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

Zackary William Nichols, Daniel O’Brien, Steven Gordon White

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. Following surgery, rehabilitation is essential to ensure a return to full function by addressing postoperative strength and neuromuscular control deficits associated with reinjury. A comprehensive rehabilitation programme following ACLR is crucial for those who intend to return to sport, as reinjury rates are high in this population; literature indicates that rupture rates are 18% or higher in the young athletic population. 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. Of concern, Leister et al 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 postoperative deficits and facilitate a safe return to sport through a wide range of exercise modalities. Rehabilitation aims to restore muscular strength, with resistance training (RT) being a crucial programme...
rehabilitation is being prescribed. Physiotherapists have also reported confusion surrounding the prescription and progression of exercises throughout ACLR rehabilitation. 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.

Although the causes of reinjury are multifactorial, an RT protocol that fails to address postoperative neuromuscular deficits is likely to be a crucial factor. 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. 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’, 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

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**Table 1 Search terms and Boolean operators**

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<th>Order of terms searched</th>
<th>Search terms and operators</th>
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<td>Search 1 (S1)</td>
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<td>Search 2 (S2)</td>
<td>(strength* OR resistance OR weight* OR exercise OR intensity OR maximal) N5/W5 (train* OR program* OR protocol*)</td>
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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, but 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. This tool is sufficiently reliable and valid for determining the methodological quality of randomised controlled trials and non-randomised trials. The modified tool has previously been used in other published systematic reviews. 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, four studies as good quality, four studies as fair quality and two studies as poor quality. 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 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. Five studies expressed intensity as a repetition maximum, ranging from 30RM to 6RM (<65% of 1RM–85% of 1RM). Six of the 11 studies reported interventions progressing in intensity from low to moderate high intensity in a periodised manner throughout the programme. The majority of RT interventions were optimised for the development of muscle endurance and hypertrophy between 60% and 80% (15RM–8RM). Perry et al’s 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 stated intensities greater than 80% of 1RM in the final rehabilitation phase; however, it did not describe specifics.
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 weight36 and extensor and flexor muscle endurance and ‘squat’ strength.33

Seven of the studies measured the LSIs.28–30,32–38 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 30 32 36 37 while hamstring LSI results ranged from 72% (±11) to 97.9% (±7.5).28 30 32 36 37 Fukuda et al.30 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.30 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 36

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.30 achieved greater than 90% LSI or higher for the single hop test (92.9%±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 study30 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.28 who included participants between 2 and 5 years following ACLR. The majority of intervention periods were 12 weeks or greater in duration (n=8).26–51 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.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.26–32 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 variations 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 30 46 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.41 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 29–32 34 35 Welling et al.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 studies29–32 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.32 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.16 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.30 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 34 Consequently, the patient must progress to power exercises to facilitate the greatest transfer of training effect.34 48 49 54 Welling et al.36 study was the only study included in this review to incorporate elements of


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RT that considered the development of power. Although Bieler et al.\(^6\) 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.\(^29,25\) 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.\(^3,9,19,22,56,58\) 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.\(^36,39\)

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.\(^6\) 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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CONTRIBUTORS ZWN designed and conceptualised the review, collected the data, analysed the results, and drafted and revised the paper. DOB contributed to the study design and provided supervision over and revised the paper.

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REFERENCES


23. Downs SH, Black N. The feasibility of creating a checklist for the assessment of the methodological quality of both randomised and


## Supplementary Table 1

*Strength Exercise Intensity Compared with Return to Sport Outcome Measures*

<table>
<thead>
<tr>
<th>Study</th>
<th>Time Post-Op/RT Intensities &amp; Graft Type</th>
<th>Quadriceps</th>
<th>Hamstrings</th>
<th>Other</th>
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<th>TH</th>
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<td>Berschin et al., 2014 [28]</td>
<td>Weeks 2-5: 50-60% 1RM Weeks 6-11: 60-80% 1RM</td>
<td>Isometric - 70% 60°s.-1 - 62%</td>
<td>Isometric - 75% 60°s.-1 - 72%</td>
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<td>Friedmann-Bette et al., 2018 [36]</td>
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<td>CON/ECC 60°s.-1 - 80% 180°s.-1 - 82% CON/ECC+ 60°s.-1 - 78% 180°s.-1 - 82%</td>
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<td>Kang et al., 2012 [32]</td>
<td>Weeks 12-24: 70% 1RM</td>
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<td>180° s.-1: 80.4 (71%↑)</td>
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<td>60° s.-1: 98.1 (21%↑)</td>
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| Kiniliki et al., 2014 [33]   | Weeks 3-15: 5-50% 1RM | Graft: HT | Early Onset (Nm/kg) | - | Early Onset | 60° s.-1: 68.8 (14%↑) | Early Onset | 180° s.-1: 77.6 (32%↑) | -  | 91.1% | 84.6% | Vertical Hop: |
|                              |                |                         | 60° s.-1: 97 (10%↑) | 180° s.-1: 103.9 (25%↑) | Standard | 60° s.-1: 197.2 (8%↑) | Standard | 60° s.-1: 81.2 (9%↑) | -  | 89.2% | 77.3% | Early Onset |
|                              |                |                         | 180° s.-1: 69.5 (8%↑) | 180° s.-1: 86.3 (18%↑) | -   |             | -   | -   | -   | -   | -    |

| Lepley et al., 2015 [34]     | Weeks 6-12: 60% 1RM | Graft: PT & HT | ECC | - | -  | OKC | - | OKC | Vertical Hop: |
|                              |                |                         | 2.1 Nm/kg | - | -   | 77% | - | 79% | OKC |
|                              |                |                         | NMES + ECC | 1.7 Nm/kg | CKC | 74% | - | CKC | OKC |
|                              |                |                         | Standard | 1.7 Nm/kg | 1.5 Nm/kg | 81% | - | CKC | 75% |

<p>| Perry et al., 2005 [30]      | Weeks 8-10: 20RM | Graft: PT and HT | - | - | - | OKC | - | OKC | Vertical Hop: |
|                              | Weeks 11-13: 6RM |                         | 77% | - | CKC | OKC | 75% | CKC | 78% |</p>
<table>
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<th>Study</th>
<th>Time post-op/RT</th>
<th>Intensities &amp; Graft Type</th>
<th>Strength LSI&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Hop Tests LSI&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risberg et al., 2007 [31]</td>
<td>Weeks 2-27: 50-80% 1RM (phase 3), 3 x 6 Reps (phase 4)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Graft: PT</td>
<td>ST 60&lt;sup&gt;a,-1&lt;/sup&gt; – 67.3% 240&lt;sup&gt;a,-1&lt;/sup&gt; – 78%</td>
<td>ST 81%</td>
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<td>Hamstrings</td>
<td>SH 83.1%</td>
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<td>Other 84.9%</td>
<td>TCH NT</td>
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<td>Other 88.5%</td>
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<td></td>
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<td></td>
<td>Other 79.8%</td>
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<tr>
<td>Santos et al., 2018 [37]</td>
<td>2-5 years, 12 weeks: 10RM</td>
<td>Graft: PT</td>
<td>Isometric - 94%&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Isometric - 107%&lt;sup&gt;c&lt;/sup&gt;</td>
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<tr>
<td></td>
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<td>Con30° 89%&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Con30° 93%&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>Con120° 93%&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Con120° 110%&lt;sup&gt;c&lt;/sup&gt;</td>
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<td></td>
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<td></td>
<td>Ecc30° 111%&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Ecc30° 128%&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>Ecc120° 104%&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Ecc120° 125%&lt;sup&gt;c&lt;/sup&gt;</td>
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<tr>
<td>Welling et al., 2019 [35]</td>
<td>Weeks 2-16: &lt;50% 1RM</td>
<td>Graft: PT &amp; HT</td>
<td>3.9mo post-op: 72% 6.6mo post-op: 84.7%</td>
<td>3.9mo post-op: 89.3%</td>
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<tr>
<td></td>
<td>Weeks 17-31: 60-80% 1RM</td>
<td></td>
<td>9.7mo post-op: 94.1%</td>
<td>3.9mo post-op: 96.6%</td>
</tr>
<tr>
<td></td>
<td>Weeks 32-48: &gt;80% 1RM</td>
<td></td>
<td>Quads PT/BW 3.2</td>
<td>2.9</td>
</tr>
</tbody>
</table>

<sup>a</sup> LSI unless unit otherwise specified  
<sup>b</sup> not specified if 6RM  
<sup>c</sup> LSI comparison between pre-intervention non-injured leg and post-intervention injured leg  
<sup>d</sup> 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; °s.-1, degrees per second; %, per cent; +, and; HL, 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.
<table>
<thead>
<tr>
<th>Study</th>
<th>Objective</th>
<th>Downs and Score</th>
<th>Participants</th>
<th>Duration</th>
<th>Exercise Parameters</th>
<th>Outcome Measures</th>
<th>Results</th>
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</thead>
<tbody>
<tr>
<td>Berschin et al., 2014</td>
<td>Investigate the effectiveness of WBV exercise in ACLR rehabilitation compared with a standard protocol</td>
<td>21 - Good</td>
<td>29/11 (m/f)</td>
<td>2 sessions per week, 10 weeks</td>
<td>Weeks 2-5: 2-4 x 12-20 reps &amp; 2-3 x 15-30 reps at 50-60% 1RM Weeks 6-11: 2-4 x 8-12 at &amp; 2-4 x 15-20 reps at 60-80% 1RM</td>
<td>Knee flx &amp; ext strength Balance Lysholm scale</td>
<td>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</td>
</tr>
<tr>
<td>Bieler et al., 2014</td>
<td>Compare high-intensity resistance training as part of ACLR rehabilitation with low intensity resistance training</td>
<td>25 - Good</td>
<td>31/19(m/f). 29.2yo (mean) 40.3mo (HRT) &amp; 16.8mo (LRT) from injury to surgery 8 weeks post-op</td>
<td>12 weeks</td>
<td>HI Weeks 8-9: 1 x 20 – 3 x 15 reps, 20RM. Weeks 10 &amp; 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 &amp; triple hop tests</td>
<td>Knee joint laxity did not change from week 7 to 20, no difference between groups ↑ muscle power HI compared with LI at 14 &amp; 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</td>
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<tr>
<td>Study</td>
<td>Objective</td>
<td>Downs and Black Score</td>
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<tr>
<td>Friedmann-Bette et al., 2018</td>
<td>Investigate the effects of concentric-eccentric overload strength training versus concentric-eccentric strength training on muscular regeneration following ACLR</td>
<td>13 - poor</td>
<td>55m/13f 25yo (mean) 12 weeks post-op</td>
<td>2 sessions per week, 12 weeks</td>
<td>6 x 8 reps, 8RM. 90s rest between sets</td>
<td>Knee ext muscle strength  CSA quad femoris Muscle biopsy sampling</td>
<td>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°s^-1 &amp; 180°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</td>
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<tr>
<td>Study</td>
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<tr>
<td>Fukuda et al., 2013</td>
<td>Determine if early start on OKC exercises would promote a clinical improvement without causing laxity post-ACLR</td>
<td>26 - Excellent</td>
<td>29m/16f 25yo (mean) 12mo from injury to surgery 1-2 weeks post-op</td>
<td>3 sessions per week, 25 weeks</td>
<td>3 x 10 reps, 10RM and 3 x 15 reps at 70% of 1RM, and isometrics</td>
<td>Knee flx, ext strength Anterior knee laxity Pain Single and triple hop tests, crossover hop test Lysholm scale</td>
<td>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</td>
</tr>
<tr>
<td>Kang et al., 2012</td>
<td>Investigate the differences in strength and endurance of patients who performed OKC and CKC exercises post-ACLR</td>
<td>15 - Fair</td>
<td>24m/12f 29yo (mean) 12 weeks post-op</td>
<td>3 sessions per week, 12 weeks</td>
<td>5 x 12 reps at 70% 1RM, 30 seconds rest between sets.</td>
<td>Knee flx, ext strength &amp; endurance Squat strength</td>
<td>OKC group demonstrated greater difference in strength and endurance of extensor muscles No difference in squat strength ↑</td>
</tr>
<tr>
<td>Kiniliki et al., 2014</td>
<td>Assess the functional outcomes of early onset progressive eccentric and concentric training in patients with ACLR</td>
<td>16 - Fair</td>
<td>31m/2f 33.2yo (mean) 3.1mo from injury to surgery 3 weeks post-op</td>
<td>3 sessions per week, 12 weeks</td>
<td>2-3 sets (2-3mins recovery between) 5%1RM - 50%1RM progressed gradually weekly</td>
<td>Knee flx and ext strength Vertical jump Single hop test Lysholm scale ACL-QoL</td>
<td>No difference in isokinetic strength of knee extensors and flexors between study and control group</td>
</tr>
</tbody>
</table>

No difference between groups in self-reported function, hop tests and pain

Vertical jump test, single hop for distance test, Lysholm knee scale, ACL-QoL demonstrated greater improvement in the study group compared with control
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**

<table>
<thead>
<tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>15 - Fair</td>
<td>23m/13f</td>
<td>2 sessions weekly, 6 weeks</td>
<td>4 x 10 reps, 60% 1RM, 2 min rests between sets</td>
<td>Quads activation and strength</td>
<td>No difference in quads strength and activation between NMES + ECC and ECC only groups at RTP</td>
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<tr>
<td></td>
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<td>21.6yo (mean)</td>
<td>78.6 days from injury to surgery</td>
<td>6 weeks post-op</td>
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<td>Strength deficits and QAF in NMES only group at RTP compared with healthy controls</td>
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<td>Healthy controls stronger than SR group at RTP</td>
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<td>NMES + ECC and ECC only groups had ↑ quads activation at RTP compared with SR and N only groups</td>
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<td>NMES + ECC and ECC only demonstrated greater strength gains compared with NMES only and SR groups</td>
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<td>ECC only ↑ quads strength compared with standard rehab at RTP</td>
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<td>Changes in quads strength related to increased quads activation</td>
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<td></td>
<td>No difference in quads strength and activation between healthy controls and NMES + ECC and ECC only at RTP</td>
</tr>
</tbody>
</table>

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**Perry et al., 2005**

**Objective:** Compare the effects of a CKC versus an OKC training regimen on knee joint laxity and function post ACLR

- **Participants:** 37m/12f
  - CKC group - 33yo (mean)
  - OKC group - 811 days from injury to surgery
  - CKC group - 811 days from injury to surgery
- **Duration:** 8 weeks post-op
- **Exercise Parameters:**
  - Wk 1-3: 3 x 20 reps, 20RM
  - Wk 4-6: 3 x 6 reps 6RM
- **Outcome Measures:**
  - Knee joint laxity
  - Single, vertical, cross-over hop tests.
  - Hughston clinic questionnaire
  - ROM
  - Knee circumference
- **Results:**
  - No difference in knee laxity between groups
  - No difference in self-reported function or functional hop tests between groups

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**Risberg et al., 2007**

**Objective:** Determine the effect of an NT program vs a strength program on knee function following ACLR

- **Participants:** 47m/27f
  - 28.4yo (mean)
  - Injury occurred less than 3 years before surgery
  - 2 weeks post-op
- **Duration:** 6 months
- **Exercise Parameters:**
  - 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
- **Outcome Measures:**
  - Cincinnati Knee Score
  - SF36
  - VAS pain and knee function
  - Knee flx, ext strength
  - Balance
  - Proprioception
  - Single, triple hop test, stair hop test
- **Results:**
  - 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

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Perry et al., 2005</td>
<td>Compare the effects of a CKC versus an OKC training regimen on knee joint laxity and function post ACLR</td>
<td>20 - Good</td>
<td>37m/12f</td>
<td>8 weeks per week</td>
<td>Wk 1-3: 3 x 20 reps, 20RM</td>
<td>Knee joint laxity</td>
<td>No difference in knee laxity between groups</td>
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<tr>
<td>Perry et al., 2005</td>
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<td>33yo (mean)</td>
<td>6 weeks</td>
<td>Wk 4-6: 3 x 6 reps 6RM</td>
<td>Single, vertical, cross-over hop tests.</td>
<td>No difference in self-reported function or functional hop tests between groups</td>
</tr>
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<td>Risberg et al., 2007</td>
<td>Determine the effect of an NT program vs a strength program on knee function following ACLR</td>
<td>22 - Good</td>
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<td>Risberg et al., 2007</td>
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<td>28.4yo (mean)</td>
<td>2-3 sessions per week</td>
<td>Phase 4: 3 x 6-8 reps</td>
<td>SF36</td>
<td>No difference between the groups for any outcome measurements at 3 months</td>
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<td>Risberg et al., 2007</td>
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<td>Injury occurred less than 3 years before surgery</td>
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<td>2 weeks post-op</td>
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<td>Proprioception</td>
<td>Single, triple hop test, stair hop test</td>
<td>Decline in quads strength and hop tests from pre-op period to 6 months post-op</td>
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<tr>
<td>Study Reference</td>
<td>Study Description</td>
<td>Participants</td>
<td>Intervention Details</td>
<td>Outcome Measures</td>
<td>Summary of Findings</td>
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<tr>
<td>Santos et al., 2018</td>
<td>Correlate possible gains in knee extensor and flexor torque generated by isokinetic training with hop tests post-ACLR</td>
<td>14 - poor, 2-5 years post-op</td>
<td>2 sessions per week, 12 weeks, 3 x 10 reps, 10RM, 3-minute rest between sets</td>
<td>Knee ext and flx strength</td>
<td>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</td>
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<tr>
<td>Welling et al. 2019</td>
<td>Compare results of a RT protocol for soccer players after ACLR with healthy controls</td>
<td>15 – fair, 24.2yo (mean), 2 weeks post-op</td>
<td>2.6 sessions (mean) per week, 10 months, Phase 2: 2 x 15-25 reps (&lt;50% 1RM), Phase 3: 2-4 x 8-10 reps (60-80% 1RM) &amp; 2 x 15-25 reps (&lt;50% 1RM), Phase 4: 5 x 3 reps (≥80% 1RM) &amp; 2 x 15-25 reps (&lt;50% 1RM)</td>
<td>Peak quads and hamstring strength</td>
<td>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 &amp; 76.3% passed hamstring LSI&gt;90%</td>
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</table>

**Abbreviation:** °, 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, neuromuscular 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