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Is resistance training intensity adequately prescribed to meet the demands of returning to sport following anterior cruciate ligament repair? A systematic review

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ABSTRACT

Objective To identify, critique and synthesise the research findings that evaluate the use of resistance training (RT) programmes on return to sport outcome measures for people following ACL repair (ACLR).

Design and data sources This systematic review included a comprehensive search of electronic databases (EBSCO health databases (CINAHL, MEDLINE, SPORTDiscus), Scopus and Pedro) performed in June 2020 and was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses checklist. Studies were appraised using the Downs and Black checklist.

Eligibility criteria Randomised and non-randomised controlled trials, longitudinal cohort studies and case series were considered for inclusion where an adequate description of the RT intervention was provided as a part of the study's ACLR rehabilitation protocol. Articles that did not include outcome measures related to return to sport criteria were excluded.

Results Eleven articles met the inclusion criteria and were subjected to appraisal and data extraction. Study quality ranged from poor to excellent. RT intensity varied considerably among studies (between 5% and >80% of one repetition maximum). Only one identified study specifically investigated the effect of a low-intensity versus high-intensity RT protocol. The majority of studies reported participant outcomes that would not meet commonly used return to sport criteria.

Conclusion There appears to be considerable variation in the intensity of RT prescribed in research for people following ACLR. Furthermore, in most of the identified studies, RT protocols promoted muscle endurance and hypertrophy without progressing to strength or power-based RT. The findings of this review provide insight into potential factors limiting returning to sport and contributing to reinjury for people following ACLR.

Key messages

What is already known

- Resistance training (RT) is an integral component of an ACL repair (ACLR) rehabilitation programme.
- Reinjury following ACLR remains high, and associated physical deficits relating to return to sport criteria are commonly observed even after a return to sport.

What are the new findings

- There is no consensus regarding optimal RT intensity (among other RT parameters) throughout ACLR rehabilitation literature.
- RT intensities found in the ACLR rehabilitation literature do not align with strength and conditioning principles and are often not optimised to develop the desired neuromuscular qualities required of return to sport criteria. This may contribute to suboptimal prescription of rehabilitation programmes and poorly prepared athletes.

INTRODUCTION

The incidence rate of primary ACL repair (ACLR) in Australia is the highest globally and continues to rise.[1] Following surgery, rehabilitation is essential to ensure a return to full function by addressing postoperative strength and neuromuscular control deficits associated with reinjury.[2–6] A comprehensive rehabilitation programme following ACLR is crucial for those who intend to return to sport, as reinjury rates are high in this population[7]; literature indicates that rerupture rates are 18% or higher in the young athletic population.[8] Despite the importance placed on rehabilitation, modifiable deficits in lower limb strength and function can extend beyond 12 months following surgery and commonly persist after returning to sport.[9] Of concern, Leister *et al*[9] reported that up to 70% of people who have already returned to sport could not pass return to sport criteria 12 months after surgery.

ACLR rehabilitation should address post-operative deficits and facilitate a safe return to sport through a wide range of exercise modalities.[10] Rehabilitation aims to restore muscular strength, with resistance training (RT) being a crucial programme component.[10] The utilisation of RT principles, while concurrently considering the stage of healing following ACLR, is a considerable challenge faced by clinicians and patients. Intensity is considered the primary component of RT to achieve the desired training effect.[10–12] RT intensity is defined as the magnitude of load of a given exercise, often expressed as a percentage of an individual's one repetition maximum (1RM).[10 13] RT is optimised to improve different aspects of neuromuscular function depending on the prescribed intensity.[14] The purpose of the exercise and corresponding intensity must be well understood to succinctly prescribe an RT programme following ACLR. Varying demands must be placed on the patient through RT to address deficiencies in muscle endurance, size, strength and power to restore the full neuromuscular function of the affected limb.[14] Panariello *et al*[5] recommended a criteria-driven framework for rehabilitation following ACLR, breaking the rehabilitation process into distinct phases. The framework was based on the hierarchy of athletic development, recognising the needs of an ACLR patient as equal to the athlete preparing for sport.

Return to sport criteria following ACLR have been developed to objectively determine when a safe return to sport following ACLR is indicated.[3 15] There is a consensus that passing the objective return to sport criteria is vital in reducing injury risk following ACLR; however, the association between current criteria and the risk of ACL graft injury is not yet clear.[16] Kyritsis *et al*[15] found a fourfold increased risk of ACL graft rupture for those patients who did not pass the return to sport criteria. Additionally, Grindem *et al*[3] estimated an 84% lower knee reinjury rate among people who passed return to sport criteria. Following a meta-analysis of return to sport criteria, Losciale *et al*[16] advocated for stricter criteria, in particular, that 100% strength and function Limb Symmetry Index (LSI) scores should be used to improve the sensitivity of criteria in predicting rerupture.

There appear to be confusion and a lack of consensus among physiotherapists surrounding ACLR rehabilitation. Physiotherapists have shown a lack of consistency when determining return to sport clearance,[17 18] and Greenberg *et al*[18] reported that 56% of physiotherapists believed 5 months of rehabilitation was sufficient following ACLR. Yet, Toole *et al*[19] demonstrated that only 44% of patients had achieved an acceptable quadriceps LSI before gaining clearance to return to sport. These findings show an inadequate return to sport decision-making process and may suggest that suboptimal rehabilitation is being prescribed.[3] Physiotherapists have also reported confusion surrounding the prescription and progression of exercises throughout ACLR rehabilitation.[20] This confusion is likely accentuated by wide variability in rehabilitation protocols, most of which do not stress the importance of addressing deficits related to reinjury.[21]

Although the causes of reinjury are multifactorial, an RT protocol that fails to address postoperative neuromuscular deficits is likely to be a crucial factor.[22] Currently, there does not appear to be any consensus for the application and progression of RT intensity throughout the ACLR rehabilitation process to address postoperative neuromuscular deficits optimally.[20 21] The objective of this systematic review was to identify, critique and synthesise the findings of research that has evaluated the effectiveness of RT programmes (where intensity has been defined) on physical return to sport outcome measures. (1) What is the quality of the literature that evaluates the effectiveness of an RT protocol (where intensity has been defined) following ACLR? (2) Does the intensity of RT described in ACLR rehabilitation literature align with recommended guidelines for RT? (3) Is the recommended intensity of RT, as detailed by the literature, sufficient to ensure that postoperative physical deficits are adequately addressed?

METHODS

This systematic review was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses checklist (2009) and registered with PROSPERO (ID: CRD42020136001).

Data sources

A comprehensive search of electronic databases was performed in June 2020. Databases included: EBSCO health databases (CINAHL, MEDLINE, SPORTDiscus), Scopus and Pedro. Two key concepts being 'anterior cruciate ligament' and 'strength training', and their alternative terms were identified and searched separately (table 1).

Inclusion/exclusion criteria

Studies were included if they were randomised or non-randomised controlled trials, longitudinal cohort studies or case series, where an adequate description of an RT intervention as a part of an ACLR rehabilitation protocol for 6 weeks or greater was provided. Exercise descriptors deemed necessary included the number of sets and

Table 1 Search terms and Boolean operators

Order of terms searched	Search terms and operators
Search 1 (S1)	(ACL OR 'anterior cruciate ligament') AND (repair or 'post-operative' OR 'post-operative' OR surgery OR 'post-surg*' OR reconstruction)
Search 2 (S2)	(strength* OR resistance OR weight* OR exercise OR intensity OR maximal) N5/W5 (train* OR program* OR protocol*)

repetitions, the type of exercise and exercise intensity. Articles were excluded if they did not include outcome measures related to common objective return to sport criteria,[16] did not report on primary data, were questionnaires and qualitative research, where full texts were not available, and were not published in a peer-reviewed journal or where an English version was not available.

Screening and study selection

Studies titles and then abstracts identified by the search were screened and read by the primary author. Full-text versions of each of these studies were reviewed to determine if the study met the inclusion and exclusion criteria. Reference lists from the identified studies were checked for possible additional studies not identified by the database search. The texts of all remaining articles were subject to quality appraisal and data extraction. Each study included in this systematic review was independently critiqued by the primary author and a second reviewer (both clinical physiotherapists). When all studies had been independently critiqued, the primary author and the second reviewer deliberated on individual results to reach a consensus on final scores.

Study quality appraisal and data extraction

A modified Downs and Black appraisal tool was used to assess the quality of selected articles.[23] This tool is sufficiently reliable and valid for determining the methodological quality of randomised controlled trials and non-randomised trials.[23] The modified tool has previously been used in other published systematic reviews.[16 24–27] The total of the appraisal scores for each study was used to indicate the overall study quality, categorised as follows: poor (14 or below), fair (15–19), good (20–25) and excellent (26–28).[24]

RESULTS

Study selection

Figure 1 illustrates the process undertaken to select the studies included for quality appraisal and data extraction. The search and screening process identified 11 articles for final quality appraisal and data extraction.

Quality of included studies

Studies varied in quality, with scores ranging from 13 to 26 out of a possible 28 (table 2). One study was categorised as excellent quality,[28] four studies as good quality,[29–32] four studies as fair quality[33–36] and two studies as poor quality.[37 38] Table 2 shows most studies scored well in reporting objectives, outcome measures, interventions and results. Studies commonly scored poorly on the items related to the inherent difficulties with researching this type of intervention and mainly affected the internal validity, such as a lack of blinding. Other items that were commonly scored poorly among studies affected the generalisability of results, including insufficient power due to a lack of participants, insufficient description of

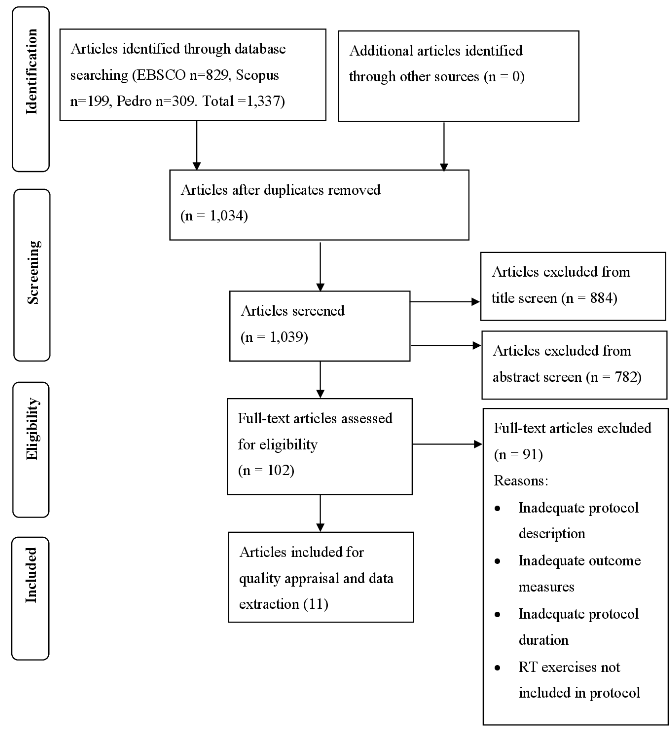

Figure 1 Search strategy and results. RT, resistance training. (Adapted from Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), 2009).

participant characteristics and facilities and equipment used not typically available to the general population.

Characteristics of included studies

Extracted data relating specifically to the research question, including RT intensities and the corresponding outcome measures associated with return to sport criteria, are summarised in the online supplemental table 1. Further information regarding the general characteristics of each reviewed study can also be found in the online supplemental table 2.

RT intensity

Seven of the studies expressed intensity as a percentage of 1RM, ranging from 5 to greater than 80% of 1RM.[28 29 32–36] Five studies expressed intensity as a repetition maximum, ranging from 30RM to 6RM (<65% of 1RM–85% of 1RM).[28 30 31 37 38] Six of the 11 studies reported interventions progressing in intensity from low to moderate high intensity in a periodised manner throughout the programme.[29–32 34 36] The majority of RT interventions were optimised for the development of muscle endurance and hypertrophy between 60% and 80% of 1RM (>15RM–8RM).[28–30 32–38] Perry *et al*'s[31] study was the only study to include RT intensities optimised to develop muscle strength (6RM or 85% of 1RM). The RT protocol described by Welling *et al*[36] stated intensities greater than 80% of 1RM in the final rehabilitation phase; however, it did not describe specifics.

Table 2 Downs and Black quality critique

	Downs and Black item number																											
Studies	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**Total**
Berschin *et al*[29]	1	1	1	1	2	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	0	1	1	0	21
Bieler *et al*[30]	1	1	1	1	2	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	0	1	1	0	25
Friedmann-Bette *et al*[37]	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	1	0	1	0	0	13
Fukuda *et al*[28]	1	1	1	1	2	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	26
Kang *et al*[33]	1	1	0	1	0	1	1	0	0	0	1	0	1	1	0	1	1	1	0	1	1	1	1	0	0	0	0	15
Kınıklı *et al*[34]	1	1	1	0	1	1	1	0	0	1	0	1	0	0	0	1	1	0	1	1	0	1	1	0	1	1	0	16
Lepley *et al*[35]	1	1	1	0	2	1	1	0	0	1	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0	1	1	15
Perry *et al*[31]	1	1	1	1	2	1	1	1	0	1	1	1	1	0	1	1	1	1	0	1	1	0	1	0	0	0	0	20
Risberg *et al*[32]	1	1	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1	0	1	1	1	0	0	22
Santos *et al*[38]	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	1	0	1	14
Welling *et al*[36]	1	1	1	1	1	1	1	0	1	1	0	0	1	0	0	1	0	1	0	1	1	0	0	0	0	0	1	15

Efficacy of interventions

Strength

Strength was measured in all studies except for the study performed by Perry *et al*.[31] The strength of either the quadriceps (knee extensors) or hamstrings (knee flexors) was assessed most commonly with an isokinetic dynamometer. Other measures relating to muscle strength that were evaluated included knee extensor muscle power,[30] quadriceps peak torque normalised to body weight[36] and extensor and flexor muscle endurance and 'squat' strength.[33]

Seven of the studies measured the LSIs.[28–30 32 36–38] Bieler *et al*[30] reported 98% (±4) LSI of the injured leg extensor power in the high-intensity RT group in comparison to 84% (±3) LSI in the low-intensity RT group following the intervention period (20 weeks post-ACLR), a statistically significant difference. Santos *et al*[38] assessed the subjects between 2 and 5 years post-ACLR and reported 111% and 128% quadriceps and hamstring LSIs, respectively, following the intervention, the highest among the included studies.

Quadriceps LSI among the remaining studies ranged from 62% (±18) to 94.1% (±14.6),[28 29 32 36 37] while hamstring LSI results ranged from 72% (±11) to 97.9% (±7.5).[28 29 32 36 37] Fukuda *et al*[28] and Welling *et al*[36] recorded the highest quadriceps LSI (94.1%±6 and 94.1±14.6) at approximately 6 and 10 months following ACLR, respectively. Welling *et al*[36] also recorded the highest hamstring LSI (97.9%±7.5). It should be noted that the study by Fukuda *et al*[28] included only participants who had undergone an ACLR using a hamstring tendon graft, while Welling *et al*[36] included participants who underwent a hamstring tendon or bone-patellar tendon graft.

Function

A variety of hop tests were used in six of the 11 studies. Bieler *et al*[30] reported 69% (±5) and 75% (±4) LSIs of the affected leg for a single and triple hop test in the high-intensity RT group, and 65% (±5) and 68% (±4) for the same measures in the low-intensity RT group following the intervention; these differences were not statistically significant. The single hop test results ranged from 65% (±5) to 95% (±8).[28 30–32 34 38] Results of the triple hop tests varied between 68% (±4) and 94%,[30 32 38] and results of the triple cross-over hop tests varied between 79% (±15) and 102%.[28 31 38]

Two studies reported hop test results and included participants approaching a traditional return to sport period immediately following intervention completion (6 months post-ACLR).[28 32] Both intervention groups in the study by Fukuda *et al*[28] achieved greater than 90% LSI or higher for the single hop test (92.3%±8.1 and 94.9±6.7) and cross-over hop tests (94.0±6.4 and 92.5±7.6). Risberg *et al*[32] reported the highest single hop and triple hop test LSI values in the neuromuscular training group (85%±11 and 89%±11, respectively) at 6 months post-ACLR, failing to achieve the return to sport criteria thresholds.

Objectives

Typically, the objectives of each study were focused on determining the effectiveness of different modes of RT, RT protocols or novel adjuncts to rehabilitation programmes against standard rehabilitation protocols, rather than explicitly investigating conventional RT as a cornerstone of the rehabilitation protocol. Only one study[30] expressly investigated a high-intensity versus low-intensity RT protocol.

Participants

The mean age of participants across all studies ranged from 22 to 33 years old; the mean age of participants across all studies was 27 years old. Males and females were included in all studies; however, the majority of participants were male. Participants who underwent either a hamstring tendon, quadriceps tendon or patella tendon graft ACLR were represented across studies.

Intervention duration

Intervention duration ranged from 6 to 41 weeks; participants completed two to three sessions per week. Interventions commenced between 1 and 12 weeks post-operatively, except Santos *et al*[38] who included participants between 2 and 5 years following ACLR. The majority of intervention periods were 12 weeks or greater in duration (n=8).[28–31 33–36 38] Fukuda *et al*,[28] Risberg *et al*[32] and Welling *et al*[36] represent the most complete rehabilitation protocols of included studies. Interventions commenced 1–2 weeks post-ACLR and were 25 weeks, 6 months and 10 months in duration, respectively. Aspects of the Risberg *et al*[32] and Welling *et al*'s[36] rehabilitation programmes were specifically designed to facilitate a return to sport.

RT effect on graft laxity

Five of the studies reviewed measured arthrometric graft laxity over the course of the intervention.[28–32] All studies reported no significant differences in graft laxity between intervention groups or any deleterious increases in joint laxity as a result of the intervention. Furthermore, no studies reported significant injury over the course of the study periods.

Adherence

Three studies specifically described adherence to RT protocols, measured by the number of planned sessions completed. Adherence rates were generally high, between 85% and 100%.[29 30 32]

DISCUSSION

This systematic review shows the disparity between the intensity of RT protocols found in the ACLR rehabilitation literature and the recommended intensities required for optimal neuromuscular development. Furthermore, it demonstrates the large variances between studies in using RT parameters post-ACLR, particularly the intensity of exercises. Protocols used RT with intensities as low as 50% of 1RM and as high as 85% of 1RM, the latter representing the lower end of the strength development continuum and only constitutes moderate intensity.[10 14 39 40] Protocols mostly incorporated RT intensities between 60% and 80% of 1RM in the mid and late stages of rehabilitation, sufficient to develop muscular endurance and stimulate hypertrophy.[14 41 42] Two studies incorporated RT that would facilitate the development of maximal force production (strength). Perry *et al*[31] prescribed exercises at 85% of 1RM and Welling *et al*[36] reported prescribing exercises above 80% of 1RM in the final phase of rehabilitation.

RT at the intensities primarily observed in the included studies limits the potential for participants to develop maximal strength.[12 14 42 43] Furthermore, these intensities fail to replicate the high physical demands required of a person during return to sport testing and of an athlete performing their sport.[43–47] This factor may contribute to the results of the included studies reflecting research that demonstrates ACLR patients often fail to achieve return to sport criteria.[3 9 15 28–32 34 37] Welling *et al*'s[36] study was the only study to report a greater than 90% LSI of both hamstring and quadriceps muscle groups among the participants. However, comparison between graft types revealed quadriceps LSI values below 90% for people who underwent a bone-patellar tendon-bone graft at 10 months post-ACLR (98.3%±8.4 and 87.1±12.5 quadriceps LSI for hamstring tendon and bone-patellar tendon-bone grafts, respectively).[36] Additionally, no other study reported restoration of strength to 90% LSI or greater of the muscle group from which the ACL graft was harvested. In the case of the person returning to sport following ACLR, it is crucial that these people eventually progress to RT employed by the injury-free population at high intensities (90% of 1RM and greater). This requirement would help to ensure that an adequate level of physical conditioning is achieved to sufficiently prepare the athlete for the rigours of sport.[10 11 48–50]

Periodisation allows a person to safely and effectively progress the RT protocol to higher intensities and facilitates maximal increases in strength.[10 51] However, only five of the 11 studies[29–32 36] used some form of linear periodisation, increasing intensity over the training period. The study by Welling *et al*[36] provides the clearest example of periodisation. The RT protocol in this study included four phases and three distinct RT microcycles over 10 months; intensity was progressed from <50% of 1RM (muscle endurance) to between 60% and 80% of 1RM (muscle hypertrophy), and finally to greater than 80% of 1RM (strength) with an emphasis on a fast concentric phase (power). The findings show that RT protocols typically only progressed from intensities optimised to promote muscle endurance to intensities optimised for muscle hypertrophy, without a further progression to strength and power. Inadequate periodisation can hinder the patient's performance in strength and function testing through a lack of progressive overload, limiting potential improvements.[52] Furthermore, RT protocols without periodisation, particularly when training at intensities optimised for hypertrophy, have been suggested to hinder physical performance through overtraining induced physical and/or mental fatigue.[12 50 51]

In athletic training, periodisation typically builds towards the athlete performing power-based RT.[10] The development of power through RT is considered an essential characteristic of an RT protocol as it reflects the demands placed on an athlete's neuromuscular system during maximal effort tasks.[53] Not only is power a defining feature of the hop test battery and agility tests commonly used in return to sport criteria, injury mechanisms typically involve maximal effort tasks that require a high power output.[3 15 54] Consequently, the patient must progress to power exercises to facilitate the greatest transfer of training effect.[3 14 48 49 54] Welling *et al*'s[36] study was the only study included in this review to incorporate elements of

RT that considered the development of power. Although Bieler *et al*[30] acknowledged the importance of power by measuring the effects of the intervention on leg extensor power, the protocol did not include RT optimised for power development. While a superior improvement in leg extensor power in the high-intensity compared with the low-intensity RT group was reported, a difference in hop test performance improvement was not seen.[30] The lack of distinction between group's hop test results may be explained by the RT protocol not progressing to power-based RT to facilitate a cross-over of training effect.

RT has been posited as the most important aspect of a rehabilitation programme following musculoskeletal injury.[10] However, rather than focusing on the application of testing foundational elements of RT, ACLR research has focused on novel interventions, accelerated protocols, training adjuncts and different types of RT.[28 29 33–35 52 55] The study carried out by Lepley *et al*[35] reflects this sentiment, which demonstrated that the addition of neuromuscular electrical stimulation to a 12-week RT protocol had no affect when comparing it to the RT protocol alone. Although current evidence-based guidelines promote the inclusion of RT from as early as 2 weeks post-ACLR, guidance for the application of RT variables including intensity is not defined.[56] More focus should be placed on investigating the foundational elements related to RT, such as exercise intensity, in this population.[10] The lack of attention on these elements in the literature reduces the importance of this aspect of ACLR rehabilitation and highlights an area that clinicians can improve.

Clinical practice

The findings of this systematic review include several implications that could affect clinical practice. The inconsistencies in RT protocols highlighted in this review reflect the existing research, which suggests that physiotherapists do not have the required information to develop suitable ACLR rehabilitation protocols.[20 21] The variability of current ACLR rehabilitation protocols in clinical practice and concurrent high reinjury rates may be explained by the lack of consistency across rehabilitation protocols used in the literature.[18 57 58]

A scarcity of literature exists that has investigated the protocols extending beyond 6 months post-ACLR. This is important for clinical practice because strength and function deficits commonly extend well beyond this time frame, suggesting that rehabilitation programmes should continue past this period.[3 9 19 22 56 59] At 6 months post-ACLR, the graft progresses through the ligamentisation phase, has undergone considerable structural and biological changes and can tolerate higher external loads.[60] Rehabilitation protocols completed before 6 months post-ACLR limit the opportunity to progress RT to higher intensities necessary for adequate physical preparation. The current literature leaves uncertainty for clinicians prescribing late-stage RT, which may be contributing to the discrepancy between clinicians' expected rehabilitation duration and a return to sport.[18] Evidence-based guidelines recommend rehabilitation continues for 9–12 months post-ACLR; however, the lack of literature accurately describing late-stage rehabilitation may be encouraging the premature completion of rehabilitation protocols and a subsequent return to sport.[56 59]

Fear of damaging the ACL graft may cause clinicians to underprescribe RT intensity. Fears about graft injury, particularly in the early and middle phases of graft healing through poor or aggressive exercise prescription, have historically been a well-debated topic.[31 61] Results reported by studies included in this review contribute to the notion that rehabilitation is safe and is not commonly the cause of complications following ACLR. No studies in this review reported serious injury or deleterious increases in graft laxity due to the exercise protocols.[28–32] Bieler *et al*[30] provide the most direct reassurance about the safety of higher intensity RT during graft proliferation and early ligamentisation (12 weeks post-ACLR). No difference was found in knee joint laxity between high-intensity and low-intensity RT groups. Furthermore, the study by Perry *et al*[31] prescribed the highest RT intensities (6RM) observed in this review during graft proliferation (from 8 weeks post-ACLR), typically considered to be a vulnerable stage of graft healing,[57] and reported no harmful effects to ligament laxity. While other parameters such as exercise type, range of movement and tempo should be considered when determining the safety of an exercise, intensities prescribed up to 6RM have been demonstrated to be safe in the early and middle stages of ACLR rehabilitation.[31]

Future research recommendations

A future trial should investigate the efficacy of a 12-month, criteria-driven, periodised rehabilitation protocol. The protocol should incorporate foundational RT principles to maximise the cross-over effect, including RT intensities up to or greater than 90% of 1RM and a microcycle focused on power development. The rehabilitation protocol should take place in a standard gym setting and progress towards independent patient-led sessions. Outcome measures should include an accepted return to sport criteria test battery, exercise tolerance (pain and swelling), training volume, adherence, long-term reinjury reporting and level of return to sport achieved.[62] Additional research investigating other foundational RT elements, particularly manipulating volume and frequency within a rehabilitation protocol, would provide further information to develop optimal RT programmes following ACLR.

Limitations

The review included studies where RT was not the primary variable being investigated. Because of this, the authors may have placed a reduced emphasis on the RT component of the protocol. The RT intensity used in these protocols may not be as applicable compared with the interventions that investigated RT as a primary variable. Furthermore, the specific outcome measures and interpretation of results were not used as inclusion criteria in this systematic review. This issue limited the ability to directly compare RT intensities and the efficacy of protocols between studies. Statistical analysis of the extracted data, such as analysing the relationship between RT intensity and outcome, was out of the scope of this systematic review. However, this could provide valuable information regarding the optimal prescription of RT intensity post-ACLR.

CONCLUSION

This systematic review highlights an area of ACLR rehabilitation that merits more high-quality research so that physiotherapists are better equipped to manage the patients successfully. There is currently no universally accepted best practice guideline for the prescription of RT following ACLR despite RT being a cornerstone of rehabilitation. Available literature detailing RT intensity within ACLR protocols is inconsistent, incomplete and mostly not aligned with recommended RT principles. Optimisation of the prescription of RT for people following ACLR could lead to improvements in strength and functional outcomes and possibly reduce reinjury rates. Recent ACLR rehabilitation research incorporating RT principles and emphasising the importance of RT has provided promising results; however, further research is required to develop guidelines to improve clarity, and in particular, to identify optimal RT variables in this population.

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REFERENCES

1. Zbrojkiewicz D, Vertullo C, Grayson JE. Increasing rates of anterior cruciate ligament reconstruction in young Australians, 2000-2015. *Med J Aust* 2018;208:354–8.
2. Edwards PK, Ebert JR, Joss B, *et al*. Patient characteristics and predictors of return to sport at 12 months after anterior cruciate ligament reconstruction: the importance of patient age and postoperative rehabilitation. *Orthop J Sports Med* 2018;6:2325967118797575.
3. Grindem H, Snyder-Mackler L, Moksnes H, *et al*. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. *Br J Sports Med* 2016;50:804–8.
4. Hewett TE, Di Stasi SL, Myer GD. Current concepts for injury prevention in athletes after anterior cruciate ligament reconstruction. *Am J Sports Med* 2013;41:216–24.
5. Panariello R, Stump T, Allen A. Rehabilitation and return to play following anterior cruciate ligament reconstruction. *Operative Techniques in Sports Medicine* 2017;25:181–93.
6. Paterno MV, Schmitt LC, Ford KR, *et al*. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med* 2010;38:1968–78.
7. Shelbourne KD, Gray T, Haro M. Incidence of subsequent injury to either knee within 5 years after anterior cruciate ligament reconstruction with patellar tendon autograft. *Am J Sports Med* 2009;37:246–51.
8. Webster KE, Feller JA. Exploring the high reinjury rate in younger patients undergoing anterior cruciate ligament reconstruction. *Am J Sports Med* 2016;44:2827–32.
9. Leister I, Kulnik ST, Kindermann H, *et al*. Functional performance testing and return to sport criteria in patients after anterior cruciate ligament injury 12-18 months after index surgery: a cross-sectional observational study. *Phys Ther Sport* 2019;37:1–9.
10. Lorenz DS, Reiman MP, Walker JC. Periodization: current review and suggested implementation for athletic rehabilitation. *Sports Health* 2010;2:509–18.
11. Hoover DL, VanWye WR, Judge LW. Periodization and physical therapy: bridging the gap between training and rehabilitation. *Phys Ther Sport* 2016;18:1–20.
12. Kraemer W, Fleck S. A review: factors in exercise prescription of resistance training. *J Strength Cond* 1988;10:36–41.
13. Goff AJ, Page WS, Clark NC. Reporting of acute programme variables and exercise descriptors in rehabilitation strength training for tibiofemoral joint soft tissue injury: a systematic review. *Phys Ther Sport* 2018;34:227–37.
14. Potter S. Review of the literature. guidelines for resistance training for Australian rules football. *JASC* 2016;24:59–68.
15. Kyritsis P, Bahr R, Landreau P, *et al*. Likelihood of ACL graft rupture: not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture. *Br J Sports Med* 2016;50:946–51.
16. Losciale JM, Zdeb RM, Ledbetter L, *et al*. The association between passing return-to-sport criteria and second anterior cruciate ligament injury risk: a systematic review with meta-analysis. *J Orthop Sports Phys Ther* 2019;49:43–54.
17. Ebert JR, Webster KE, Edwards PK, *et al*. Current perspectives of Australian therapists on rehabilitation and return to sport after anterior cruciate ligament reconstruction: A survey. *Phys Ther Sport* 2019;35:139–45.
18. Greenberg EM, Greenberg ET, Albaugh J, *et al*. Rehabilitation practice patterns following anterior cruciate ligament reconstruction: a survey of physical therapists. *J Orthop Sports Phys Ther* 2018;48:801–11.
19. Toole AR, Ithurburn MP, Rauh MJ, *et al*. Young athletes cleared for sports participation after anterior cruciate ligament reconstruction: how many actually meet recommended return-to-sport criterion cutoffs? *J Orthop Sports Phys Ther* 2017;47:825–33.
20. von Aesch AV, Perry M, Sole G. Physiotherapists' experiences of the management of anterior cruciate ligament injuries. *Phys Ther Sport* 2016;19:14–22.
21. Makhni EC, Crump EK, Steinhaus ME, *et al*. Quality and variability of online available physical therapy protocols from academic orthopaedic surgery programs for anterior cruciate ligament reconstruction. *Arthroscopy* 2016;32:1612–21.
22. Welling W, Benjaminse A, Seil R, *et al*. Low rates of patients meeting return to sport criteria 9 months after anterior cruciate ligament reconstruction: a prospective longitudinal study. *Knee Surg Sports Traumatol Arthrosc* 2018;26:3636–44.
23. Downs SH, Black N. The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and

non-randomised studies of health care interventions. *J Epidemiol Community Health* 1998;52:377–84.
24 Hooper P, Jutai JW, Strong G, *et al*. Age-related macular degeneration and low-vision rehabilitation: a systematic review. *Can J Ophthalmol* 2008;43:180–7.
25 Irving DB, Cook JL, Menz HB. Factors associated with chronic plantar heel pain: a systematic review. *J Sci Med Sport* 2006;9:11–22.
26 Mosler AB, Agricola R, Weir A, *et al*. Which factors differentiate athletes with hip/groin pain from those without? A systematic review with meta-analysis. *Br J Sports Med* 2015;49:810.
27 Munn J, Sullivan SJ, Schneiders AG. Evidence of sensorimotor deficits in functional ankle instability: a systematic review with meta-analysis. *J Sci Med Sport* 2010;13:2–12.
28 Fukuda TY, Fingerhut D, Moreira VC, *et al*. Open kinetic chain exercises in a restricted range of motion after anterior cruciate ligament reconstruction: a randomized controlled clinical trial. *Am J Sports Med* 2013;41:788–94.
29 Berschin G, Sommer B, Behrens A, *et al*. Whole body vibration exercise protocol versus a standard exercise protocol after ACL reconstruction: a clinical randomized controlled trial with short term follow-up. *J Sports Sci Med* 2014;13:580–9.
30 Bieler T, Sobol NA, Andersen LL, *et al*. The effects of high-intensity versus low-intensity resistance training on leg extensor power and recovery of knee function after ACL-reconstruction. *Biomed Res Int* 2014;2014:1–11.
31 Perry MC, Morrissey MC, King JB, *et al*. Effects of closed versus open kinetic chain knee extensor resistance training on knee laxity and leg function in patients during the 8- to 14-week post-operative period after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2005;13:357–69.
32 Risberg MA, Holm I, Myklebust G, *et al*. Neuromuscular training versus strength training during first 6 months after anterior cruciate ligament reconstruction: a randomized clinical trial. *Phys Ther* 2007;87:737–50.
33 Kang H, Jung J, Yu J. Comparison of strength and endurance between open and closed kinematic chain exercises after anterior cruciate ligament reconstruction: randomized control trial. *J. Phys. Ther* 2012;24:1055–7.
34 Kınıklı GI, Yüksel I, Baltacı G, *et al*. The effect of progressive eccentric and concentric training on functional performance after autogenous hamstring anterior cruciate ligament reconstruction: a randomized controlled study. *Acta Orthop Traumatol Turc* 2014;48:283–9.
35 Lepley LK, Wojtys EM, Palmieri-Smith RM. Combination of eccentric exercise and neuromuscular electrical stimulation to improve quadriceps function post-ACL reconstruction. *Knee* 2015;22:270–7.
36 Welling W, Benjaminse A, Lemmink K, *et al*. Progressive strength training restores quadriceps and hamstring muscle strength within 7 months after ACL reconstruction in amateur male soccer players. *Phys Ther Sport* 2019;40:10–18.
37 Friedmann-Bette B, Profit F, Gwechenberger T, *et al*. Strength training effects on muscular regeneration after ACL reconstruction. *Med Sci Sports Exerc* 2018;50:1152–61.
38 Santos HH, Sousa CdeO, Medeiros CLP, *et al*. Correlation between eccentric training and functional tests in subjects with reconstructed ACL. *Revista Brasileira de Medicina do Esporte* 2018;24:471–6.
39 González-Badillo JJ, Izquierdo M, Gorostiaga EM. Moderate volume of high relative training intensity produces greater strength gains compared with low and high volumes in competitive weightlifters. *J Strength Cond Res* 2006;20:73–81.
40 Fry AC. The role of resistance exercise intensity on muscle fibre adaptations. *Sports Med* 2004;34:663–79.
41 Toigo M, Boutellier U. New fundamental resistance exercise determinants of molecular and cellular muscle adaptations. *Eur J Appl Physiol* 2006;97:643–63.
42 Schoenfeld BJ. Is there a minimum intensity threshold for resistance training-induced hypertrophic adaptations? *Sports Med* 2013;43:1279–88.
43 Cormie P, McGuigan MR, Newton RU. Adaptations in athletic performance after ballistic power versus strength training. *Med Sci Sports Exerc* 2010;42:1582–98.
44 Gonzalo-Skok O, Tous-Fajardo J, Arjol-Serrano JL, *et al*. Improvement of repeated-sprint ability and horizontal-jumping performance in elite young basketball players with low-volume repeated-maximal-power training. *Int J Sports Physiol Perform* 2016;11:464–73.
45 Jensen R, Ebben W. Knee function, strength and resumption of preinjury sports participation in young athletes following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther* 2007;49:145–53.
46 Lamont HS, Cramer JT, Bemben DA, *et al*. Effects of 6 weeks of periodized squat training with or without whole-body vibration on short-term adaptations in jump performance within recreationally resistance trained men. *J Strength Cond Res* 2008;22:1882–93.
47 Tramel W, Lockie RG, Lindsay KG, *et al*. Associations between absolute and relative lower body strength to measures of power and change of direction speed in division II female Volleyball players. *Sports* 2019;7:160.
48 Cormie P, McGuigan MR, Newton RU. Developing maximal neuromuscular power: part 2 - training considerations for improving maximal power production. *Sports Med* 2011;41:125–46.
49 DeWeese BH, Hornsby G, Stone M. The training process: planning for strength–power training in track and field. Part 2: practical and applied aspects. *J Sport Health Sci* 2015;4:318–24.
50 Stone M, O'Bryant H, Garhammer J. A theoretical model of strength training. *Natl Strength Condit Assoc J* 1982;4:36–9.
51 Strohacker K, Fazzino D, Breslin WL, *et al*. The use of periodization in exercise prescriptions for inactive adults: a systematic review. *Prev Med Rep* 2015;2:385–96.
52 Beynnon BD, Johnson RJ, Naud S, *et al*. Accelerated versus nonaccelerated rehabilitation after anterior cruciate ligament reconstruction: a prospective, randomized, double-blind investigation evaluating knee joint laxity using roentgen stereophotogrammetric analysis. *Am J Sports Med* 2011;39:2536–48.
53 Cormie P, McGuigan MR, Newton RU. Developing maximal neuromuscular power: Part 1--biological basis of maximal power production. *Sports Med* 2011;41:17–38.
54 Wetters N, Weber AE, Wuerz TH. Mechanism of injury and risk factors for anterior cruciate ligament injury. *Oper Tech Sports Med* 2016;24:2–6.
55 Ohta H, Kurosawa H, Ikeda H, *et al*. Low-load resistance muscular training with moderate restriction of blood flow after anterior cruciate ligament reconstruction. *Acta Orthop Scand* 2003;74:62–8.
56 van Melick N, van Cingel REH, Brooijmans F, *et al*. Evidence-Based clinical practice update: practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus. *Br J Sports Med* 2016;50:1506–15.
57 Ardern CL, Taylor NF, Feller JA, *et al*. Sports participation 2 years after anterior cruciate ligament reconstruction in athletes who had not returned to sport at 1 year: a prospective follow-up of physical function and psychological factors in 122 athletes. *Am J Sports Med* 2015;43:848–56.
58 Webster KE, Feller JA, Leigh WB, *et al*. Younger patients are at increased risk for graft rupture and contralateral injury after anterior cruciate ligament reconstruction. *Am J Sports Med* 2014;42:641–7.
59 Ebert JR, Edwards P, Yi L, *et al*. Strength and functional symmetry is associated with post-operative rehabilitation in patients following anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2018;26:2353–61.
60 Scheffler SU, Unterhauser FN, Weiler A. Graft remodeling and ligamentization after cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2008;16:834–42.
61 Noehren B, Snyder-Mackler L. Who's afraid of the big bad wolf? open-chain exercises after anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther* 2020;50:473–5.
62 Ardern CL, Glasgow P, Schneiders A, *et al*. 2016 consensus statement on return to sport from the first world Congress in sports physical therapy, Bern. *Br J Sports Med* 2016;50:853–64.

Supplementary Table 1

Strength Exercise Intensity Compared with Return to Sport Outcome Measures

Study	Time Post-Op/RT Intensities & Graft Type	Strength LSI[a]			Hop Tests LSI[a]			
		Quadriceps	Hamstrings	Other	SH	TH	TCH	Other
Berschin et al., 2014 [28]	Weeks 2-5: 50-60% 1RM Weeks 6-11: 60-80% 1RM Graft: PT	Isometric - 70% $60^{os.-1}$ - 62%	Isometric - 75% $60^{os.-1}$ - 72%	-	-	-	-	-
Bieler et al., 2014 [29]	HI group Weeks 8-9: 20RM Weeks 10 & 11: 15RM Weeks 12-13: 12RM Weeks 14-20: 8RM LI group Weeks 8-9: 30RM Weeks: 10-20: 20RM Graft: PT & HT	-	-	Quadriceps Power: HI 97.5% LI 83.5%	HI 69% LI 65%	HI 75% LI 68%	-	-
Friedmann-Bette et al., 2018 [36]	Weeks 12-24: 8RM Graft: QT & HT	CON/ECC $60^{os.-1}$ - 80% $180^{os.-1}$ - 82% CON/ECC+ $60^{os.-1}$ - 78% $180^{os.-1}$ - 82%	-	-	-	-	-	-
Fukuda et al., 2013 [27]	Weeks 1/2-26/27: 10RM & 70% 1RM Graft: HT	EOKC 94.1% LOKC 89.5%	EOKC 84.5% LOKC 87.4%	-	EOKC 92.3% LOKC 94.9%	-	EOKC 94% LOKC 92.5%	-

Study	**Time post-op/RT Intensities & Graft Type**	**Strength LSI[a]**			**Hop Tests LSI[a]**			
		Quadriceps	**Hamstrings**	**Other**	**SH**	**TH**	**TCH**	**Other**
Kang et al., 2012 [32]	Weeks 12-24: 70% 1RM Graft: not disclosed	OKC (lb-ft) $60^{os.-1}$ - 118 (65% ↑) $180^{os.-1}$ - 80.4 (71%↑) CKC (lb-ft) $60^{os.-1}$ - 98.1 (21% ↑) $180^{os.-1}$ - 51.2 (160%↑)	OKC (lb-ft) $60^{os.-1}$ - 69.5 (94% ↑) $180^{os.-1}$ - 64.9 (45%↑) CKC (lb-ft) $60^{os.-1}$ - 55.6 (80% ↑) $180^{os.-1}$ – 40.8 (237%↑)	Squat (kg): OKC 164.7 (17% ↑) CKC 155.1 (17% ↑) Endurance (lb-ft): OKC Ext 80.4 (71%↑) Flx 51.2 (65%↑) CKC Ext 64.9 (45%↑) Flx 40.8 (237%↑)	-	-	-	-
Kiniliki et al., 2014 [33]	Weeks 3-15: 5-50% 1RM Graft: HT	Early Onset (Nm/kg) $60^{os.-1}$ - 68.8 (14%↑) $180^{os.-1}$ - 77.6 (32%↑) Standard (Nm/kg) $60^{os.-1}$ - 69.5 (8%↑) $180^{os.-1}$ - 63.5 (13%↑)	Early Onset (Nm/kg) $60^{os.-1}$ - 97 (10%↑) $180^{os.-1}$ - 103.9 (25%↑) Standard (Nm/kg) $60^{os.-1}$ - 81.2 (9%↑) $180^{os.-1}$ - 86.3 (18%↑)	-	Early Onset 91.1% Standard 84.6%	-	-	Vertical Hop: Early Onset 89.2% Early Onset 77.3%
Lepley et al., 2015 [34]	Weeks 6-12: 60% 1RM Graft: PT & HT	ECC 2.1 Nm/kg NMES + ECC 1.7 Nm/kg NMES 1.7 Nm/kg Standard 1.5 Nm/kg	-	-	-	-	-	-
Perry et al., 2005 [30]	Weeks 8-10: 20RM Weeks 11-13: 6RM Graft: PT and HT	-	-	-	OKC 77% CKC 74%	-	OKC 79% CKC 81%	Vertical Hop: OKC 75% CKC 78%

Study	Time post-op/RT Intensities & Graft Type	Strength LSI[a]			Hop Tests LSI[a]			
		Quadriceps	**Hamstrings**	**Other**	**SH**	**TH**	**TCH**	**Other**
Risberg et al., 2007 [31]	Weeks 2-27: 50-80% 1RM (phase 3), 3 x 6 Reps (phase 4) [b] Graft: PT	ST $60^{os.-1}$ – 67.3% $240^{os.-1}$ – 78% NT $60^{os.-1}$ – 79.1% $240^{os.-1}$ – 79%	ST $60^{os.-1}$ – 88.3% $240^{os.-1}$ – 94.7% NT $60^{os.-1}$ – 86.3% $240^{os.-1}$ – 90.8%	-	ST 81% NT 84.9%	ST 83.1% NT 88.5%	-	Stairs Hop: ST 79.8% NT 79.8%
Santos et al., 2018 [37]	2-5 years, 12 weeks: 10RM Graft: PT	Isometric - 94% [c] Con30$^{os.-1}$ - 89% [c] Con120$^{os.-1}$ - 93% [c] Ecc30$^{os.-1}$ - 111% [c] Ecc120$^{os.-1}$ - 104% [c]	Isometric - 107% [c] Con30$^{os.-1}$ - 105% [c] Con120$^{os.-1}$ - 110% [c] Ecc30$^{os.-1}$ - 128% [c] Ecc120$^{os.-1}$ - 125% [c]	-	93%	94%	102%	Figure-8 Hop: 101%
Welling et al., 2019 [35]	Weeks 2-16: <50% 1RM Weeks 17-31: 60-80% 1RM Weeks 32-48: >80% 1RM [d] Graft: PT & HT	3.9mo post-op: 72% 6.6mo post-op: 84.7% 9.7mo post-op: 94.1%	3.9mo post-op: 89.3% 6.6mo post-op: 96.6% 9.7mo post-op: 97.9%	Quads PT/BW 3.9mo post-op: 2.4 6.6mo post-op: 2.9 9.7mo post-op: 3.2	-	-	-	-

[a] LSI unless unit otherwise specified
[b] not specified if 6RM
[c] LSI comparison between pre-intervention non-injured leg and post-intervention injured leg
[d] Approximate weeks stated. Progression through stages of training varied depending on the individual (up to 4 weeks)
Note: In studies where only the raw data for return to sport outcome measures were reported, LSI's were calculated where possible; otherwise, percentage increases have been provided.
Abbreviations: PT, patellar tendon; $^{os.-1}$, degrees per second; %, per cent; +, and; HI, high intensity; LI, low intensity; HT, hamstring tendon; QT, quadriceps tendon; CON, concentric; ECC, eccentric; ECC+, eccentric overload; EOKC/LOKC, early/late start open kinetic chain; OKC, open kinetic chain; CKC, closed kinetic chain; kg, kilograms; Ext, Extension; Flx, Flexion; ST, strength training; lb-ft, pounds per feet; mo, months, NM/kg, newton-meters per kilogram; NT, neuromuscular training; ↑, increased/improved; N, neuromuscular electrical stimulation; post-op, post-operative; Quads PT/BW, quadriceps peak torque normalised to bodyweight; RM, repetition maximum; SH, single-hop; TH, triple hop; TCH, triple crossover hop

Supplementary Table 2

General Characteristics of Studies

Study	Objective	Downs and Black Score	Participants	Duration	Exercise Parameters	Outcome Measures	Results
Berschin et al., 2014	Investigate the effectiveness of WBV exercise in ACLR rehabilitation compared with a standard protocol	21 - Good	29/11 (m/f) 27.5yo (mean) 86.6 days from injury to surgery 1-week post-op	2 sessions per week, 10 weeks	Weeks 2-5: 2-4 x 12-20 reps & 2-3 x 15-30 reps at 50-60% 1RM Weeks 6-11: 2-4 x 8-12 at & 2-4 x 15-20 reps at 60-80% 1RM	Knee flx & ext strength Balance Lysholm scale	No difference in knee joint laxity between groups, within 2mm of contralateral side Strength deficits improvements similar between groups WBV superior to standard protocol to improve balance Lysholm scores improved in both groups, no difference between groups
Bieler et al., 2014	Compare high-intensity resistance training as part of ALCR rehabilitation with low intensity resistance training	25 - Good	31/19(m/f). 29.2yo (mean) 40.3mo (HRT) & 16.8mo (LRT) from injury to surgery 8 weeks post-op	12 weeks	HI Weeks 8-9: 1 x 20 – 3 x 15 reps, 20RM. Weeks 10 & 11: 1 x 15 - 3 x 12 reps, 15RM Weeks 12-13: 1 x 12 – 3 x 10 reps, 12RM. Weeks 14-20: 1 x 8 – 3 x 8 reps, 8RM LI Weeks 8-9: 1 x 30 – 2 x 20 reps, 30RM. Weeks 10-20: 1 x 20 – 2 x 20 reps, 20RM	Knee joint laxity Leg extensor power KOOS Lysholm scale Tegner scale Single & triple hop tests	Knee joint laxity did not change from week 7 to 20, no difference between groups ↑ muscle power HI compared with LI at 14 & 20 weeks No difference in hop test results No difference between groups in self-assessed function. Lysholm: 80 both groups Tegner: HI 4, LI 3 KOOS: pre-surgery levels at 20 weeks both groups No difference in adherence

Study	Objective	Downs and Black Score	Participants	Duration	Exercise Parameters	Outcome Measures	Results
Friedmann-Bette et al., 2018	Investigate the effects of concentric-eccentric overload strength training versus concentric-eccentric strength training on muscular regeneration following ACLR	13 - poor	55m/13f 25yo (mean) 12 weeks post-op	2 sessions per week, 12 weeks	6 x 8 reps, 8RM. 90s rest between sets	Knee ext muscle strength CSA quad femoris Muscle biopsy sampling	MCSA: - 4% ↑ (CON/ECC) - 11% ↑ (CON/ECC+) (no sig. difference) Graft type did not affect MSCA FCSA: ↑ in FCSA for all fiber types after 12 weeks (no difference between groups) Greater type 1 fibers in ST group than in PT ↑ in peak torque at both velocities ($60^{\circ s.-1}$& $180^{\circ s.-1}$) in both groups (no difference between groups) Type of graft effected peak torque - higher peak torque of semi-ten group Peak torque correlated with MCSA in both training groups ↑ in type 1 fibres in CON/ECC+ group Myofibers expressing MHCneo ↑, higher in CON/ECC+ group

Study	Objective	Downs and	Participants	Duration	Exercise	Outcome	Results

		Black Score			Parameters	Measures	
Fukuda et al., 2013	Determine if early start on OKC exercises would promote a clinical improvement without causing laxity post-ACLR	26 - Excellent	29m/16f 25yo (mean) 12mo from injury to surgery 1-2 weeks post-op	3 sessions per week, 25 weeks	3 x 10 reps, 10RM and 3 x 15 reps at 70% of 1RM, and isometrics	Knee flx, ext strength Anterior knee laxity Pain Single and triple hop tests, cross-over hop test Lysholm scale	No difference in laxity between groups EOKC group had improved quads strength at 19weeks, 25 weeks and 17 months compared with 12 weeks post-op. LOKC groups sig. difference in quads strength only at 17 months compared with 12 weeks post-op No difference between groups in self-reported function, hop tests and pain
Kang et al., 2012	Investigate the differences in strength and endurance of patients who performed OKC and CKC exercises post-ACLR.	15 - Fair	24m/12f. 29yo (mean). 12 weeks post-op.	3 sessions per week, 12 weeks.	5 x 12 reps at 70% 1RM, 30 seconds rest between sets.	Knee flx, ext strength & endurance Squat strength	OKC group demonstrated greater difference in strength and endurance of extensor muscles No difference in squat strength ↑
Kiniliki et al., 2014	Assess the functional outcomes of early onset progressive eccentric and concentric training in patients with ACLR	16 - Fair	31m/2f. 33.2yo (mean) 3.1mo from injury to surgery 3 weeks post-op	3 sessions per week, 12 weeks	2-3 sets (2-3mins recovery between) 5%1RM - 50%1RM progressed gradually weekly	Knee flx and ext strength Vertical jump Single hop test Lysholm scale ACL-QoL	No difference in isokinetic strength of knee extensors and flexors between study and control group Vertical jump test, single hop for distance test, Lysholm knee scale, ACL-QoL demonstrated greater improvement in the study group compared with control

Study	Objective	Downs and Black Score	Participants	Duration	Exercise Parameters	Outcome Measures	Results

Study	**Objective**	**Downs and Black Score**	**Participants**	**Duration**	**Exercise Parameters**	**Outcome Measures**	**Results**
Lepley et al., 2015	Determine if a combination of NMES and eccentric exercise would be effective at improving quadriceps muscle strength in patients following ACLR	15 - Fair	23m/13f. 21.6yo (mean) 78.6 days from injury to surgery 6 weeks post-op	2 sessions weekly, 6 weeks	4 x 10 reps, 60% 1RM, 2 min rests between sets	Quads activation and strength	No difference in quads strength and activation between NMES + ECC and ECC only groups at RTP Strength deficits and QAF in NMES only group at RTP compared with healthy controls Healthy controls stronger than SR group at RTP NMES + ECC and ECC only groups had ↑ quads activation at RTP compared with SR and N only groups NMES + ECC and ECC only demonstrated greater strength gains compared with NMES only and SR groups ECC only ↑ quads strength compared with standard rehab at RTP Changes in quads strength related to increased quads activation No difference in quads strength and activation between healthy controls and NMES + ECC and ECC only at RTP

Study	Objective	Downs and Black Score	Participants	Duration	Exercise Parameters	Outcome Measures	Results
Perry et al., 2005	Compare the effects of a CKC versus an OKC training regimen on knee joint laxity and function post ACLR	20 - Good	37m/12f 33yo (mean) CKC group - 811 days from injury to surgery OKC group – 1340 days from injury to surgery 8 weeks post-op	2 sessions per week, 6 weeks	Wk 1-3: 3 x 20 reps, 20RM Wk 4-6: 3 x 6 reps 6RM	Knee joint laxity Single, vertical, cross-over hop tests. Hughston clinic questionnaire ROM Knee circumference	No difference in knee laxity between groups No difference in self-reported function or functional hop tests between groups
Risberg et al., 2007	Determine the effect of an NT program vs a strength program on knee function following ACLR	22 - Good	47m/27f 28.4yo (mean) Injury occurred less than 3 years before surgery 2 weeks post-op	2-3 sessions per week, 6 months	Phase 3: 3 x 12-15 reps progressing to 3 x 8-12 reps at 50-80% 1RM Phase 4: 3 x 6-8 reps	Cincinatti Knee Score SF36 VAS pain and knee function Knee flx, ext strength Balance Proprioception Single, triple hop test, stair hop test	91% adherence in ST group. 71% adherent in NT group (80% or > attendance) No difference in knee joint laxity between groups at 6 months No difference between the groups for any outcome measurements at 3 months No difference in muscle strength variables Decline in quads strength and hop tests from pre-op period to 6 months post-op

Santos et al., 2018	Correlate possible gains in knee extensor and flexor torque generated by isokinetic training with hop tests post-ACLR	14 - poor	16n 2-5 years post-op	2 sessions per week, 12 weeks	3 x 10 reps, 10RM, 3-minute rest between sets	Knee ext and flx strength Single, triple, crossover, figure 8 hop tests	Knee ext strength deficit in affected leg at pre-training Knee ext strength deficits remained post-training ↑ in knee flx strength post-training compared with knee ext SH, TH and F8 tests ↑ compared with pre-training Moderate correlation between knee ext strength and single hop for AL, strong correlation for NAL Moderate correlation between knee flx strength and SH
Welling et al. 2019	Compare results of a RT protocol for soccer players after ACLR with healthy controls	15 – fair	38m 24.2yo (mean) 2 weeks post-op	2.6 sessions (mean) per week, 10 months	Phase 2: 2 x 15-25 reps (<50% 1RM) Phase 3: 2-4 x 8-10 reps (60-80% 1RM) & 2 x 15-25 reps (<50% 1RM) Phase 4: 5 x 3 reps (>80% 1RM) & 2 x 15-25 reps (<50% 1RM)	Peak quads and hamstring strength	4 months post-ACLR quads strength weaker than control 7 months post-ACLR no difference in quads or hamstring strength compared to control 10 months post-ACLR hamstring strength greater than control 10 months post-ACLR 65.8% passed quads & 76.3% passed hamstring LSI>90%

Abbreviation: $^{\circ}s^{-1}$, degrees per second; %, percent; +, and; >, greater than; ACL-QoL, anterior cruciate ligament quality of life; WBV, whole body vibration; Sig., Significant; RCT, randomised controlled trial; m, male; f, female; yo, years old; flx, flexor; ext, extensor; RT, resistance training; HI, high intensity; LI, low intensity; ↑, increased/improved; CON, concentric; ECC, eccentric; ECC+, eccentric overload; CSA, cross-sectional area; MCSA, muscle cross-sectional area; FCSA, fascicle cross-sectional area; PT, patellar tendon graft; ST, semitendinosis tendon graft; mm, millimetres; MHCneo, neonatal myosin heavy-chain (measure of muscle regeneration/remodelling); NMES, neurmomuscular electrical stimulation; OKC, open kinetic chain; CKC, closed kinetic chain; EOKC/LOKC, early/late start open kinetic chain; NMES, neuromuscular electrical stimulation; RTP, return to play; SR, standard rehabilitation; Pre-op, pre-operative; Post-op, post-operative; QAF, quadriceps activation failure; ROM, range of movement; NT, neuromuscular training; s, seconds; ST, strength training; AL, affected limb; NAL, non-affected limb; Reps, repetitions; SH, single hop; TH, triple hop; F8, figure 8 hop