and 60º/seconds in a concentric and eccentric mode were performed	Between ACLR groups Contralateral limb Control group	Hip flexion strength in ACL reconstructed patients either with patellar tendon or hamstrings grafts, one year after reconstruction is significantly decreased compared to healthy controls ($p < 0.0001$). Patients reconstructed with patellar tendon have stronger hip flexors than those reconstructed with hamstrings graft ($p < 0.0001$)	Controlled cohort study
Baltaci et al. (2012) No specified	15 29.6 ± 5.9	Isokinetic concentric knee extension and flexion strength (60º/s and 180º/s)	Contralateral limb Control group	When the operated knees were compared to the healthy side, mean limb symmetry index was over 92% (with two cases at 88%). When the dominant leg was compared to the non-dominant leg in the control group, the mean limb symmetry index was over 95%.	Controlled cohort study
Timmins et al. (2016) Multidirectional sports (elite soccer and AFL players)	15 ST 24.5 ± 4.2	MVIC of knee flexor at 0º, and average peak force during the Nordic hamstring exercise	Contralateral limb Control group	Eccentric strength was lower in the ACLR limb when compared with the contralateral uninjured limb. Fascicle length, MVIC, and eccentric strength were not different between the left and right limb in the control group	Controlled cohort study

(ACL) anterior cruciate ligament, (ACLR) anterior cruciate ligament reconstruction, (BPTB) bone-patellar tendon-bone, (ST) semitendinosus tendon, (STG) semitendinosus and gracilis tendon, (SL) single leg, (CMJ) countermovement jump, (DJ) drop jump, (RTS) return to sports, (3D) three dimensional, (GRF) ground reaction force, (VGRF) vertical ground reaction force, (PVGRF) peak vertical ground reaction force, (Hz) hertz, (MVC) maximal voluntary contraction, (MVIC) maximal voluntary isometric contraction, (ROM) range of motion, (ISO) isokinetic, (LSI) limb symmetry index, (ES) effect size, (AAI) absolute asymmetry index.

all studies examined. 3 articles were published in open access journals with chargeable publication fees.

4. Results of individual studies

4.1. Strength

The total number of ACLR participants included in this systematic review was 701. Xergia et al. (Xergia et al., 2013) examined strength in participants (n = 22) at approximately 7 months post-ACLR (bone-patellar tendon-bone graft (BPTB)). They found reduced strength in the ACLR limb compared to controls (n = 22), and inter-limb asymmetries in the ACLR group. Norouzi et al. (Norouzi et al., 2019) analysed strength in 3 different groups: 1) healthy controls (n = 15); 2) ACLR participants who passed (n = 14); and 3) failed RTS criteria (n = 13). They showed no significant difference between ACLR and healthy participants in strength at an average of 7.5 months following surgery. Holsgaard- Larsen et al. (Holsgaard-Larsen et al., 2014) measured strength in ACLR (n = 23) and healthy participants (n = 25 with matched MET score) at approximately 2 years post ACLR. They found greater inter-limb strength asymmetries in ACLR vs. healthy participants. Mohammadi et al. (Mohammadi et al., 2013) assessed strength in male soccer players (n = 21 BPTB and semitendinosus and gracilis tendon (n = 21 STG graft) and matched controls (n = 21). The results revealed strength deficits between the ACLR limb and healthy controls at 8 months post-surgery. Miles et al. (Miles & King, 2019) (n = 44) assessed strength in ACLR (BPTB and STG groups) and healthy participants (n = 22) during late phase rehabilitation, reporting between group differences and greater inter-limb asymmetries only in ACLR participants. Similarly, O'Malley et al. (O'Malley et al., 2018) evaluated strength in individuals at least 6 months after ACLR (n = 118 Patellar Tendon (PT)) and healthy participants (n = 44). They also showed between groups differences and greater inter-limb asymmetries only in ACLR participants. Welling et al. (Welling et al., 2019) measured strength in 38 amateur male soccer players at two different time-points (7 and 10 months) post ACLR (14 BPTB 24 STG) and healthy participants (n = 30). They found no differences between groups in peak torque at 7 and 10 months, with the exception of the hamstrings which was greater in the ACLR group at 10 months.

Krolikowska et al. (Królikowska et al., 2019) examined strength in 2 groups of active males (total n = 143 STG) (randomized based on the completion or not of ≥6 months postoperative physiotherapy supervision). Assessment took place at approximately 7 months post ACLR in comparison with matched controls (n = 98). They observed reduced strength and significant inter-limb asymmetries in the ACLR participants compared to matched controls. Almeida et al. (Almeida et al., 2018) showed significant differences in strength and inter-limb strength asymmetries in professional soccer players at 6 months post ACLR (n = 20 STG) compared to healthy players (n = 20). Mouzopoulos et al. (Mouzopoulos et al., 2015) found strength differences between amateur male athletes 1 year post ACLR (n = 68, 32 BPTB 36 STG) and healthy controls (n = 68). Baltaci et al. (Baltaci et al., 2012) revealed no significant difference in strength between limbs and groups in male adults 20 months post ACLR (n = 15) and matched controls (n = 15). Timmins et al. (Timmins et al., 2016) evaluated strength in 15 (ST) elite athletes who had returned to pre-injury levels of competition and training following ACLR (median time since surgery = 3.5 years), indicating greater strength deficits and greater inter-limb asymmetries compared to matched controls (n = 52).

4.2. RFD and power

Castanharo et al. (Castanharo et al., 2011) measured single joint power in a CMJ in a ACLR (n = 12) and a non-injured control group (n = 17). At more than 2 years post-surgery, they found reduced knee joint power on the ACLR side than the contralateral limb, but no differences in jump height between groups. Similarly, O'Malley et al. (O'Malley et al., 2018) reported significant between limbs and group differences in knee and hip power contribution during a single leg CMJ in multidirectional sport athletes > 6 months (n = 118) following ACLR compared to healthy controls (n = 44). Read et al. (Read et al., 2020) measured RFD and peak power during a bilateral CMJ in ACLR (n = 124) participants (at 6-9 and >9 months post-surgery) and matched controls (n = 204). The results showed significant between groups and inter-limb differences in peak power and eccentric deceleration RFD between the ACLR participants and healthy controls.

4.3. Synthesis of results

Due to the different assessment modes, only 5 of the 14 studies were deemed eligible for inclusion in a meta-analysis (262 participants) (Almeida et al., 2018; Miles & King, 2019; Mohammadi et al., 2013; O'Malley et al., 2018; Welling et al., 2019). These studies measured peak knee extension and flexion torque with an isokinetic dynamometer at 60^{o}/s in participants involved in multidirectional sports. Separate analysis was also performed to examine differences based on different graft types (BPTB/PT and STG). If studies contained measures taken at different time points, only the data measured at the first time point beyond the 6 months postsurgical period were used in the meta-analysis. Comparisons between the ACLR limb and the dominant limb of the healthy group were quantitatively synthesized. The uninvolved limb was not considered as a suitable reference limb due to the bilateral strength reductions observed in the post-surgical period (Wellsandt, Failla, & Snyder-Mackler, 2017). Knee extension and flexion strength pooled results are presented in Figs. 2-5.

4.3.1. Peak knee extension strength

Pooled data showed moderate evidence indicating a large negative effect (g = -0.89, 95% CI [-1.33, -0.44]; I^2 = 72%) of ACLR on involved limb peak knee extension torque compared to the dominant limb of the healthy controls at more than 6 months post-surgery.

Subgroup analysis revealed no significant difference between groups (BPTB/PT vs STG, p = 0.18), showing strong evidence of a large effect of ACLR on knee extension peak torque in BPTB/PT (g = -1.31, 95% CI [-1.62,-0.99]; I^2 = 0%) reconstructed knees compared to the dominant limb of healthy controls. Moderate evidence of a large effect was shown in STG (g = -0.81, 95% CI [-1.47, -0.15]; I^2 = 59%) reconstructed knees compared to the dominant limb of healthy controls.

4.3.2. Peak knee flexion strength

Pooled data showed moderate evidence indicating a small negative effect (g = -0.44, 95% CI [-0.78, -0.10]; I^2 = 55%) of ACLR on peak knee flexion torque on the involved limb compared to the dominant limb of the healthy controls > 6 months post-surgery.

Subgroups analysis revealed no significant difference between groups (BPTB/PT vs STG, p = 0.10), showing strong evidence of a moderate effect of ACLR on knee flexion peak torque in.

BPTB/PT (g = -0.39, 95% CI [-0.68, -0.10]; I^2 = 0%), and strong evidence of a large effect in STG (g = -0.82, 95% CI [-1.24, -0.40]; I2 = 0%) reconstructed knees compared to the dominant limb of healthy controls.

5. Discussion

The aim of this review was to synthesize and critically evaluate the available literature pertaining to athletic performance capacities in physically active adult males who were in the later stages of rehabilitation (>6 months) post ACLR compared to healthy, non-injured controls. Our particular focus was on strength, RFD, power, and reactive strength, to more clearly elucidate the magnitude of performance deficits compared to the healthy matched controls. The main findings revealed significant deficits and greater between limb asymmetries in knee extensor and flexor strength. Also, lower peak knee joint power at the knee in the ACLR limb during jumping tasks appears compensated by a higher proportion of power generated at the hip. Preliminary evidence also indicated that reductions in eccentric deceleration RFD on the involved limb are present in male adults at more than 6 months following ACLR, compared to matched controls.

5.1. Effect of ACLR on maximal strength measured during isokinetic dynamometry

The magnitude of residual deficits in knee extension strength following ACLR showed moderate to large effect sizes in injured male multidirectional field sport athletes who were >6 months post-surgery in comparison to healthy individuals (Almeida et al., 2018; Miles & King, 2019; Mohammadi et al., 2013; O'Malley et al., 2018; Welling et al., 2019). Compared to the dominant limb of matched controls, the ACLR limb displayed large deficits in knee extension peak torque ($g = -0.89$, 95% CI [-1.33, -0.44]) and small deficits in knee flexion peak torque ($g = -0.44$, 95% CI [-0.78, -0.10]). Deficits in knee extension peak torque were further pronounced in BPTB/PT grafts ($g = -1.31$, 95% CI [-1.62, -0.99]), whereas deficits in knee flexion peak torque were more evident in STG grafts ($g = -0.82$, 95% CI [-1.24, -0.40]). This may have significant implications for re-injury risk considering that quadriceps strength deficits prior to return to multidirectional sport is a significant predictor of knee re-injury (Grindem et al., 2016; Wellsandt et al., 2017). Furthermore, knee extensor strength deficits have been associated with lower levels of self-reported outcomes (Perraton et al., 2017; Pietrosimone et al., 2016), increased risk of osteoarthritis (Sinding, Nielsen, & Hvid, 2020), impaired functional performance (Birchmeier et al., 2019), and quality of life (Filbay, Ackerman, Russell, Macri, & Crossley, 2014). Furthermore, linear regression models have shown small to moderate correlation values between peak knee extension torque, kinetic and kinematic variables in individuals following ACLR (Birchmeier et al., 2019; Miles & King, 2019; O'Malley et al., 2018); thus, suggesting a significant interaction among fundamental physical capacities such as strength and more complex athletic tasks.

Level of sports participation may be an important factor to consider. One study (Almeida et al., 2018) analysed professional soccer players in Brazilian football teams at 6 months post ACLR and revealed large differences in knee extension peak torque in the reconstructed knee (291.3 ± 45.5 Nm/Kg) compared to the dominant limb of healthy professional soccer players (358 ± 44.2 Nm/Kg). Conversely, in Dutch amateur soccer players who were 7 months post-surgery

(Welling et al., 2019), no significant differences were present. As the healthy control group consisting of professional players [56] achieved higher peak torque values than amateur non-injured controls [54], this reinforces the need to consider absolute and relative torque values and not just limb symmetry. In addition, strength values in the later stages of rehabilitation, where possible, should compare performance to normative values representative of the athletes' level of competition to account for the unique characteristics and functional demands of the studied population.

Only one study included in our review included a progressive strength training intervention during rehabilitation in athletes post ACLR, comparing maximal strength to healthy controls at 4, 7 and 10 months after surgery (Welling et al., 2019). Results showed that the documented program (mean frequency 2.6 sessions per week), as outlined by the American College of Sports Medicine (Garber et al., 2011), was effective not only in attenuating strength deficits at 7 months ($g = -0.19$, 95%CI [-0.67, 0.29]), but also to reach superior values (>3.0 Nm/kg) than the dominant limb of healthy controls and LSI of more than 90% by 10 months. These findings indicate that observed residual strength deficits (Almeida et al., 2018; Holsgaard-Larsen et al., 2014; Królikowska et al., 2019; Miles & King, 2019; Mohammadi et al., 2013; Mouzopoulos et al., 2015; O'Malley et al., 2018; Timmins et al., 2016; Welling et al., 2019; Xergia et al., 2013) are trainable and levels of performance comparable to healthy controls are possible during rehabilitation following ACLR. Thus, sports and healthcare professionals should be encouraged to adopt targeted rehabilitation strategies focusing on maximal strength, that include specific exercise selection, dosage and progressions. Briefly, current evidence indicates single-joint (e.g. leg extension/curl) and multi-joint exercises (e.g. split squat, front/back squat, deadlift) involving a load (or intensity) of 80-100% of the participant's one RM, utilizing approximately 1-6 repetitions, across 3-5 sets, with rest periods of 3-5 min, and a frequency of 2-3 times per week (American College of Sport, 2009; Morton, Colenso-Semple, & Phillips, 2019; Suchomel, Nimphius, Bellon, & Stone, 2018). For detailed information regarding practical applications to return athletes to high performance we recommend recently published articles (Buckthorpe, 2019; Buckthorpe & Della Villa, 2019; Lorenz & Reiman, 2011; Maestroni, Read, Bishop, & Turner, 2020; Welling et al., 2019).

Our findings also show that graft type needs to be taken into consideration when assessing maximal strength and subsequently designing rehabilitations programs. Independent from graft type, knee extensor strength in multidirectional athletes >6 months following ACLR appear significantly compromised ($g = -0.89$, 95% CI [-1.33, -0.44]). Knee flexor strength should be also targeted due to residual deficits in hamstring strength ($g = -0.44$, 95% CI [-0.78, -0.10]), especially in athletes whose elected surgery was a STG (g = -0.82, 95% CI [-1.24, -0.40]). Differences between graft types were also observed in studies analysing knee extension and flexion strength in recreational athletes at isokinetic velocities different than 60^{o}/s (Królikowska et al., 2019; Xergia et al., 2013). More pronounced knee extension strength deficits were found in BPTB grafts (Xergia et al., 2013), whereas knee flexion strength deficits were more evident in STG grafts (Królikowska et al., 2019). In addition, one study (Mouzopoulos et al., 2015) showed significantly greater hip flexion strength (measured concentrically and eccentrically at 60^{o}/s and 120^{o}/s) in amateur male athletes with a BPTB graft (n = 32) than in the STG group (n = 36) at 1-year post ACLR ($p < 0.0001$). Both groups displayed inferior values when compared to matched controls.

5.2. Assessment modes to determine maximal strength

The majority of studies used an isokinetic dynamometer at a variety of test speeds (60^{o}/s, 120^{o}/s, 180^{o}/s and 300^{o}/s) for both the quadriceps and hamstring muscles (Almeida et al., 2018; Baltaci et al., 2012; Królikowska et al., 2019; Miles & King, 2019; Mohammadi et al., 2013; O'Malley et al., 2018; Welling et al., 2019; Xergia et al., 2013). Other testing modes included isometric MVIC on a dynamometer (Holsgaard-Larsen et al., 2014; Norouzi et al., 2019; Timmins et al., 2016), or uniaxial load cells (Timmins et al., 2016) Surprisingly, none of the eligible and included studies evaluated multi-joint strength levels (e.g. back squats, isometric mid-thigh pull). Although single-joint strength assessment is required and provides an indication of specific deficits in muscles directly associated with the injured site following ACLR, research has shown that multi-joint strength capacities display a heightened transfer to athletic performance (Suchomel et al., 2018). Specifically, moderate to high correlations between multi-joint strength levels and jumping, sprinting and COD performance were reported in a recent systematic review (Suchomel, Nimphius, & Stone, 2016). Therefore, future research is warranted to examine 'global system' strength in athletes following ACLR to determine their level of readiness to re-perform using sport relevant capacity tests.

The two studies that measured quadriceps MVIC (Holsgaard-Larsen et al., 2014; Norouzi et al., 2019) with a stabilized dynamometry (in sitting at 90^{o} knee flexion) did not detect any knee extension MVIC deficit compared to the contralateral limb. Instead, conflicting results were found in knee flexion MVIC. One study (Holsgaard-Larsen et al., 2014) showed 22% inter-limb asymmetry in hamstring MVIC (measured in 90^{o} knee flexion), whereas no differences were observed when hamstring MVIC was tested at 0^{o} knee flexion (Timmins et al., 2016). It appears that differences in quadriceps strength were more apparent in studies using isokinetic dynamometry (Almeida et al., 2018; Miles & King, 2019; Mohammadi et al., 2013; O'Malley et al., 2018; Welling et al., 2019), which may be more sensitive in detecting strength deficits throughout the range of motion analysed, compared to a stabilized dynamometry at a specific joint-angle only. Also, these results indicate that measuring hamstrings strength at a specific joint angle may not be sufficient to detect deficits. Although knee positions near full extension are often frequently reported as part of the ACL injury mechanism (Walden et al., 2015), it is also important to note that smaller knee flexion angles (i.e. $< 30^{o}$) expose the ACL to high strain magnitudes (Markolf et al., 1995; Petersen & Zantop, 2007; Yasuda et al., 2008), which may preclude assessment in these ranges during the earlier stages of rehabilitation. In most studies using isokinetic dynamometry, it is unclear at which angle peak torque occurred. Therefore, information about muscle performance during specific ranges of motion or shifts in peak torque angles occurring following ACLR are limited, with existing studies reporting contrasting results (Cinar-Medeni, Harput, & Baltaci, 2019; Makihara, Nishino, Fukubayashi, & Kanamori, 2006; Ohkoshi, Inoue, Yamane, Hashimoto, & Ishida, 1998). Among the studies included in this review, only Krolikowska et al. (Królikowska et al., 2019) reported a shift of ACLR limb knee flexor muscles peak torque angle at 180^{o}/s towards extension in participants with shorter supervised postsurgical rehabilitation, compared to the other two groups.

5.3. Effect of ACLR on maximal strength - summary of findings

Taken together, the synthesized data from our review suggests that: (1) isokinetic dynamometry is more sensitive in detecting force production deficits than MVIC assessment; (2) subjects receiving a BPTB autograft display greater deficits in quadriceps strength and should be more closely monitored in their knee extensor strength capacity over the course of rehabilitation and prior to RTS; (3) subjects receiving STG autograft show deficits in hamstring strength although this is not consistent across all studies which imply particular attention during rehabilitation; (4) subjects receiving a BPTB autograft might be slower in achieving key rehabilitation milestones such as 90% LSI; (5) physiotherapy programs with specific emphasis on strength are capable of achieving the targeted strength values comparable to those of healthy matched controls; (6) in addition to LSI and absolute peak forces, normative values appear of utmost importance to assess rehabilitation status to remove the confounding factor of using the contralateral limb as the only reference value which may overestimate knee function.

5.4. Effect of ACLR on rate of force development and power

Only one study (Read et al., 2020) meeting our inclusion criteria reported RFD in physically active male adults following ACLR compared to controls at more than 6 months post ACLR. Read et al. (Read et al., 2020) showed that eccentric deceleration RFD on the involved limb was significantly lower in athletes > 6 months post ACLR vs. matched controls and they also displayed a greater eccentric deceleration RFD asymmetry index. Interestingly, no meaningful between group differences were observed in eccentric mean force. Eccentric deceleration RFD provides an indication of the rate of force rise as the athletes decelerate their mass in the final phase of the descent. Eccentric mean force examines the entire lowering phase and these data suggest that rate-related variables may be more sensitive to identify between-limb deficits after injury but this requires further investigation.

Castanharo et al. (Castanharo et al., 2011) assessed single joint power contributions (i.e. physical capacity containing both force and velocity) in the CMJ, comparing an ACLR group (adult males with STG graft ≥ 2 years post-surgery) to a control group. They found no significant differences in jump height between groups, but peak knee joint power on the ACLR limb was 13% lower than the contralateral side. O'Malley et al. (O'Malley et al., 2018) also reported significant inter-limb asymmetries in hip power contribution ($d = 0.75$), knee power contribution ($d = -0.37$) and single leg CMJ peak power ($d = -0.47$, $\beta = 0.99$). Similar differences in peak power $LSI_{modified}$ ($d = -0.61$), hip ($d = 0.61$), and knee power contribution ($d = -0.40$) were also found between the ACLR limb and the dominant limb of the control group. Collectively, these studies indicated that in the ACLR limb, a higher proportion of power is generated at the hip to compensate lower peak knee joint power when generating propulsive forces in tasks such as unilateral jumping. No values regarding the epoch taken to generate force were reported. Therefore, speculation of differences in RFD in the different phases of the CMJ cannot be made. This impeded accurate data extraction regarding RFD values in these studies.

Although there was a paucity of data to examine the effect of ACLR on RFD, the ability of key musculature such as the quadriceps to generate force rapidly in ACLR cohorts is important to optimise lower extremity loading characteristics in hopping and jumping (Birchmeier et al., 2019; Pua et al., 2017). Therefore, knee extensor RFD/RTD has been suggested as a useful component to include in RTS decision making (Angelozzi et al., 2012; Hsieh et al., 2015). Furthermore, Angelozzi et al. (Angelozzi et al., 2012) showed that although peak force differences between-limbs had normalised 6 months post ACLR, residual deficits in RFD during and isometric leg press were identified. However, these authors (Angelozzi et al., 2012) also showed that targeted interventions are successful in restoring these capacities to their pre-injury levels. Further research is warranted to investigate if deficits in eccentric deceleration RFD are trainable and if deficits in this physical capacity are associated with the secondary injuries following ACLR.

5.5. Effect of ACLR on reactive strength

We did not find any studies meeting our inclusion criteria that measured reactive strength in physically active male adults who were more than 6 months following ACLR in comparison to matched controls. King et al. (King et al., 2018) examined RSI in an ACLR male adult population involved in multidirectional sports approximately at 9 months post-surgery (n = 156, mean age 24.8 ± 4.8) although this study did not include a control group. Reductions in RSI were observed in the ACLR limb compared to the contralateral (21% between-limb deficit; d = -0.73.). Previously, Flanagan et al. (Flanagan, Galvin,& Harrison, 2008) evaluated RSI in ten participants (8 men, 2 women at a mean time from ACLR of 27.0 ± 14.5 months) using a jump sledge apparatus with the body weight supported, sliding on a fixed track inclined at 30^{o} to the horizontal. Their results showed high LSI in RSI post ACLR, but the subjects were over 2 years post-surgery, and the demands of the task may be less demanding with lower ground reaction forces. Considering the importance of reactive strength in jumping, change of direction and metabolic cost of running (Li et al., 2019; Maloney et al., 2017), further research is required to examine reactive strength levels in male adults during the later stages of rehabilitation and RTS following ACLR. Furthermore, it may be prudent to examine changes in SSC function following ACLR and their responsiveness to targeted rehabilitation strategies. The available evidence indicates that plyometric training is used sparingly during ACL rehabilitation (Ebert et al., 2018); thus, more studies are required to determine if residual deficits in this fundamental physical quality are present in comparison to healthy controls.

5.6. Level of evidence, quality and risk of bias in individual studies

All included research were controlled cohort studies; therefore, the level of evidence was 3. The included studies presented a high methodological quality (based on the modified Downs and Black scale). Risk of bias assessment (based on the PEDro scale) is presented in Table 2. The most frequent sources of methodological considerations were: blinding of outcome assessors and participants allocation (due to obvious limitations in ACLR cohorts), distribution and adjustment for confounders, and sample size calculation. Most of the distribution of principal confounders (age, time after surgery, physical activity levels, etc.) were clearly described, except for a minority of studies where graft type used was not mentioned. This has been shown to influence important clinical outcomes (Huber et al., 2019; Miles & King, 2019). However, all articles reported clear eligibility criteria, similar baseline across groups, complete outcome measures and adequate statistical analysis between groups for at least one key outcome

Table 2 PEDro score of each study.

PEDro scale	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Total score
Xergia SA (2013)	✓	X	X	✓	X	X	X	✓	✓	✓	✓	6
Mohammadi F (2013)	✓	X	X	✓	X	X	X	✓	✓	✓	✓	6
Miles and King (2019)	✓	X	X	✓	X	X	X	✓	✓	✓	✓	6
O’Malley E (2018)	✓	X	X	✓	X	X	X	✓	✓	✓	✓	6
Castanharo R (2011)	✓	X	X	✓	X	X	X	✓	✓	✓	✓	6
Norouzi S (2019)	✓	X	X	✓	X	X	X	✓	✓	✓	✓	6
Holsgaard-Larson A (2014)	✓	X	X	✓	X	X	X	✓	✓	✓	✓	6
Read P (2020)	✓	X	X	✓	X	X	X	✓	✓	✓	✓	6
Welling (2019)	✓	X	X	✓	X	X	X	✓	✓	✓	✓	6
Królikowska (2019)	✓	X	X	✓	X	X	X	✓	✓	✓	✓	6
Almeida (2018)	✓	X	X	✓	X	X	X	✓	✓	✓	✓	6
Mouzopoulos (2015)	✓	X	X	✓	X	X	X	✓	✓	✓	✓	6
Baltaci (2012)	✓	X	X	✓	X	X	X	✓	✓	✓	✓	6
Timmins (2016)	✓	X	X	✓	X	X	X	✓	✓	✓	✓	6

Table 3 OCEBM level and modified Downs and Black scores of each study.

Modified Downs and Black scores	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Item 12	Item 13	Item 14	Item 15	Total score	OCEBM level (Lv)
Xergia SA (2013)	1	1	1	1	1	1	1	0	1	1	1	2	0	1	1	14	Lv3b
Mohammadi F (2013)	1	1	1	1	1	1	1	0	1	1	1	2	0	1	1	14	Lv3b
Miles and King (2019)	1	1	1	1	1	1	1	0	1	1	1	2	0	1	1	14	Lv3b
O’Malley E (2018)	1	1	1	1	1	1	1	0	1	1	1	2	0	1	1	14	Lv3b
Castanharo R (2011)	1	1	1	1	1	1	1	0	1	1	1	2	0	0	1	13	Lv3b
Norouzi S (2019)	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	12	Lv3b
Holsgaard-Larson A (2014)	1	1	1	1	1	1	1	0	1	1	1	2	0	1	1	14	Lv3b
Read P (2020)	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	12	Lv3b
Welling (2019)	1	1	1	1	1	1	1	0	1	1	1	1	0	1	1	13	Lv3b
Królikowska (2019)	1	1	1	1	1	1	1	0	1	1	1	2	0	1	1	14	Lv3b
Almeida (2018)	1	1	1	1	1	1	1	0	1	1	1	2	0	1	1	14	Lv3b
Mouzopoulos (2015)	1	1	1	1	1	1	1	0	1	1	1	2	0	0	0	12	Lv3b
Baltaci (2012)	1	1	1	1	1	1	1	0	1	1	1	1	0	0	0	11	Lv3b
Timmins (2016)	1	1	1	1	1	1	1	0	1	1	1	2	0	1	1	14	Lv3b

5.7. Limitations

We decided to exclude adolescent and paediatric ACLR cohorts owing to the lack of substantial high quality evidence regarding management in this population (Ardern et al., 2018; Burland et al., 2018; Henry et al., 2009; Moksnes, Engebretsen, & Risberg, 2012). In addition, females were not examined due to their different anthropometric, hormonal, training and kinematic features when compared to males (Capogna, Mahure, Mollon, & Duenes, 2019; Ford, Myer, & Hewett, 2003; Herzberg et al., 2017; Hewett, Myer, & Ford, 2006; Lohmander, Ostenberg, Englund, & Roos, 2004; Mayhew, Hancock, Rollison, Ball, & Bowen, 2001; Sugimoto, Myer, McKeon, & Hewett, 2012; Walts et al., 2008). Finally, we included only articles where a control group was present; thus, decreasing the overall pool of studies in this review. Due to the observed reductions in contralateral limb function following ACLR, using the non-injured limb as a reference and only quantifying LSI only may overestimate the functional improvements observed during rehabilitation (Patterson et al., 2020; Wellsandt et al., 2017). Instead, we included studies that compared the ACLR limb with the dominant limb of matched controls to increase the methodological quality of our review and conclusions drawn from the quantitative analysis. Finally, despite our strict criteria and the homogeneous assessment mode included in the meta-analysis, there was high statistical heterogeneity across the studies when these were analysed without differentiating graft types. Heterogeneity was significantly lowered when subgroups were created according to graft type, suggesting that studies evaluating strength outcomes should report this as part of the participant information.

5.8. Practical recommendations and future research

Deficits in knee extensor and flexor peak torque were detected in the ACLR limb of male adults in most studies even after having completed rehabilitation and returned to sports. Knee extensor strength deficits were more evident in subjects with a BPTB compared to STG grafts, where hamstring strength appeared more compromised. However, both knee extensors and flexors strength deficits have shown to reduce by implementing targeted interventions with a maximal strength emphasis adopted during rehabilitation (Królikowska et al., 2019; Welling et al., 2019).

O'Malley et al. (O'Malley et al., 2018) provided normative values for quadriceps and hamstring strength (i.e. 240 = -270% and 150 = -160% of their body mass on isokinetic dynamometer at 60°/s) which correlated with optimal rehabilitation status. Welling et al. (Welling et al., 2019) suggested that quadriceps peak torque normalised to bodyweight should be > 3.0 Nm/kg at 60°/s. Therefore, it appears vital that quadriceps and hamstring strengthening should continue to be part of a rehabilitation programme until these minimum requirements are met. It is also recommended to further enhance strength beyond these values and target RFD to increase capacity in sport relevant physical qualities. Future studies should examine optimal normative strength values for proximal and distal lower limb components as well as global measures of strength (e.g. back squat, front squat, mid-thigh pull, etc.) considering the limited ability of LSI in estimating knee function and performance.

Finally, due to its high correlation with SSC performance, future research should analyse reactive strength in male adults following ACLR.

6. Conclusions

The findings from our synthesis of the available literature suggests that knee extensor and flexor strength deficits are still present at more than 6 months following ACLR. These appear to be influenced by graft types and importantly can be mitigated by targeted rehabilitation programs. Key rehabilitation milestones should include both absolute strength scores and LSI compared to healthy controls or pre-injury values to provide a more complete understanding of knee function and rehabilitation status. Due to the paucity of studies investigating RFD and reactive strength in this population, no definitive conclusions can be drawn between these fundamental physical determinants and rehabilitation status and this warrants further research.

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Appendix A. Supplementary data

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