Resistance Training Intensity Following an Anterior Cruciate Ligament Repair: A Systematic Review

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Glossary of Terms

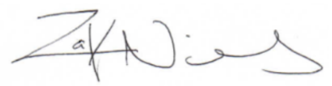
Resistance training (RT) intensity. RT intensity is commonly presented in one of two ways in the literature, either as a percentage of an individual's one repetition maximum (1RM) strength test, or alternatively expressed on a repetition maximum continuum (e.g. 8-12RM). For the purpose of this dissertation intensity will be presented as it has been stated in the study that is being referred to. Where needed to enable comparison, the alternative expression will be placed in brackets. When expressed generally throughout this dissertation (i.e. not in relation to a specific study), percentage of 1RM will be used. For reference, Table 1 serves as a guide to translate RT intensity from percentage of 1RM to the corresponding repetition maximum.

Abbreviations

ACL. Anterior cruciate ligament
ACLR. Anterior cruciate ligament repair
LSI. Leg symmetry index
RM. Repetition maximum
RT. Resistance training

Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.



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Abstract

Introduction. Anterior cruciate ligament repair (ACLR) is becoming increasingly common in Australia. Strength and functional deficits commonly persist beyond a person's return to sport following an ACLR, and reinjury rates are high. Resistance training (RT) is considered a key component to an ACLR rehabilitation protocol. Furthermore, RT intensity is a crucial variable determining the physiological response of the neuromuscular system. Currently the optimal prescription of RT intensity following ACLR is unknown, and there is no universally accepted best-practice approach to prescribing an RT program following ACLR.

Objective. This systematic review aimed to identify, critique and synthesise the findings of research that has evaluated the effectiveness of RT programs on physical return to sport outcome measures. This review will present the quality of the identified literature, the alignment of current ACLR RT protocols with recommended RT guidelines and the sufficiency of current RT protocols to achieve return to sport criteria and address post-ACLR deficits.

Methods. A comprehensive search of electronic databases (EBSCO health databases [CINAHL, MEDLINE, SPORTDiscus], Scopus and Pedro) was performed and identified studies relevant to the objective. A quality critique of the selected studies was undertaken using a modified Downs and Black appraisal tool. Data central to the study objective were extracted and presented.

Results. In total 10 articles were retained for final review, five of which were categorised as excellent or good quality. Study quality ranged from excellent to poor. RT intensity varied greatly among studies (between 5% and >80% of 1RM). Only one identified study specifically investigated the effect of a low versus high intensity RT protocol. One study investigated the effects of a rehabilitation protocol from time of surgery to beyond six months post-surgery. The majority of studies reported objective data relating to strength and function that would not pass recommended return to sport thresholds.

Conclusion: RT intensity reported in ACLR rehabilitation literature varies considerably. Furthermore, there appears to be no consensus regarding optimal RT intensity following ACLR. Most RT protocols promoted muscle endurance and hypertrophy. Best-practice guidelines informed by high quality evidence are needed to optimise function and minimise risk of reinjury following ACLR.

Resistance Training Intensity Following an Anterior Cruciate Ligament Repair: A Systematic Review

Chapter 1: Introduction

The anterior cruciate ligament (ACL) is a critical contributor to knee joint stability, helping to control anterior translation of the tibia relative to the femur and internal rotation (Duthon et al., 2006). ACL injury mechanisms most commonly involve a sudden and high velocity pivot, deceleration and change of direction, or landing from a jump (Wetters, Weber, Wuerz, Schub, & Mandelbaum, 2016). ACL rupture accounts for a large proportion of knee injuries and the current consensus for best management among the younger athletic population to facilitate return to sport is for surgical ACL repair (ACLR) (Ithurburn, Longfellow, Thomas, Paterno, & Schmitt, 2019; Tsoukas, Fotopoulos, Basdekis, & Makridis, 2016).

The incidence rate of primary ACLR in Australia is 77.4 per 100,000, the highest in the world (Zbrojkiewicz, Vertullo, & Grayson, 2018). This rate dwarfs that of comparable countries including New Zealand (37 per 100,000) and the United States (52 per 100,000) (Zbrojkiewicz et al., 2018). Furthermore, in Australia the rate is trending upwards steeply. The incidence of primary ACLR increased by 43% between 2000/2001 and 2014/2015 (Zbrojkiewicz et al., 2018). The cost of a single ACLR in Australia ranges between $5000 and $14,000, and in 2017 the total cost was estimated at $142 million per year (RACS, 2017; Zbrojkiewicz et al., 2018). Surgery alone represents a substantial economic burden; however, there are additional long-term costs associated with ACLR, including the economic and societal costs of rehabilitation and chronic disease later in life (Filbay & Grindem, 2019).

Health professionals recommend that a comprehensive rehabilitation protocol is completed following ACLR (Edwards et al., 2018). Rehabilitation is particularly important for people who intend on returning to sport as reinjury rates are higher in this population compared with those who do not return to sport (Shelbourne, Gray, & Haro, 2009). Rehabilitation aims to restore function by addressing post-operative strength and neuromuscular control deficits associated with reinjury through the prescription of a supervised, criteria-driven protocol (Edwards et al., 2018; Grindem, Snyder-Mackler, Moksnes, Engebretsen, & Risberg, 2016; Hewett, Di Stasi, & Myer, 2013; Panariello, Stump, & Allen, 2017; Paterno et al., 2010).

ACLR rehabilitation should address post-operative deficits and facilitate return to sport through a wide-range of exercise modalities including cardiovascular, range of movement, proprioceptive and neuromuscular exercises. An essential component of rehabilitation should be the restoration of muscular strength, with some authors suggesting that resistance training (RT) is the most important aspect of a rehabilitation program (Lorenz, Reiman, & Walker, 2010). Furthermore, the intensity of prescribed resistance exercises is considered the primary component of RT to achieve the desired training effect (Hoover, VanWye, & Judge, 2016; Kraemer, Fleck, & Deschenes, 1988; Lorenz et al., 2010).

Return to sport criteria are an established clinical tool to determine a patient's readiness for returning to high risk sport, and have been developed to assess the desired physical qualities necessary for a safe return to sport (Losciale, Zdeb, Ledbetter, Reiman, & Sell, 2019). Return to sport criteria typically include achievement of greater than 90% leg strength symmetry, a hop test battery and patient-reported outcome measures such as the Knee Outcome Survey (Grindem et al., 2016). Edwards et al. (2018) demonstrated that completion of a comprehensive rehabilitation program was predictive of return to sport 12 months after surgery. A comprehensive program was described as one that included completion of greater than six months of supervised rehabilitation incorporating structured gym exercises and agility, landing and hop-based exercises (Edwards et al., 2018). A greater proportion of these participants achieved physical return to sport criteria (37%) compared with those who underwent incomplete rehabilitation (5%) 12 months after surgery (Edwards et al., 2018).

Re-rupture following ACLR is common. Literature indicates that re-rupture rates are 18% or higher in the young athletic population (Webster & Feller, 2016), and only 60% of athletes who have undergone an ACLR return to their pre-injury level of sport (Ardern, Taylor, Feller, Whitehead, & Webster, 2015). Despite the importance placed on a thorough rehabilitation program, modifiable deficits in lower limb strength and function related to reinjury can extend beyond 12 months following surgery, and commonly persist after return to sport (Leister et al., 2019). Of concern, Leister et al. (2019) reported that as few as 30% of people who have already returned to sport could pass return to sport criteria 12-18 months after surgery. This prolonged deficit may reflect poor prescription or completion of rehabilitation protocols following ACLR.

There appears to be confusion and a lack of consensus among physiotherapists surrounding ACLR rehabilitation. Surveys of physiotherapists have shown a lack of consistency when determining return to sport clearance (Ebert et al., 2019; Greenberg, Greenberg, Albaugh, Storey, & Ganley, 2018), and Greenberg et al. (2018) reported that 56% of physiotherapists believed five months of rehabilitation was sufficient following ACLR. Additionally, Toole et al.

(2017) demonstrated that only 44% of patients had achieved a quadriceps limb symmetry index (LSI) of greater than 90% at the time of clearance to return to sport. These findings show an inadequate consideration of established criteria by surgeons and physiotherapists that were involved in the return to sport decision making process. Furthermore it may suggest that suboptimal rehabilitation is being prescribed to prepare patients for a return to sport and to mitigate the risk of reinjury (Grindem et al., 2016). Physiotherapists have also reported confusion surrounding the prescription and progression of exercises throughout ACLR rehabilitation (von Aesch, Perry, & Sole, 2016). This confusion is likely accentuated by wide variability in available standardised rehabilitation protocols, the majority of which do not stress the importance of addressing impairments related to reinjury prior to return to sport (Makhni et al., 2016). Although the causes of reinjury are multifactorial, a resistance training (RT) protocol that fails to address post-operative neuromuscular deficits is likely to be one important factor (Welling et al., 2018). Currently there does not appear be any consensus for the application and progression of RT intensity throughout the ACLR rehabilitation process to optimally address post-operative strength deficits. Furthermore, it is unclear whether prescription of insufficient RT intensity is contributing to the undesirable outcomes commonly described in this population.

The objective of this systematic review was to identify, critique and synthesise the findings of research that has evaluated the effectiveness of RT programs (where intensity has been defined) on physical return to sport outcome measures. While it is recognised that the success of ACLR rehabilitation can be measured through many different means, this systematic review focussed on the RT reported in literature, and has purposefully not explored the impact of patient reported outcome measures or psychological readiness on successful return to sport.

Research Questions

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 indicated by the literature, sufficient to ensure that post-operative physical deficits are adequately addressed, enabling patients to meet physical return to sport criteria?

Clinical Significance

Reviewing ACLR rehabilitation RT intensity will shed light on a critical aspect of rehabilitation that may need to improve. This review will help to draw attention to an aspect of the rehabilitation process that may be significantly contributing to the high reinjury rates in the ACLR population. The results and synthesised discussion will help to inform further areas of research, improve the clinical application and effectiveness of RT following ACLR, and ultimately lead to a potential reduction in reinjury and improved outcomes for patients.

Dissertation Structure

This chapter (Chapter 1) has outlined the need for and the objectives of the study. Chapter 2 presents a narrative review of important background information with respect to key factors that need to be considered when prescribing an RT program following ACLR. This chapter will provide context to the overall dissertation. Chapter 3 describes the methods and findings of the systematic review of the literature. The quality of the research, findings and key data including the RT intensity utilised within study protocols and the effectiveness of these protocols will be presented. Chapter 4 will synthesise the results of the systematic review through a discussion, culminating in identifying the clinical implications of the systematic review and identifying areas of future research.

Chapter 2: ACLR Rehabilitation Resistance Training Principles and Considerations

This chapter provides important detail and considerations about the prescription of RT following ACLR. The chapter begins with a brief overview of tissue healing following ACLR. Next is a description of RT and the importance of exercise intensity and information about the periodisation of an ACLR RT framework. The chapter concludes with a summary of existing return to sport criteria as a measure of rehabilitation success.

Tissue Healing

When prescribing ACLR rehabilitation and determining the appropriate level of intensity, the stage of healing, including graft ligamentisation and integration of the graft into the bone, must be considered (Scheffler, Unterhauser, & Weiler, 2008). Ligamentisation describes the biological changes that occur in the donor graft following ACLR. These changes are the result of functional adaptation of the tissue to the specific mechanical loads and the biological environment to which it is exposed (Scheffler et al., 2008). The mechanical loads have implications for the biomechanical properties of the graft, and in turn, are an important consideration when prescribing RT (Scheffler et al., 2008).

Graft healing can be separated into several key phases. Early graft healing commences from the time of repair until approximately the fourth week post-operatively. It is characterised by graft swelling, necrosis and a reduction of cells within the graft. Remodelling begins in the superficial layers of the graft as early as the first one to two weeks (Scheffler et al., 2008). The collagen structure, and therefore mechanical properties of the graft, are still largely maintained. Because of this, the graft insertion sites are the weakest point of the repair during this phase (Scheffler et al., 2008). Despite the vulnerability of the graft, it is recognised that sufficient loading of the graft at this time is important to promote an increase in tensile strength (Ohno, Yasuda, Yamamoto, Kaneda, & Hayashi, 1993).

The proliferation phase occurs during the fourth and twelfth weeks post-operatively, when cellular activity is most prevalent and revascularisation commences. Most of the histological change and remodelling in the graft is observed at this time, owed to the release of growth factors that peak at the third and sixth weeks and cease at the twelfth (Kuroda, Kurosaka, Yoshiya, & Mizuno, 2000; Scheffler et al., 2008). The increase in fibroblasts contributes to the restoration of graft tension. However, it is during this period, specifically weeks six to eight, when the graft is at its weakest mechanically due to a loss of collagen density and organisation, hyper-revascularisation, and cellular proliferation (Scheffler et al., 2008). Although the graft appears vulnerable during this phase, it should be acknowledged that accelerated rehabilitation protocols are safe and do not appear to have a detrimental biomechanical effect on the graft (Beynnon et al., 2011).

The final stage of healing is known as ligamentisation. This phase is characterised by the ongoing remodelling of the graft and does not have a definitive endpoint. Between six and 12 months post-operatively the mechanical strength and biological properties of the graft move closer to, although not equal to, that of an intact ACL (Scheffler et al., 2008). Animal models have demonstrated the ‘functional adaptation effect’ occurring within the graft; a term used to describe the mechanical and biological changes soft tissues undergo as a result of the mechanical forces and biological environment to which they are exposed (Scheffler et al., 2008). In the case of a typical ACLR (hamstring or patella tendon autograft), graft properties shift from tendinous to ligamentous during this stage. Mechanical strength appears to reach a maximum at approximately 12 months; however, research suggests that they never reach the same strength as that of an intact ACL (Ng, Oakes, Deacon, McLean, & Eyre, 1996; Scheffler et al., 2008; Weiler, Hoffmann, Bail, Rehm, & Sudkamp, 2002). Additionally, histological differences in collagen type compared with the intact ACL have been observed in animal models at one year, although there is evidence that this returns to normal within three years of surgery (Ng et al., 1996).

Separate to the healing of the graft, healing of the articular surfaces of the knee joint must also be considered following ACLR. Articular surface and subchondral bone injuries of the knee during acute ACL rupture are common (Driban, Lohmander, & Frobell, 2017; Frobell et al., 2008). Bone marrow lesions, otherwise referred to as “bone bruises”, have been shown on magnetic resonance imaging to occur in up to 98% of acute ACL injuries, alongside a 57% cortical fracture rate, the majority of which occur in the lateral compartment (Driban et al., 2017; Frobell et al., 2008). Bone bruise healing is variable and dependent on severity. In more severe cases resolution of the lesion may take more than a year (Nagelli & Hewett, 2017). Additionally, meniscal injuries have been shown to occur in 39% of ACL injuries (Felli et al., 2016). Premature stress to these injured tissues may prolong a metabolic and degenerative joint environment following an ACLR (Nagelli & Hewett, 2017). Because of this, monitoring of patient symptoms and consideration of articular lesion severity and location should be made when prescribing and progressing exercise following ACLR (Lorenz et al., 2010).

Resistance Training (RT)

RT is a fundamental exercise modality utilised to improve athletic performance and condition athletes to the physical demands of their sport (referred to as sport-readiness) (Hoover et al., 2016; Lauersen, Andersen, & Andersen, 2018). Additionally, RT plays a role in reducing the risk of injury (Lauersen et al., 2018). Recent research has demonstrated a relationship between greater lower body strength and a reduced incidence of injury in athletes playing competitive sport (Malone, Hughes, Doran, Collins, & Gabbett, 2019). The utilisation of fundamental RT principles, while concurrently considering the stage of healing following ACLR, is a considerable challenge faced by physiotherapists and patients. However, prescription of an appropriate RT protocol remains an essential component of ACLR rehabilitation. Although the graft's integrity and the biological environment of the knee joint is altered following surgery (Scheffler et al., 2008; Song et al., 2017), the basic underlying principles and goals of RT do not change.

The forces an athlete is exposed to during sport provide some insight into the level of lower limb strength development required through the appropriate progression of RT following ACLR. Knee joint ground reaction forces in a controlled environment during plyometric exercises can be nearly 10 times bodyweight (Jensen & Ebben, 2007). This load reflects the more than four-fold increased risk of ACL re-rupture in patients who return to level one sport (cutting, jumping, pivoting) (Grindem et al., 2016).

There are six foundational elements of training which should be considered when prescribing and progressing an ACLR rehabilitation program. These are mode, intensity, specificity, duration, volume and frequency (Hoover et al., 2016). This dissertation focuses on RT intensity. RT (the mode) is a central, and considered by some authors as the most important, element of a rehabilitation program (Goff, Page, & Clark, 2018; Lorenz et al., 2010). Intensity is considered the principal variable of RT that determines the specific physiological adaptations produced (Hoover et al., 2016; Kraemer et al., 1988; Lorenz et al., 2010).

Intensity

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) strength test, or as a repetition maximum continuum (for example, 8-12RM) (Goff et al., 2018; Lorenz et al., 2010). The latter expression of intensity is more commonly used in rehabilitation as testing to obtain 1RM is generally unsafe in injured populations (Lorenz et al., 2010). Table 1 shows percentage of 1RM and the equivalent repetition maximum (Potter, 2016). High-intensity RT refers to high load with low repetitions; conversely, low-intensity refers to low load and high repetitions (Lorenz et al., 2010).

Table 1

Percentage of Repetition Maximum and Equivalent Repetition Maximums

Percentage of 1 Repetition Maximum	Repetition Maximum
100%	1
95%	2
90%	4
85%	6
80%	8
75%	10
70%	11
65%	15

Adapted from Potter (2016)

Adequate intensity is essential to elicit optimal physiological neuromuscular adaptations (Lorenz et al., 2010). However, it should be recognised that RT is a physiological stressor which demands a response by the body. Appropriately prescribed intensity is important in the rehabilitation process to induce the desired adaptation while maintaining tissue health (Hoover et al., 2016). RT must be prescribed at ever-increasing intensities to elicit a continually adaptive physiological response; this is known as progressive overload (Hoover et al., 2016). If insufficient stress or exercise intensity is prescribed, the desired adaptations, namely muscle hypertrophy, increased muscle strength and rate of force development, will not occur. Conversely, if excessive intensity is prescribed the body will struggle to restore homeostasis; this is referred to as over-training (Hoover et al., 2016). This consideration is especially important in the ACLR population where potentially detrimental effects to the healing graft and joint surfaces need to be considered (Morrissey, Perry, & King, 2009; Nyland, Brand, & Fisher, 2010; Scheffler et al., 2008).

Higher intensities between 85% 1RM and 95% 1RM (6RM and 2RM) are necessary to optimise strength improvements (Kraemer et al., 1988). Furthermore, moderate to high intensity RT has been shown to be more effective at improving explosive tasks over low intensity RT (Sousa et al., 2018). A meta-analysis performed by Lauersen et al. (2018) demonstrated the importance of sufficient RT intensity in the athletic population, where programs with higher intensities correlated strongly with injury prevention. High-intensity training modalities are also required to improve functional performance by replicating the physical demands of sport such as high-speed changes of direction, jumping and landing (Cormie, McGuigan, & Newton, 2010; Gonzalo-Skok et al., 2016; Lamont et al., 2008). Research determining the relationship between lower limb strength and functional performance measures has found mixed results (Sheppard, Dawes, Jeffreys, Spiteri, & NImphius, 2014). However, a recent study demonstrated the role lower limb strength plays in athletic performance, revealing strong correlations between lower limb strength and functional measures including the modified t-test and the triple hop test in collegiate volleyball players (Tramel, Lockie, Lindsay, & Dawes, 2019). Furthermore, experimental evidence has shown improvements in power, jump squat and depth jump performance following completion of moderate to high intensity RT protocols (75% to 90% of 1RM) in both healthy untrained and athletic populations (Cormie et al., 2010; Gonzalo-Skok et al., 2016; Lamont et al., 2008).

Phases of resistance training following ACLR

RT is optimised to improve different aspects of neuromuscular function depending on the intensity that is prescribed. To succinctly prescribe an RT program following ACLR the purpose of the exercise and corresponding intensity must be well understood. To restore full neuromuscular function of the affected limb varying demands must be placed on the patient through RT to address deficiencies in muscle endurance, size, strength and power.

Hypertrophy. Hypertrophy refers to an increase in cross-sectional area of muscle tissue. This is important, particularly in the initial stages of rehabilitation, as considerable atrophy is observed following ACLR (Gerber et al., 2007). Hypertrophy at this stage prepares both the muscle and the patient overall for high-intensity strength and power training in the later stages of rehabilitation; furthermore, an increase in muscle size increases the potential gain in strength and power (Stone, O'Bryant, Garhammer, McMillan, & Rozenek, 1982). Optimal intensities are low for the development of muscle size and endurance, approximately 60-80% of 1RM (Potter, 2016; Stone et al., 1982).

Strength. Strength is defined as the ability of the muscle to generate maximum force and is improved through both nervous system adaptations and changes in muscular morphology (Cormie, McGuigan, & Newton, 2011a; Potter et al., 2016). The recommended intensity range to improve strength is approximately 85-100% of 1RM (Kraemer et al., 1988; Potter, 2016). Measures of lower limb maximum force production are universally used in ACLR return to sport criteria to determine readiness for sport, highlighting the importance of RT at these intensities to develop this characteristic (Losciale et al., 2019).

Power. Power involves a combination of force and velocity (that is, the ability to produce force quickly) and best reflects the demands placed on muscle during high-risk sport (Potter, 2016; Stone et al., 1982). Applying the principle of specificity, power development is an essential component of athletic performance, particularly when change of direction or explosive movement is required, and is reflected in the hop tests commonly included in return to sport criteria (DeWeese, Hornsby, Stone, & Stone, 2015; Grindem et al., 2016; Kyritsis, Bahr, Landreau, Miladi, & Witvrouw, 2016; Potter, 2016; Stone et al., 1982). Optimal intensities to develop power depend on the body area being trained (Soriano, Jimenez-Reyes, Rhea, & Marin, 2015), and are typically performed at light to moderate intensities to allow for the higher velocity of the given movement. For example, intensities between 30-70% of 1RM are known to provide optimal load for power production during a squat (Potter, 2016; Soriano et al., 2015).

Periodisation

Organised progression of exercise intensity should be made throughout the rehabilitation process to safely promote neuromuscular adaptations (Hoover et al., 2016). Periodisation describes a long-term approach to RT, sequentially and systematically progressing different elements of the exercise protocol, in particular intensity, to achieve the desired training effect (Hoover et al., 2016; Potter, 2016). A meta-analysis by Williams, Tolusso, Fedewa, and Esco (2017) demonstrated that periodisation of RT is superior to non-periodised training in producing strength gains. Although higher intensities are required to ensure an optimal training effect, they are not appropriate in the early stages of the rehabilitation process (Hoover et al., 2016). Periodisation provides an effective framework which can safely guide physiotherapists and their patients in the prescription and progression of appropriate and adaptation inducing phases of RT following ACLR (Hoover et al., 2016; Horschig, Neff, & Serrano, 2014).

There are two widely accepted approaches to periodisation in RT: linear and non-linear periodisation (Lorenz et al., 2010). Linear periodisation breaks a 12-month training period into mesocycles (approximately four months), and microcycles (approximately four weeks). Each microcycle has a distinct training goal with reflective training intensity (Lorenz et al., 2010). Microcycle training goals typically progress through muscle endurance, hypertrophy, strength development and power development stages. A non-linear approach manipulates intensity within each week of training. With this approach aspects of endurance, hypertrophy, strength and power are performed weekly (Lorenz et al., 2010).

Linear periodisation is recommended in the ACLR population as it allows for higher intensities to be introduced later in the rehabilitation process. Further benefiting the patient, linear periodisation allows the lengthy rehabilitation process to be broken into distinct phases with clear short-term goals to work towards (Hoover et al., 2016). Additionally, linear periodisation is more efficient at producing increases in strength compared with a non-linear approach (Painter et al., 2012). This is important to note in the context of ACLR rehabilitation, as improved training efficiency represents less overall training volume for the same gain in strength. Reduced training volume may mediate the risk of injuries related to overtraining and, of particular importance to the amateur athlete, represents a reduced time commitment (Brooks, Fuller, Kemp, & Reddin, 2008; Quarrie et al., 2001).

Panariello et al. (2017) recommended a criteria driven framework for rehabilitation following ACLR, utilising a periodised approach by breaking the rehabilitation process into distinct phases. The framework was based on the hierarchy of athletic development, and was originally developed to identify the necessary stages an athlete must progress through in order to achieve optimal athletic development. The framework was modified to recognise the needs of an ACLR patient as equal to the athlete preparing for sport, while allowing for restoration of mobility and neuromuscular function before introducing traditional strength and conditioning principles (Appendix A). The framework is separated into five phases; RT is commenced at the second stage, and is progressed through increasing intensities along the rehabilitation process. Table 2 shows an adaptation of the ACLR rehabilitation framework presented by Panariello et al. (2017) with consideration of periodisation and the traditional phases of RT with corresponding intensities (Painter et al., 2012; Stone et al., 1982).

Table 2

Periodised Protocol for ACLR Resistance Training

	Rehabilitation Phases			
	II	III	IV	V
Goal	Muscle hypertrophy & endurance – preparation for high intensity RT	Strength – Increase force production, late stage preparation for power	Power – increase in RFD & function e.g. jump & COD, reduced fatigue	Discharge criteria & RTS
Intensity	3-5 sets of 8-15 reps at 8-15RM	3-5 sets of ≤6 reps at ≥6RM	3-5 sets of 2-3 reps & plyometrics	Strength & conditioning in the context of given sport

Adapted from Panariello et al. (2017)
Abbreviations: Reps, repetitions; RM, repetition maximum; RFD, rate of force development; COD, change of direction; RTS, return to sport
Note: Phase I is absent from the table as it is focussed on the reduction of swelling and pain, and restoration of range of movement. Phase I does not include prescription of resistance training.

Return to Sport Criteria and Reinjury

Return to sport criteria following ACLR have been developed to objectively determine when a safe return to sport following ACLR is indicated. Table 3 provides an example of this (Grindem et al., 2016; Kyritsis et al., 2016). While there is a consensus that passing objective return to sport criteria is important in reducing injury risk following ACLR, the effectiveness of current criteria to predict a second ACL injury is not yet clear (Losciale et al., 2019). Following a meta-analysis of return to sport criteria, Losciale et al. (2019) advocated for more strict criteria to improve the sensitivity of criteria in predicting risk of reinjury. In particular it was suggested that patients should achieve 100% strength and function LSI scores. An LSI is determined by dividing the injured leg's strength or function score with the non-injured leg's score and then multiplying this by 100 (expressed as a percentage). The current LSI standard used is 90% or greater. Kyritsis et al. (2016) found a fourfold increased risk of ACL graft rupture for those people who did not pass return to sport criteria. Additionally, Grindem et al. (2016), estimated an 84% lower knee reinjury rate among people who passed return to sport criteria and promoted the inclusion of lower limb strength outcomes as a criterion for a return to sport.

Table 3

Return to Sport Criteria

Test	**Return to Sport Discharge Criteria**
Strength	LSI >90% quadriceps & hamstrings
Single hop	LSI >90%
Triple hop	LSI >90%
Triple crossover hop	LSI >90%
On-field sports specific rehabilitation	Fully completed
Running t test	<11s

Adapted from Grindem et al. (2016) and (Kyritsis et al., 2016)
Abbreviations: LSI, limb symmetry index

Lower limb strength plays an important role in mitigating the risk of reinjury. Grindem et al. (2016) reported that quadriceps strength deficit before returning to sport was a predictor of reinjury; every 1% increase in strength symmetry accounted for a 3% decreased reinjury rate. For context, of the people who returned to sport with LSI below 90%, 33% sustained reinjuries, compared with 13% of those who demonstrated strength symmetry above 90%. Similarly, Kyritsis et al. (2016) reported an increased risk of ACL reinjury in people who demonstrated a lower hamstring to quadriceps strength ratio. Grindem et al. (2016) also revealed a relationship between time from surgery and reinjury following ACLR, where 40% of people who returned to sport before nine months from surgery sustained reinjuries, compared with 19% of those who returned to sport after nine months. It has been suggested that time from surgery is simply a surrogate measure of increased time for a patient to address strength deficits (Losciale et al., 2019).

Chapter 3: Systematic Review

The systematic review will principally address the research objective relating to the quality of the literature that evaluates the effectiveness of RT where intensity has been defined. Additionally, it will inform the discussion through identification of RT intensities found in the ACLR rehabilitation literature and corresponding results. The chapter begins by describing the search strategy and quality assessment used in the study. Following this, the results of the quality assessment and key extracted data, including results related to the research objectives, are presented.

Search Strategy

A comprehensive search of electronic databases was performed in June 2019. Databases included: EBSCO health databases (CINAHL, MEDLINE, SPORTDiscus), Scopus and Pedro. Two key concepts being “anterior cruciate ligament” and “strength training” were identified and searched separately. Alternative terms that reflected these concepts were also used (Table 4). “Anterior cruciate ligament” and the alterative terms were designated as “search 1” (S1), and “strength training” and the alternative terms were designated as “search 2” (S2). S1 and S2 were first searched independently and the number of results noted. Final results were determined by combining S1 and S2. Search terms were combined with “AND” and all alternatives for either anterior cruciate ligament and strength training were combined with ‘OR’, or a proximity operator. This process was performed for each database to ensure all relevant studies would be identified through an efficient and systematic process. Boolean and proximity operators and truncation symbols used were specific to the database searched. Appendix B provides an example of the search strategy and findings for the EBSCO health databases.

Table 4

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*)

Titles of all identified studies were considered. Studies were retained if the title indicated primary research had been undertaken regarding post-operative ACL interventions. Duplicates were discarded. The abstracts of the retained studies were read for relevance and studies were retained if an exercise-based protocol was included in the intervention. Full-text versions of each of these studies were obtained and reviewed to determine if the study met the inclusion and exclusion criteria. Reference lists from the identified studies were reviewed for possible additional studies not identified by the database search. Finally, the texts of all remaining articles were subject to quality appraisal and data extraction. EBSCO health databases were searched first as they were the largest and most comprehensive collection of resources, followed by Scopus and then Pedro. The search strategy for the Pedro database was altered as the search tool did not allow Boolean Operators, and was significantly smaller than EBSCO health databases and Scopus; the search term ‘anterior cruciate ligament’ was used for the Pedro database.

Inclusion Criteria

Randomised and non-randomised controlled trials, longitudinal cohort studies and case series were all considered for inclusion in the review. Articles were included where an adequate description of an RT intervention as a part of an ACLR rehabilitation protocol for six weeks or greater was provided. The RT intervention did not necessarily have to be the primary independent variable investigated. For example, a study investigating the effectiveness of a neuromuscular electrical stimulation protocol against a standard rehabilitation protocol could be included. Exercise descriptors deemed necessary for the study to be included were: the number of sets and repetitions of a given RT protocol, the type of exercise and exercise intensity. Exercise intensity could either be measured as a percentage of one-repetition maximum or ‘*n*’ repetition maximum.

Exclusion Criteria

Meta-analyses, questionnaires and qualitative research were excluded. Studies where full texts were not available, were not published in a peer-reviewed journal or where an English version was not available were discarded.

Study Quality Appraisal and Data Extraction

A modified Downs and Black appraisal tool (Appendix C) was used to assess the quality of selected articles (Downs & Black, 1998). This tool is sufficiently reliable and valid for assessing the methodological quality of both randomised controlled trials and non-randomised trials (Downs & Black, 1998). The Downs and Black tool is a checklist of 27 questions where results can be quantified as a numerical value. Items were either scored a one or zero, with the exception of item five which was scored between a zero and two, for a highest total possible score of 28. The modified tool has previously been used in other published systematic reviews (Hooper, Jutai, Strong, & Russell-Minda, 2008; Irving, Cook, & Menz, 2006; Losciale et al., 2019; Mosler, Agricola, Weir, Holmich, & Crossley, 2015; Munn, Sullivan, & Schneiders, 2010). The total of the appraisal scores for each study were used to give an indication of overall study quality, categorised as follows: poor (14 or below), fair (15-19), good (20-25) and excellent (26-28) (Hooper et al., 2008). The results from each study were weighted accordingly.

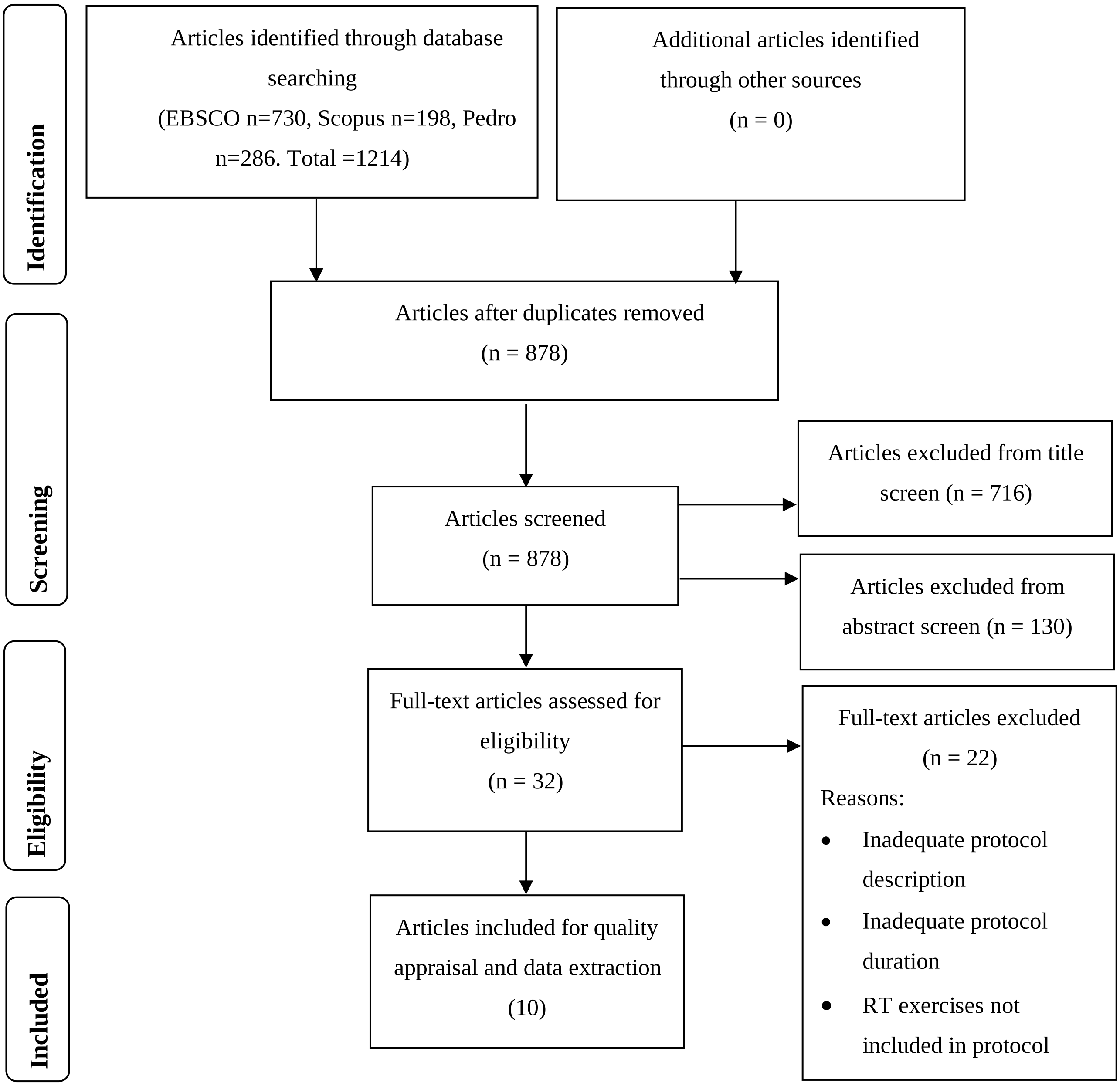
Each study included in this systematic review was independently critiqued by the student researcher and the second reviewer (both clinical physiotherapists). Before commencing the evaluation of included studies, the Downs and Black tool was discussed and a trial appraisal of an article not related to the current research was performed together to ensure consistency in interpretation of each item. When all studies had been independently critiqued the student researcher and the second reviewer deliberated on individual results to come to a consensus on final scores. Disagreements between scores were mediated by the research supervisor.

Data from each study were extracted relating to study objective, number of participants, participant characteristics, parameters of the intensity of the RT protocol and intervention length. Results from each study were extracted and stored on an Excel spreadsheet. Extracted data were tabled for ease of comparison between the different studies.

Results

Study Selection

Figure 1 illustrates the process undertaken to select the studies included for quality appraisal and data extraction. The initial search across all databases identified 1214 articles. This total was reduced to 978 following the removal of duplicates. Four hundred and ninety-four articles were identified via EBSCO health databases, 198 via Scopus, and 286 via Pedro. Following the screening of titles across all databases, 716 articles were excluded, and a further 130 were excluded after reading abstracts. This resulted in identifying 32 articles to be read in full. Articles at this stage were most commonly excluded due to inadequate exercise protocol description, or inadequate exercise protocol duration. One article was excluded as it was essentially a continuation of the primary study (Risberg & Holm, 2009). No additional articles were identified through screening of reference lists. Ten articles were included for final quality appraisal and data extraction.



Adapted from (PRISMA, 2009)

Figure 1. Search strategy and results

Quality of Included Studies

Table 5 provides detail on the individual Downs and Black item and total scores for each included study. Studies varied in quality with scores ranging from 13 to 26 out of a possible 28 (see Table 5 for detail). One study (Fukuda et al., 2013) was categorised as excellent quality, four studies (Berschin, Sommer, Behrens, & Sommer, 2014; Bieler et al., 2014; Perry, Morrissey, King, Morrissey, & Earnshaw, 2005; Risberg, Holm, Myklebust, & Engebretsen, 2007) as good quality, three studies (Kang, Jung, & Yu, 2012; Kınıklı, Yüksel, Baltacı, & Atay, 2014; Lepley, Wojtys, & Palmieri-Smith, 2015) as fair quality, and two studies (Friedmann-Bette et al., 2018; Santos et al., 2018) as poor quality.

Most studies scored well in the reporting of objectives, outcomes measures, interventions and results. This reflects the inclusion criteria of the current systematic review which required adequate description of the intervention in particular. Accurate outcome measures were deemed to have been used by all studies. Individual item trends revealed that studies commonly scored poorly on the Downs and Black items that relate to the inherent difficulties with researching this type of intervention, and mostly affected the internal validity. The majority of studies did not blind the intervention to participants (n=8 out of 10) and did not conceal the intervention assignment from staff and participants (n=9). Seven studies either had insufficient power due to a lack of participants or did not report any power calculations. Seven studies also failed to adequately describe the characteristics of participants lost to follow up. Half of the studies provided insufficient detail regarding the confounding variables of each group, and half of the studies were conducted in facilities that were not representative of the typical facilities available to the general ACLR population (e.g., the use of specialist RT equipment), making it more difficult to generalise these results.

Table 5

Downs and Black Quality Critique

Studies	Downs & Black Item Number																										
	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., 2014	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., 2014	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., 2018	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., 2013	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., 2012	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
Kiniliki et al., 2014	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., 2015	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., 2005	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., 2007	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., 2018	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

Characteristics of Included Studies

For clarity, extracted data relating specifically to the research question, including RT intensities and corresponding results related to return to sport criteria, are presented first and are summarised in Table 6. Table 7 provides further information regarding the general characteristics of each included study.

Resistance training intensity

Six of the studies expressed intensity as a percentage of 1RM. These intensities ranged from 5 - 80% of 1RM (>25RM - 8RM) (Berschin et al., 2014; Fukuda et al., 2013; Kang et al., 2012; Kınıklı et al., 2014; Lepley et al., 2015; Risberg et al., 2007). Five studies expressed intensity as a repetition maximum, varying from 30RM to 6RM (<65% - 85% of 1RM) (Bieler et al., 2014; Friedmann-Bette et al., 2018; Fukuda et al., 2013; Perry et al., 2005; Santos et al., 2018). The study by Fukuda et al. (2013) utilised both methods of description. Five of the 10 studies reported interventions progressing in intensity from low to high intensity over the duration of the intervention. Most commonly this was done in a periodised manner by concurrently reducing the number of repetitions performed per set (Berschin et al., 2014; Bieler et al., 2014; Kınıklı et al., 2014; Perry et al., 2005; Risberg et al., 2007). The majority of RT interventions were optimised for the development of muscle endurance and hypertrophy, between 60 - 80% of 1RM (>15RM - 8RM) (Berschin et al., 2014; Bieler et al., 2014; Friedmann-Bette et al., 2018; Fukuda et al., 2013; Kang et al., 2012; Kınıklı et al., 2014; Lepley et al., 2015; Risberg et al., 2007; Santos et al., 2018). Most commonly RT interventions included intensities between 70 - 80% of 1RM. The study performed by Perry et al. (2005) was the only study to include interventions where RT intensities were optimised for the development of muscle strength. RT intensity in this study was progressed to 6RM (85% of 1RM). Although the study by Risberg et al. (2007) also prescribed RT sets of six repetitions, it was not specified if this was prescribed as a submaximal exercise or at 6RM. No studies prescribed intensities of 90% of 1RM (4RM) or greater.

Table 6

Strength Exercise Intensity Compared with Return to Sport Outcome Measures

Study	Time Post-op/RT Intensities	Strength LSI[a]			Hop Tests LSI[a]			
		Quadriceps	**Hamstrings**	**Other**	**SH**	**TH**	**TCH**	**Other**
Berschin et al., 2014	Weeks 2-5: 50-60% 1RM Weeks 6-11: 60-80% 1RM	Isometric - 70% $60^{\circ}s^{-1}$ - 62%	Isometric - 75% $60^{\circ}s^{-1}$ - 72%	-	-	-	-	-
Bieler et al., 2014	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	-	-	Quadriceps Power: HI 97.5% LI 83.5%	HI 69% LI 65%	HI 75% LI 68%	-	-
Friedmann-Bett et al., 2018	Weeks 12-24: 8RM	CON/ECC $60^{\circ}s^{-1}$ - 80% $180^{\circ}s^{-1}$ - 82% CON/ECC+ $60^{\circ}s^{-1}$ - 78% $180^{\circ}s^{-1}$ - 82%	-	-	-	-	-	-
Fukuda et al., 2013	Weeks 1/2-26/27: 10RM & 70% 1RM	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	Strength LSI$_a$			Hop Tests LSI$_a$			
		Quadriceps	Hamstrings	Other	SH	TH	TCH	Other
Kang et al., 2012	Weeks 12-24: 70% 1RM	OKC (lb-ft) 60°$_{s.-1}$ - 118 (65% ↑) 180°$_{s.-1}$ - 80.4 (71%↑) CKC (lb-ft) 60°$_{s.-1}$ - 98.1 (21% ↑) 180°$_{s.-1}$ - 51.2 (160%↑)	OKC (lb-ft) 60°$_{s.-1}$ - 69.5 (94% ↑) 180°$_{s.-1}$ - 64.9 (45%↑) CKC (lb-ft) 60°$_{s.-1}$ - 55.6 (80% ↑) 180°$_{s.-1}$ – 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	Weeks 3-15: 5-50% 1RM	Early Onset (Nm/kg) 60°$_{s.-1}$ - 68.8 (14%↑) 180°$_{s.-1}$ - 77.6 (32%↑) Standard (Nm/kg) 60°$_{s.-1}$ - 69.5 (8%↑) 180°$_{s.-1}$ - 63.5 (13%↑)	Early Onset (Nm/kg) 60°$_{s.-1}$ - 97 (10%↑) 180°$_{s.-1}$ - 103.9 (25%↑) Standard (Nm/kg) 60°$_{s.-1}$ - 81.2 (9%↑) 180°$_{s.-1}$ - 86.3 (18%↑)	-	Early Onset 91.1% Standard 84.6%	-	-	Vertical Hop: Early Onset 89.2% Early Onset 77.3%
Lepley et al., 2015	Weeks 6-12: 60% 1RM	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	Weeks 8-10: 20RM Weeks 11-13: 6RM	-	-	-	OKC 77% CKC 74%	-	OKC 79% CKC 81%	Vertical Hop: OKC 75% CKC 78%

Study	Time post-op/RT Intensities	Strength LSI[a]			Hop Tests LSI[a]			
		Quadriceps	**Hamstrings**	**Other**	**SH**	**TH**	**TCH**	**Other**
Risberg et al., 2007	Weeks 2-27: 50-80% 1RM (phase 3), 3 x 6 Reps (phase 4) [b]	ST $60°s^{-1}$ – 67.3% $240°s^{-1}$ – 78% NT $60°s^{-1}$ – 79.1% $240°s^{-1}$ – 79%	ST $60°s^{-1}$ – 88.3% $240°s^{-1}$ – 94.7% NT $60°s^{-1}$ – 86.3% $240°s^{-1}$ – 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	2-5 years, 12 weeks: 10RM	Isometric - 94% [c] Con$30°s^{-1}$ - 89% [c] Con$120°s^{-1}$ - 93% [c] Ecc$30°s^{-1}$ - 111% [c] Ecc$120°s^{-1}$ - 104% [c]	Isometric - 107% [c] Con$30°s^{-1}$ - 105% [c] Con$120°s^{-1}$ - 110% [c] Ecc$30°s^{-1}$ - 128% [c] Ecc$120°s^{-1}$ - 125% [c]	-	93%	94%	102%	Figure-8 Hop: 101%

[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
Abbreviations: $°s^{-1}$, degrees per second; %, percent; +, and; HI, high intensity; LI, low intensity; OKC, open kinetic chain; CKC, closed kinetic chain; CON, concentric; ECC, eccentric; ECC+, eccentric overload; EOKC/LOKC, early/late start open kinetic chain; kg, kilograms; Ext, Extension; Flx, Flexion; ST, strength training; lb-ft, pounds per feet; NM/kg, newton meters per kilogram; NT, neuromuscular training; ↑, increased/improved; N, neuromuscular electrical stimulation; RM, repetition maximum; SH, single hop; TH, triple hop; TCH, triple crossover hop

Efficacy of interventions

This review has focussed on the study results that directly relate to the return to sport criteria discussed in Chapter 2 as a measure of intervention efficacy. Table 6 highlights the RT intensities utilised in the intervention protocols and summarises the results related to the criteria. No included study included a complete return to sport test battery as an outcome measure. Furthermore, no studies included a running t test as an outcome measure. The outcome measures assessed in the study by Santos et al. (2018) most comprehensively covered tests of the return to sport test battery. Quadriceps and hamstrings strength were assessed as well as the three hop tests (single hop, triple hop and triple hop-crossover tests). However, it should be noted that in this study the strength of the injured leg post-intervention was measured against the uninjured leg pre-intervention to determine LSI. All other studies included outcome measures that assessed a part of the return to sport battery. However, in some cases only the raw data for the tests were provided and not measured as an LSI. LSI's have been calculated for these studies where possible, otherwise percentage increases have been provided and can be found in Table 6.

Strength. Strength was measured in all studies except for the study performed by Perry et al. (2005). Strength of either the quadriceps (knee extensors) and hamstrings (knee flexors), or both were assessed most commonly with an isokinetic dynamometer. When measured isokinetically, strength was measured at either 60 degrees per second or 180 degrees per second. Bieler et al. (2014) measured knee extensor power, a combination of force and velocity rather than strength, using a leg extensor power rig, attempting to better reflect the functional demands of muscles. In addition to knee extensor and flexor strength, Kang et al. (2012) measured extensor and flexor muscle endurance (average power over 20 repetitions) and squat strength by determining the 1RM on a leg press machine.

Six of the studies reported leg strength results as an LSI (Berschin et al., 2014; Bieler et al., 2014; Friedmann-Bette et al., 2018; Fukuda et al., 2013; Risberg et al., 2007; Santos et al., 2018). Bieler et al. (2014) 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, a statistically significant difference. The study by Santos et al. (2018) assessed subjects between two and five years post-ACLR and reported 111% and 128% quadriceps and hamstrings LSI's, respectively, following the intervention, the highest among included studies.

Quadriceps LSI's among remaining studies ranged between 62% (±18) and 94% (±12) (Berschin et al., 2014; Bieler et al., 2014; Friedmann-Bette et al., 2018; Fukuda et al., 2013;

Risberg et al., 2007; Santos et al., 2018), while hamstring LSI results ranged between 72% (±11) and 95% (±16) (Berschin et al., 2014; Bieler et al., 2014; Friedmann-Bette et al., 2018; Fukuda et al., 2013; Risberg et al., 2007; Santos et al., 2018). The study by Fukuda et al. (2013) recorded the highest quadriceps LSI (94% ± 6), while the study by Risberg et al. (2007) (95% ± 16) recorded the highest hamstrings LSI of these studies following the intervention period. Both of these measures were taken at approximately six months following ACLR. It should be noted that the study by Fukuda et al. (2013) included only participants who had undergone an ACLR utilising a hamstring tendon graft, while the study by Risberg et al. (2007) included only participants who had undergone an ACLR utilising a patellar tendon graft.

Function. Table 6 shows that a variety of hop tests were utilised to assess knee function in six of the 10 studies. Tests included: the single hop test, triple hop test, triple crossover hop test, vertical hop test, stair hop test and vertical jump (Bieler et al., 2014; Fukuda et al., 2013; Kınıklı et al., 2014; Perry et al., 2005; Risberg et al., 2007; Santos et al., 2018). Bieler et al. (2014) reported 69% (± 5) and 75% (±4) LSI 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. Unlike the strength LSI's in the same study, these differences were not statistically significant. Of the hop tests that were described in the return to sport criteria earlier, the single hop test results ranged between 65% (±5) and 95% (±8) (Bieler et al., 2014; Fukuda et al., 2013; Kınıklı et al., 2014; Perry et al., 2005; Risberg et al., 2007; Santos et al., 2018). Results of the triple hop tests varied between 68% (±4) and 94% (Bieler et al., 2014; Risberg et al., 2007; Santos et al., 2018), and results of the triple crossover hop tests varied between 79% (±15) and 102% (Fukuda et al., 2013; Perry et al., 2005; Santos et al., 2018).

Two studies reported hop test results and included participants approaching a traditional return to sport time period immediately following intervention completion (six months post ACLR) (Fukuda et al., 2013; Risberg et al., 2007). The study by Fukuda et al. (2013) reported highest singe hop test LSI values in the late start open kinetic chain group of (94% ±7) and highest triple crossover hop test LSI values in the early start open kinetic chain group (94% ±6) at 25 weeks post-ACLR. Both groups in this study achieved return to sport criteria thresholds of 90% or greater for these tests. The study by Risberg et al. (2007) reported highest single hop and triple hop test LSI values in the neuromuscular training group (85% ±11 and 89% ±11 respectively) at six months post-ACLR. Both neuromuscular training and strength training groups in this study failed to achieve return to sport criteria thresholds, with no statistically significant difference between groups.

Table 7

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 ($60°_{s.-1}$& $180°_{s.-1}$) 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

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

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

Abbreviation: $°_{s.-1}$, 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

Objectives of included studies

Typically, objectives of each study were focussed on determining the effectiveness of different modes of RT, or novel adjuncts to rehabilitation programs against standard rehabilitation protocols, rather than specifically investigating conventional RT as a cornerstone of the rehabilitation protocol. Only one study (Bieler et al., 2014) explicitly investigated a high versus low intensity RT protocol. Two studies (Kang et al., 2012; Perry et al., 2005) investigated closed versus open kinetic chain RT and one (Friedmann-Bette et al., 2018) compared a concentric-eccentric versus concentric-eccentric overload RT protocol. Two studies (Fukuda et al., 2013; Kınıklı et al., 2014) investigated early start or accelerated rehabilitation protocols against a delayed or traditional protocol start time. The remaining studies investigated either a neuromuscular training protocol (Risberg et al., 2007), whole body vibration (Berschin et al., 2014) or a neuromuscular stimulation plus eccentric RT protocol against a neuromuscular stimulation protocol, an eccentric RT protocol and standard protocol (Lepley et al., 2015). Santos et al. (2018) investigated the possible correlations between strength gains and hop tests utilising a standardised isokinetic training protocol.

Participants

Participant characteristics were adequately described in most cases, with the exception of Kang et al., (2012) who did not report the length of time from injury to surgery or the surgical procedure performed on the participants, and Santos et al., (2018) who did not describe the age or sex of participants. The mean age of participants across all studies ranged from 22 years to 33 years old, the mean age of participants across all studies was 28 years old. Age was not used as an inclusion or exclusion criteria in any of the included studies. Males and females were included in all studies; however, the majority of participants in all studies were male (306 males and 125 females across all studies). Both participants who underwent hamstring tendon and patella tendon graft ACL repairs were represented across studies. Three studies (Berschin et al., 2014; Risberg et al., 2007; Santos et al., 2018) included only participants who received patellar tendon grafts, two studies (Fukuda et al., 2013; Kınıklı et al., 2014) included only participants who received hamstring tendon grafts, four studies (Bieler et al., 2014; Friedmann-Bette et al., 2018; Lepley et al., 2015; Perry et al., 2005) included both participants who received patellar or hamstring tendon grafts, and one study (Kang et al., 2012) did not specify the surgical procedure.

Intervention duration

Intervention duration ranged from 6 - 25 weeks; participants completed between two to three sessions per week. Interventions commenced between 1 - 12 weeks post-operatively, with the exception of Santos et al. (2018), who included participants between 2 - 5 years following ACLR. The study by Berschin et al. (2014) was the only study to include an intervention period that did not extend into the ligamentisation phase of graft healing. All other studies intervention periods extended for at least four weeks into this phase. The majority of intervention periods were 12 weeks or greater in duration (n=7) (Berschin et al., 2014; Bieler et al., 2014; Fukuda et al., 2013; Kang et al., 2012; Kınıklı et al., 2014; Lepley et al., 2015; Perry et al., 2005; Santos et al., 2018). The studies by Fukuda et al. (2013) and Risberg et al. (2007) represent the most complete rehabilitation protocols of included studies. Interventions commenced one to two weeks post-ACLR and were 25 weeks and six months in duration respectively. Aspects of the Risberg et al. (2007) rehabilitation program were specifically designed to facilitate a return to sport. Studies investigating interventions that commenced in the early graft healing phase did not commence RT using an external load immediately due to the necessity of controlling pain and swelling (Berschin et al., 2014; Fukuda et al., 2013; Kınıklı et al., 2014; Risberg et al., 2007).

Resistance training effect on graft laxity

Half of the included studies assessed knee joint laxity (anterior displacement of the tibia on the femur) as a measure of intervention safety. All studies measuring graft laxity reported no deleterious consequences of the applied interventions, this included rehabilitation protocols with closed and open kinetic chain exercises (Berschin et al., 2014; Bieler et al., 2014, Fukuda et al., 2013; Perry et al., 2005; Risberg et al., 2007). Of particular interest to this systematic review, the study by Bieler et al. (2014) found no difference in knee joint laxity between high and low intensity RT interventions. Furthermore, no studies reported significant injury as a result of the intervention.

Adherence

Three studies specifically described adherence to RT protocols. Adherence was measured by the number of planned sessions completed. Adherence rates were generally high, between 85 - 100% (Berschin et al., 2014; Bieler et al., 2014; Risberg et al., 2014). Bieler et al. (2014) reported slightly higher, although not significantly different, adherence rates in the high intensity training group as compared with the low intensity training group, 22/24 and 20/24 respectively.

Chapter 4: 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 has revealed the large variances between studies in the utilisation of RT parameters post-ACLR, in particular, the intensity of exercises. Protocols utilised 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 (Potter, 2016). Most commonly protocols incorporated RT intensities between 60 - 80% of 1RM in the mid and late stages of rehabilitation, sufficient to develop muscular endurance and stimulate hypertrophy (Potter, 2016; Schoenfeld, 2013). Only one study incorporated the prescription of exercises that would facilitate the development of maximal force production (strength) at 85% of 1RM (Perry et al., 2005), the next highest being 80% of 1RM (Berschin et al., 2014; Bieler et al., 2014; Friedmann-Bette et al., 2018; Risberg et al., 2007).

RT at the intensities primarily observed in the protocols utilised by the included studies limits the potential for participants to develop maximal strength (Cormie et al., 2010; Kraemer et al., 1988; Potter, 2016; Schoenfeld, 2013). Furthermore, these intensities fail to replicate the high physical demands required of a person during functional return to sport testing and of an athlete returning sport (Cormie et al., 2010; Gonzalo-Skok et al., 2016; Jensen & Ebben, 2007; Lamont et al., 2008; Tramel et al., 2019). In the case of the person returning to sport following ACLR, it is important that these people eventually progress to RT employed by the injury-free population at high intensities (90% of 1RM and greater). This change would help to ensure that an adequate level of physical conditioning is achieved to sufficiently prepare the athlete for the rigours of sport (Cormie, McGuigan, & Newton, 2011b; DeWeese et al., 2015; Hoover et al., 2016; Lorenz et al., 2010; Stone et al., 1982).

Periodisation allows a person to safely and effectively progress the RT protocol to higher intensities and facilitates maximal increases in strength (Lorenz et al., 2010; Strohacker, Fazzino, Breslin, & Xu, 2015). However, only four of the 10 studies (Berschin et al., 2014; Bieler et al., 2014; Perry et al., 2005; Risberg et al., 2007) utilised some form of linear periodisation, increasing RT intensity over the training period. The remainder of the studies did not periodise their RT protocol, maintaining the same RT intensity for the duration of the intervention. The study by Bieler et al. (2014) gives the clearest example of periodisation. The high-intensity protocol in this study included three distinct microcycles over 12 weeks; intensity was progressed from 20RM (<65% 1RM) (muscle endurance), to between 15RM and 12RM (65

- 70% 1RM), and finally to 8RM (80% 1RM) (muscle hypertrophy and strength), between weeks 8 - 20 post-ACLR. All other studies utilised only two clear microcycles. These studies typically only progressed from RT intensities optimised for the promotion of muscle endurance to intensities optimised for muscle hypertrophy, without a further progression to strength and power. The exception to this was the study by Perry et al. (2005), as the rehabilitation protocol utilised in this study unconventionally progressed RT intensity from 20RM (<65% 1RM) immediately to 6RM (85% 1RM) (endurance to strength-based RT). Ultimately an absence of, or inadequate, periodisation could have hindered patient's performance in strength and function testing through a lack of progressive overload, limiting potential improvements (Strohacker et al., 2015). Furthermore, RT protocols without periodisation, particularly when training at intensities optimised for endurance and hypertrophy, have been suggested to hinder physical performance through over-training induced physical and/or mental fatigue (Kraemer et al., 1988; Stone et al., 1982; Strohacker et al., 2015).

In athletic training periodisation typically builds towards the athlete performing power-based RT. 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 (Cormie, McGuigan, & Newton, 2011a). Not only is power a defining feature of the hop test battery and t-tests commonly used in return to sport criteria, injury mechanisms typically involve maximal effort tasks that require a high power output (Grindem et al., 2016; Kyritsis et al., 2016; Wetters et al., 2016). Consequently, it is important for the ACLR patient to progress to power exercises to facilitate the greatest transfer of training effect specifically for high-risk tasks (Cormie et al., 2011b; DeWeese et al., 2015; Grindem et al., 2016; Potter, 2016; Wetters et al., 2016). However, none of the interventions in the included studies progressed the rehabilitation protocol to include what would be considered effective power-based RT. The study by Bieler et al. (2014) was the only study to specifically acknowledged the importance of power in this context. Despite this study 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. The lack of difference between groups hop test results may be explained by the RT protocol not progressing to power-based RT to facilitate a cross-over of training effect.

Return to sport criteria that assess lower limb strength and function are effective tools to help determine patient readiness for returning to high-risk tasks following ACLR (Grindem et al., 2016; Kyritsis et al., 2016). However, the RT intensities of ACLR rehabilitation protocols identified by this systematic review do not align with RT recommendations and protocols designed to improve maximal force production or optimise functional performance in healthy populations (Cormie et al., 2010; Lamont et al., 2008; Potter, 2016; Schoenfeld, 2013). This may be a factor contributing to the results of the included studies reflecting research that demonstrates ACLR patients often fail to achieve return to sport criteria despite their importance (Berschin et al., 2014; Bieler et al., 2014; Friedmann-Bette et al., 2018; Fukuda et al., 2013; Grindem et al., 2016; Kınıklı et al., 2014; Kyritsis et al., 2016; Leister et al., 2019; Perry et al., 2005; Risberg et al., 2007).

Very few of the included studies reported strength and function outcome measure results that would meet return to sport criteria. The study by Santos et al. (2018) was the only included study to report outcomes following the intervention that were universally above 90% LSI for the strength and hop tests. However, participants recruited for this study were between two and five years post-ACLR. Participants were already close to or beyond return to sport criteria thresholds for the outcome measures assessed at the commencement of the intervention. Of the remaining studies, only two of the five that included hop test LSI's (Fukuda et al., 2013; Kınıklı et al., 2014), and only two of the four studies that included strength test LSI's (Fukuda et al., 2013; Risberg et al., 2007), reported at least one result above the 90% LSI return to sport threshold. Significantly, no study reported restoration of strength to 90% LSI or greater of the muscle group from which the ACL graft was harvested. Furthermore, the more favourable LSI strength outcomes reported in the study by Fukuda et al. (2013) would have likely been influenced by the use of a handheld dynamometer to measure strength. These devices yield significantly different results and are less sensitive to differences in leg strength in comparison with using an isokinetic dynamometer (Deones, Wiley, & Worrel, 1994).

Only two studies included an intervention that extended beyond six months post-ACLR (Fukuda et al., 2013; Risberg et al., 2007). Some participants in these studies may have been approaching a typical return to sport phase of rehabilitation. The study by Risberg et al. (2007) compared two different interventions that began post-operatively and extended beyond six months post patellar tendon graft ACLR. In the study (Risberg et al., 2007), each intervention group either performed a neuromuscular training protocol (balance, dynamic joint stability, plyometric and sport-specific exercise and agility drills) or an RT protocol. No statistical difference in outcomes was observed between groups for strength or functional measures. Participants from both groups achieved greater than 90% in only one of four LSI strength tests (knee extension was only 79%±17 at best across both groups), while both hop tests assessed were below 90% LSI. The study by Fukuda et al. (2013) reported the most favourable hop test results and was measured at 25 weeks post-ACLR. Contrasting the rehabilitation protocols utilised by Risberg et al. (2007), the protocols in this study included both progressive RT and progressive neuromuscular training. Hop tests for both early and late start groups achieved over 90% LSI’s by 25 weeks post-ACLR despite the RT protocol utilising a lower RT intensity. Research has shown that completion of a comprehensive rehabilitation protocol (at least six months or greater in duration that included RT and neuromuscular exercises) following ACLR was predictive of a return to sport (Edwards et al., 2018). The superior hop test outcomes reported by the Fukuda et al. (2013) study over the study by Risberg et al. (2007) similarly allude to the importance of a comprehensive rehabilitation protocol to improve functional performance measures.

The results reported by Fukuda et al. (2013) and Risberg et al. (2007) indicate that additional variables other than the RT parameters affect functional test results post-ACLR. The study by Kınıklı et al. (2014) supports this, reporting a mean single hop test LSI of 91% (±9) at only 16 weeks post-ACLR in the intervention group. The intervention involved performance of an early onset leg press exercise on specialised equipment that mimicked neuromuscular function during a squat jump, at low intensities (5 - 50% 1RM) in addition to the standard rehabilitation protocol provided (RT intensities were not defined for this aspect of protocol). This was found to be a significantly greater improvement compared with the control group which averaged an LSI of 85% (±7) at 16 weeks post-ACLR. Despite the differences in function no significant difference in strength improvements between groups was detected. These results emphasise the importance of specificity and appropriate exercise selection, another foundational element of training (DeWeese et al., 2015). The findings also suggest that RT with higher intensities is not necessarily required to pass return to sport criteria thresholds for some hop tests, providing RT is performed alongside specific neuromuscular exercises throughout rehabilitation.

There was only one study identified by this systematic review that specifically investigated RT intensity (Bieler et al., 2014). This study provides some evidence to support the use of high over low-intensity RT to improve return to sport related outcomes post-ACLR. However, methodological flaws meant that the results might under-estimate the differences observed between the intervention group hop test results in addition to the lack of power-based RT previously discussed. The inclusion of a specific plantarflexor exercise in the low intensity protocol and absence of this in the high intensity protocol resulted in an additional independent variable. Plantar-flexor strength is an important contributor to jumping and landing mechanics, and strengthening of the gastrocnemius muscle has been shown to improve jump performance (Chiu, Yaremki, & vonGaza, 2017; Kakihana & Suzuki, 2001; Lesinski, Prieske, Beurskens, Behm, & Granacher, 2017). The inclusion of such an exercise in the low intensity protocol may have mediated the differences found between the functional outcomes of the two groups. Nonetheless, this study provides good quality evidence in support of the safety and efficacy of moderate RT intensities progressing from 20RM to 8RM from weeks 8 - 20 post-ACLR over a lower intensity RT protocol.

RT has been posited as the most important aspect of a rehabilitation program following musculoskeletal injury (Lorenz et al., 2010). However, research has focussed on novel approaches, accelerated protocols, adjuncts such as neuromuscular electrical stimulation, blood flow restriction, vibration training, and different types of RT such as open versus closed kinetic chain and eccentric versus concentric loading (Berschin et al., 2014; Beynnon et al., 2011; Fukuda et al., 2013; Kang et al., 2012; Kınıklı et al., 2014; Lepley et al., 2015; Ohta et al., 2003). The study carried out by Lepley et al. (2015) highlights this sentiment, which demonstrated that the addition of neuromuscular electrical stimulation to a 12 week RT protocol had no effect when comparing it to the RT protocol alone. Valuable insight has been gained through the available literature, however more focus should be placed on investigating the foundational elements related to RT in this population (Lorenz et al., 2010). The lack of attention on these elements in the literature reduces the importance of this aspect of ACLR rehabilitation, and indicates an area in which physiotherapists can improve.

Strengths and Limitations of the Systematic Review

This systematic review included several key strengths. First, this seminal study has acknowledged the importance of RT intensity and identified and critiqued the RT intensities being utilised in ACLR rehabilitation protocols. It has provided valuable information previously not available that is directly applicable to the clinical setting, which may lead to improved outcomes for patients. Second, an extensive search of the literature was performed, utilising multiple databases that increased the likelihood that all available relevant studies were identified. There were no further studies included by cross-checking reference lists of included studies, supporting the robustness of the initial search strategy. Third, the primary purpose of the systematic review was to identify RT intensity, rather than investigate the efficacy of a given intervention. This purpose allowed the inclusion of a wide range of literature, providing a sufficient number of high-quality studies from which to draw data. Finally, although the Downs and Black tool was originally developed to assess randomised trials only, it has since been validated to assess non-randomised trials, increasing the potential number of studies that could be included (Downs & Black, 1998).

This systematic review was not without limitations. First, the review included studies where RT was not the primary variable being investigated. Because of this, authors may have placed a reduced emphasis on the RT component of the protocol. The RT intensity utilised in these protocols may not be as applicable compared with the interventions that investigated RT as a primary variable. Second, no included study was performed with an Australian cohort, reducing the generalisability of results of the systematic review to an Australian audience. Furthermore, many of the facilities where rehabilitation protocols were completed were not reflective of what is available to the general population. Protocols typically called for the completion of supervised sessions two to three times per week. This is important to note as increased physiotherapy supervision during ACLR rehabilitation has been correlated with improved function (Krolikowska, Czamara, Szuba, & Reichert, 2018). However, completion of frequent supervised sessions for many people in Australia is not feasible. This point is particularly relevant to the amateur athlete wishing to rehabilitate to return to sport as the rehabilitation period is likely to be lengthy and more costly. Lastly, the use of specific outcome measures and interpretation of results were not used as inclusion criteria in this systematic review. This 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 would provide additional valuable information regarding the optimal prescription of RT intensity post-ACLR.

Clinical Implications

The findings of this systematic review include several implications that could affect clinical practice. The inconsistencies in RT protocols highlighted in this review are supported by existing research which suggests that physiotherapists do not have the required information available to develop suitable ACLR rehabilitation protocols (Makhni et al., 2016; von Aesch et al., 2016). von Aesch et al. (2016) carried out research that revealed physiotherapists had difficulty interpreting contradictory research to guide the prescription and progression of RT during ACLR rehabilitation. Additionally, a systematic review by Makhni et al. (2016) found a wide range of variability and a lack of detail in the prescription of RT recommended by orthopaedic ACLR rehabilitation protocols available online. The variability of current ACLR rehabilitation protocols in clinical practice and concurrent high reinjury rates (Ardern et al., 2015; Greenberg et al., 2018; Webster, Feller, Leigh, & Richmond, 2014), may be explained by the lack of consistency across rehabilitation protocols utilised in the literature. It should also be noted that while the studies included in this systematic review reported specifically on RT intensity, many studies were excluded due to insufficient reporting of exercise parameters. This sentiment is supported by Goff et al. (2018) who highlighted inadequacies in the reporting of program variables across the knee injury rehabilitation literature, contributing to the lack of clarity and direction for the prescription of RT in this population.

A scarcity of literature exists that has investigated protocols extending beyond six months post-ACLR. This is important for clinical practice because strength and function deficits commonly extend well beyond this time frame, suggesting that rehabilitation programs should continue past this period (Ebert et al., 2018; Grindem et al., 2016; Leister et al., 2019; Toole et al., 2017; Welling et al., 2018). Furthermore, despite the importance placed on the achievement of return to sport criteria, there were no studies identified by this systematic review that provided an example of a rehabilitation protocol successfully restoring strength and function as determined by the global achievement of return to sport criteria. While two of the studies did not include an intervention that progressed beyond the proliferation phase of ligament healing at 12 weeks post-ACLR (Berschin et al., 2014; Lepley et al., 2015), the majority were completed by six months post-ACLR (Bieler et al., 2014; Friedmann-Bette et al., 2018; Fukuda et al., 2013; Kang et al., 2012; Kınıklı et al., 2014; Perry et al., 2005).

Six months post-ACLR represents a commonly recommended return to sport time frame (Greenberg et al., 2018). This is also the stage when the graft is progressing through the ligamentisation phase, has undergone considerable structural and biological change and can tolerate higher external loads (Scheffler et al., 2008). Although all studies reported improved outcomes following the intervention period, the majority of participants would not have passed return to sport criteria. Given that studies did not extend beyond six months post-ACLR, the opportunity to progress RT to higher intensities necessary for adequate physical preparation for a return to sport was limited. A recent survey of physiotherapists has shown a discrepancy between the expected duration of ACLR rehabilitation (eight months) and anticipated return to sport time frames (9-12 months), showing that there is a gap in the provision of rehabilitation between time of discharge and a return to sport (Greenberg et al., 2018). The current literature leaves significant uncertainty for clinicians prescribing late-stage RT, which may be contributing to this discrepancy and shortfall in return to sport rehabilitation. Furthermore, the lack of literature describing and supporting late-stage rehabilitation may be encouraging the premature completion of rehabilitation protocols and subsequent return to sport clearance by clinicians (Ebert et al., 2018).

Time from surgery is suggested to be the major mitigating factor determining outcomes following ACLR rehabilitation (Nagelli & Hewett, 2017). Nagelli and Hewett (2017) recommended a return to sport time frame of two years given factors associated with reinjury extending beyond 18 months post-ACLR, including reduced strength and the biological healing of the graft. However, factors related to reinjury may be mitigated through the application of optimal rehabilitation protocols (Grindem et al., 2016; Kyritsis et al., 2016). Higher RT intensities are not only important to build adequate muscular strength and improve functional performance, but may also be important to continue to develop ligament strength through functional adaptation (Scheffler et al., 2008). Instead of promoting a return to sport from six months post-ACLR, it may be a more appropriate time frame, depending on patient progress, to commence high intensity and power-based RT. This would allow for improved physical preparation, considering both muscular and ligamentous adaptations through periodisation of the rehabilitation protocol.

One factor that may cause a tendency for clinicians to under-prescribe RT intensity could be a fear of damaging the ACL graft. Fears about graft injury, particularly in the early and middle phases of graft healing through poor or aggressive exercise prescription, has historically been a well-debated topic (Perry et al., 2005). This is evidenced in the ACLR rehabilitation literature by commonly including measures of graft laxity (Berschin et al., 2014; Bieler et al., 2014, Fukuda et al., 2013; Perry et al., 2005; Risberg et al., 2007). These debates have typically revolved around open kinetic chain exercises and accelerated rehabilitation protocols. Fears surrounding rehabilitation exercise adverse effects on graft laxity have largely been unfounded, where higher relative ACL strains have been shown to occur during a normal gait cycle as compared with typically prescribed ACLR rehabilitation RT exercises (Escamilla, Macleod, Wilk, Paulos, & Andrews, 2012; Taylor et al., 2013). Experimental evidence also supports this notion. A study performed by Beynnon et al. (2011) was not included in this review due to insufficient reporting of intensity; however the authors compared two post-ACLR rehabilitation protocols with identical exercise dosing over two time frames (19 and 32 weeks), and found no difference in graft laxity between groups. Additionally, Fukuda et al. (2013) found no difference in graft laxity with early commencement of open kinetic chain exercises, four weeks post-ACLR (the beginning of the proliferation stage) at 70% of 1RM. These studies demonstrate the safety of what can be considered more aggressive exercise prescription.

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 as a result of the exercise protocols (Berschin et al., 2014; Bieler et al., 2014, Fukuda et al., 2013; Perry et al., 2005; Risberg et al., 2007). Bieler et al. (2014) provides the most direct reassurance as to 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 groups despite the high intensity intervention group commencing 8RM RT at 14 weeks post-ACLR. Furthermore, the study by Perry et al. (2005) prescribed the highest RT intensities (6RM) observed in this review during graft proliferation (starting from eight weeks post-ACLR), typically considered to be a vulnerable stage of graft healing, and reported no deleterious effects to ligament laxity. While other parameters such as exercise type, range of movement and tempo should be considered when determining the safety of the exercise, intensities prescribed up to 6RM have been demonstrated to be safe in the early and middle stages of ACLR rehabilitation (Perry et al., 2005).

Practice recommendations

Consideration of the foundational elements of RT, in particular intensity and the concurrent consideration of the healing knee following surgery, is fundamental to the ACLR rehabilitation process. The current prescription of ACLR rehabilitation protocols should be viewed critically by physiotherapists to identify possible areas of improvement. It must be considered that RT protocols prescribed at insufficient intensities to restore function and adequately prepare the patient for the rigours of high-demand sport may be contributing to high reinjury rates and poor outcomes. Clinicians should consider using return to sport criteria to assist with the decision-making process throughout rehabilitation, rather than only relying on time from surgery. Return to sport criteria can empower physiotherapists to encourage patients to address identified deficits through further rehabilitation. Thoughtful prescription and logical progression of RT should be made throughout the course of the rehabilitation process up until and beyond return to sport.

The application of a single ACLR rehabilitation protocol for all patients is inappropriate as it does not accommodate for the variation of individual patient characteristics and goals. However, the development of a non-time dependent, milestone-driven guideline for the prescription and progression of an RT protocol would be a useful tool for physiotherapists. This guideline should be based on the foundational elements of RT and consider stages of healing following ACLR. Development through clinical trials would be beneficial to determine the most efficacious and safe prescription of RT variables, in particular, exercise intensity.

Future Research Recommendations

A recently published study (not included in the systematic review as it was not published at the time the search was undertaken) investigated the effects of an RT protocol following ACLR in soccer players and provides a foundation for future research in this area (Welling, Benjaminse, Lemmink, Dingenen, & Gokeler, 2019). This study produced more favourable results than previous studies in the same field, through the prescription of a well-considered rehabilitation protocol centred around a periodised RT protocol (see Appendix D). Specifically, no differences in hamstring or quadriceps strength were found when compared with healthy controls at seven months post-ACLR. Furthermore, almost 70% of participants scored 90% or higher in quadriceps LSI and were stronger than healthy controls at 10 months post-ACLR. This study utilised a criteria-driven rehabilitation framework. RT intensity was progressed through periodisation from less than 50% 1RM to 60-80% 1RM, to greater than 80% of 1RM over the intervention period. Crucially, aspects of muscle endurance, hypertrophy, strength and power were considered in determining the protocol. The time frame of the intervention was approximately 10 months, although progression to a return to sport was determined by individual patient progress. Results demonstrated a clinically meaningful improvement in quadriceps strength from four to seven months and from seven to 10 months after ACLR, stressing the importance of late-stage rehabilitation described earlier.

While there are many facets to explore concerning ACLR rehabilitation, RT is a cornerstone to restoring function, and perhaps the most important component of a comprehensive rehabilitation program (Lorenz et al., 2010). There is currently only one study available that has investigated ACLR rehabilitation protocols with a specific focus on the safety and efficacy of different levels of RT intensity (Bieler et al., 2014). To provide an improved understanding of the most effective prescription of RT intensity and the role RT intensity plays in achieving return to sport criteria, a randomised controlled trial is recommended.

Based on the findings of this review a future trial should investigate the efficacy of a 12-month, criteria driven, periodised rehabilitation protocol. To maximise the cross-over effect to function the protocol should incorporate foundational RT principles, including RT intensities up to 90% of 1RM and greater and a microcycle focused on power development. Comparisons should be made to a lower intensity protocol and a non-periodised protocol. The protocol should include only exercises that are able to be performed in a standard gym setting, and progress towards independent patient-led sessions to improve the generalisability of the protocol. Consideration should be made to include female participants, as well as participants returning to a variety of different level one sports. Outcome measures should include all previously described return to sport criteria (Table 3), tolerance (pain and swelling response to exercise sessions), adherence (number of sessions completed and the Sports Injury Rehabilitation Adherence Scale [Appendix E] to measure in-session adherence inclusive of level of in-training effort), and long-term return to sport and activity. Reinjury data (including but not limited to re-rupture) 24 months post ACLR or greater should also be recorded. Additional research investigating other foundational elements of RT, in particular manipulating volume and frequency within a rehabilitation protocol, would provide further information to develop optimal RT programs following ACLR.

Conclusion

This systematic review highlights an area of ACLR rehabilitation that merits more high-quality research so that physiotherapists are better equipped to successfully manage patients. There is currently no universally accepted best practice guideline for the prescription of RT following ACLR. Available literature detailing RT intensity within ACLR protocols is inconsistent, incomplete and largely not aligned with recommended RT principles. This finding may explain the apparent lack of consensus between rehabilitation providers on the ACLR rehabilitation process. Optimisation of the prescription of RT for people following ACLR could lead to improvements in strength and functional outcomes, and possibly reduce reinjury rates. Guidelines are needed that provide clarity for clinicians and in turn, improve patient outcomes. 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, and in particular to identify optimal RT variables.

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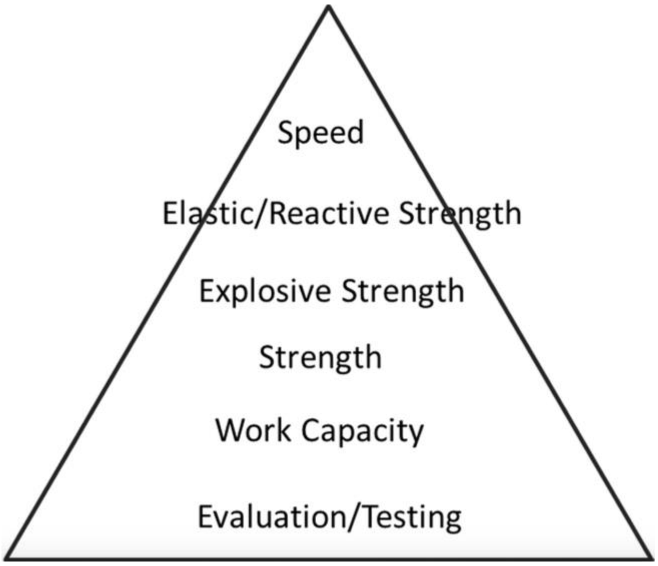
Appendices

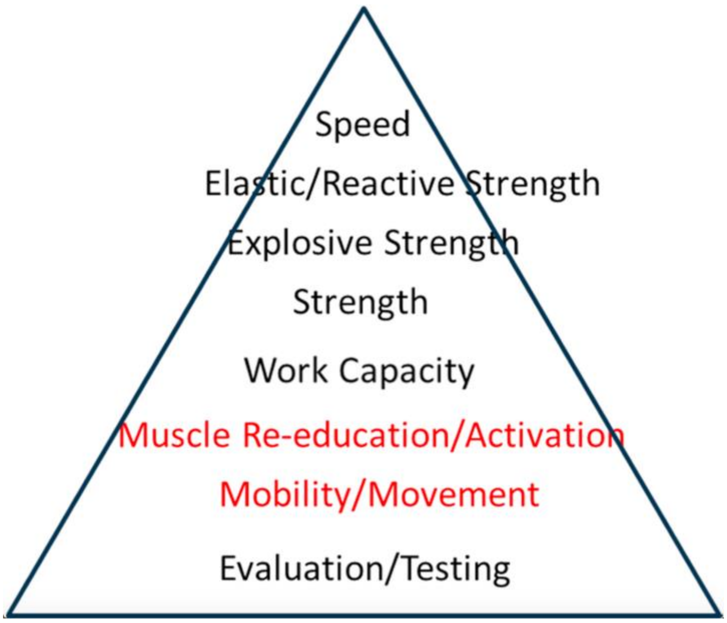
Appendix A

Hierarchy of Athletic Development



Extracted from Panariello et al. (2017)

Modified hierarchy of athletic development



Extracted from Panariello et al. (2017)

Appendix B

Database Search Strategy

Title

A Systematic Review Exploring the Relationship Between Strength Exercise Intensity and Risk of Reinjury in Sports Following an Anterior Cruciate Ligament Repair

Research questions

1. What is the quality of the literature that prescribes resistance training intensity following ACLR?
2. Does the prescribed intensity of resistance exercises during ACLR rehabilitation align with recommended guidelines for resistance training?
3. Is the recommended intensity of resistance training, as indicated by the literature, sufficient to enable patients to meet physical return to sport criteria and reduce reinjury rates?

Key concepts

Strength exercise intensity

ACL reconstruction

Outcome

Database collection

EBSCO health databases (CINAHL Complete, MEDLINE, SPORTDiscus with Full Text)
(searched on 21/06/2019 – note increased numbers since search on 14/06/2019)

S1 - (ACL OR "anterior cruciate ligament") AND (repair or "post operative" OR "post-operative" OR surgery OR "post-surg*" OR reconstruction)

Results – 32117

S2 – (strength* OR resistance OR weight* OR exercise OR intensity OR maximal) N5 (train* OR program* OR protocol*)

Results – 187997

S1(E) AND S2(E)

Results – 730

Appendix C

Downs and Black Items extracted from (Downs & Black, 1998)

Appendix

Checklist for measuring study quality

Reporting

1. *Is the hypothesis/aim/objective of the study clearly described?*

yes	1
no	0

2. *Are the main outcomes to be measured clearly described in the Introduction or Methods section?*
   If the main outcomes are first mentioned in the Results section, the question should be answered no.

yes	1
no	0

3. *Are the characteristics of the patients included in the study clearly described ?*
   In cohort studies and trials, inclusion and/or exclusion criteria should be given. In case-control studies, a case-definition and the source for controls should be given.

yes	1
no	0

4. *Are the interventions of interest clearly described?*
   Treatments and placebo (where relevant) that are to be compared should be clearly described.

yes	1
no	0

5. *Are the distributions of principal confounders in each group of subjects to be compared clearly described?*
   A list of principal confounders is provided.

yes	2
partially	1
no	0

6. *Are the main findings of the study clearly described?*
   Simple outcome data (including denominators and numerators) should be reported for all major findings so that the reader can check the major analyses and conclusions. (This question does not cover statistical tests which are considered below).

yes	1
no	0

7. *Does the study provide estimates of the random variability in the data for the main outcomes?*
   In non normally distributed data the inter-quartile range of results should be reported. In normally distributed data the standard error, standard deviation or confidence intervals should be reported. If the distribution of the data is not described, it must be assumed that the estimates used were appropriate and the question should be answered yes.

yes	1
no	0

8. *Have all important adverse events that may be a consequence of the intervention been reported?*
   This should be answered yes if the study demonstrates that there was a comprehensive attempt to measure adverse events. (A list of possible adverse events is provided).

yes	1
no	0

9. *Have the characteristics of patients lost to follow-up been described?*
   This should be answered yes where there were no losses to follow-up or where losses to follow-up were so small that findings would be unaffected by their inclusion. This should be answered no where a study does not report the number of patients lost to follow-up.

yes	1
no	0

10. *Have actual probability values been reported (e.g. 0.035 rather than <0.05) for the main outcomes except where the probability value is less than 0.001?*

yes	1
no	0

External validity

All the following criteria attempt to address the representativeness of the findings of the study and whether they may be generalised to the population from which the study subjects were derived.

11. *Were the subjects asked to participate in the study representative of the entire population from which they were recruited?*
    The study must identify the source population for patients and describe how the patients were selected. Patients would be representative if they comprised the entire source population, an unselected sample of consecutive patients, or a random sample. Random sampling is only feasible where a list of all members of the relevant

population exists. Where a study does not report the proportion of the source population from which the patients are derived, the question should be answered as unable to determine.

yes	1
no	0
unable to determine	0

12. *Were those subjects who were prepared to participate representative of the entire population from which they were recruited?*
The proportion of those asked who agreed should be stated. Validation that the sample was representative would include demonstrating that the distribution of the main confounding factors was the same in the study sample and the source population.

yes	1
no	0
unable to determine	0

13. *Were the staff, places, and facilities where the patients were treated, representative of the treatment the majority of patients receive?*
For the question to be answered yes the study should demonstrate that the intervention was representative of that in use in the source population. The question should be answered no if, for example, the intervention was undertaken in a specialist centre unrepresentative of the hospitals most of the source population would attend.

yes	1
no	0
unable to determine	0

Internal validity - bias

14. *Was an attempt made to blind study subjects to the intervention they have received ?*
For studies where the patients would have no way of knowing which intervention they received, this should be answered yes.

yes	1
no	0
unable to determine	0

15. *Was an attempt made to blind those measuring the main outcomes of the intervention?*

yes	1
no	0
unable to determine	0

16. *If any of the results of the study were based on "data dredging", was this made clear?*
Any analyses that had not been planned at the outset of the study should be clearly indicated. If no retrospective unplanned subgroup analyses were reported, then answer yes.

yes	1
no	0
unable to determine	0

17. *In trials and cohort studies, do the analyses adjust for different lengths of follow-up of patients, or in case-control studies, is the time period between the intervention and outcome the same for cases and controls ?*
Where follow-up was the same for all study patients the answer should yes. If different lengths of follow-up were adjusted for by, for example, survival analysis the answer should be yes. Studies where differences in follow-up are ignored should be answered no.

yes	1
no	0
unable to determine	0

18. *Were the statistical tests used to assess the main outcomes appropriate?*
The statistical techniques used must be appropriate to the data. For example non-parametric methods should be used for small sample sizes. Where little statistical analysis has been undertaken but where there is no evidence of bias, the question should be answered yes. If the distribution of the data (normal or not) is not described it must be assumed that the estimates used were appropriate and the question should be answered yes.

yes	1
no	0
unable to determine	0

19. *Was compliance with the intervention/s reliable?*
Where there was non compliance with the allocated treatment or where there was contamination of one group, the question should be answered no. For studies where the effect of any misclassification was likely to bias any association to the null, the question should be answered yes.

yes	1
no	0
unable to determine	0

20. *Were the main outcome measures used accurate (valid and reliable)?*

For studies where the outcome measures are clearly described, the question should be answered yes. For studies which refer to other work or that demonstrates the outcome measures are accurate, the question should be answered as yes.

yes	1
no	0
unable to determine	0

Internal validity - confounding (selection bias)

21. *Were the patients in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited from the same population?*
For example, patients for all comparison groups should be selected from the same hospital. The question should be answered unable to determine for cohort and case-control studies where there is no information concerning the source of patients included in the study.

yes	1
no	0
unable to determine	0

22. *Were study subjects in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited over the same period of time?*
For a study which does not specify the time period over which patients were recruited, the question should be answered as unable to determine.

yes	1
no	0
unable to determine	0

23. *Were study subjects randomised to intervention groups?*
Studies which state that subjects wererandomised should be answered yes except where method of randomisation would not ensure random allocation. For example alternate allocation would score no because it is predictable.

yes	1
no	0
unable to determine	0

24. *Was the randomised intervention assignment concealed from both patients and health care staff until recruitment was complete and irrevocable?*
All non-randomised studies should be answered no. If assignment was concealed from patients but not from staff, it should be answered no.

yes	1
no	0
unable to determine	0

25. *Was there adequate adjustment for confounding in the analyses from which the main findings were drawn?*
This question should be answered no for trials if: the main conclusions of the study were based on analyses of treatment rather than intention to treat; the distribution of known confounders in the different treatment groups was not described; or the distribution of known confounders differed between the treatment groups but was not taken into account in the analyses. In non-randomised studies if the effect of the main confounders was not investigated or confounding was demonstrated but no adjustment was made in the final analyses the question should be answered as no.

yes	1
no	0
unable to determine	0

26. *Were losses of patients to follow-up taken into account?*
If the numbers of patients lost to follow-up are not reported, the question should be answered as unable to determine. If the proportion lost to follow-up was too small to affect the main findings, the question should be answered yes.

yes	1
no	0
unable to determine	0

Power

27. *Did the study have sufficient power to detect a clinically important effect where the probability value for a difference being due to chance is less than 5%?*
Sample sizes have been calculated to detect a difference of x% and y%.

	Size of *smallest* intervention group	
A	$<n_1$	0
B	n_1–n_2	1
C	n_3–n_4	2
D	n_5–n_6	3
E	n_7–n_8	4
F	n_8+	5

Appendix D

ACLR Resistance Training Protocol (Welling et al., 2019)

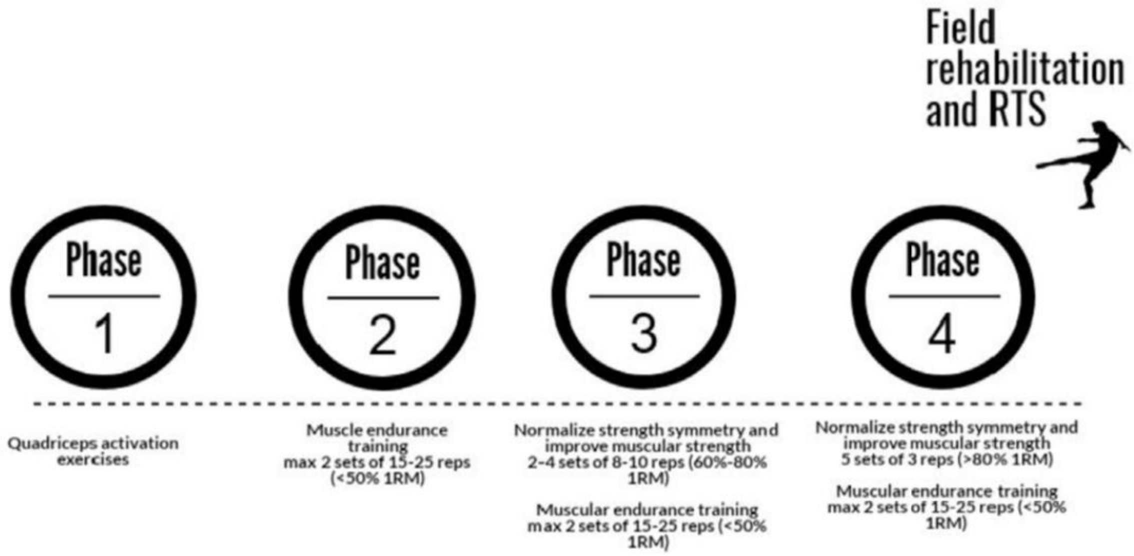


Fig. 1. Timeline of the different phases within the strength training protocol, including training parameters. 1RM = one-repetition maximal, RTS = return to sport.

Table 2
Criteria within the rehabilitation protocol.

Activity	Strength criteria
Return to running	LSI >70% at 60°/s for both quadriceps and hamstring strength (Rambaud et al., 2018)
Return to sport specific training	Males: PT/BW for quadriceps muscle strength males >1.6 at 180°/s and >1.4 at 300°/s in extension for the injured leg
	Females: PT/BW for quadriceps muscle strength >1.5 at 180°/s and >1.3 at 300°/s in extension for the injured leg (Myer et al., 2008)
Return to on-field rehabilitation	LSI >85% at 60°/s, 180°/s and 300°/s for both quadriceps and hamstring strength (Karasel et al., 2010)
Return to sport	LS I>90% at 60°/s, 180°/s and 300°/s for both quadriceps and hamstring strength PT/BW > 3.0 for quadriceps muscle strength at 60°/s in extension for the injured leg H/Q ratio >55% for females and >62.5% for males for the injured leg at 300°/s (Gokeler, Welling, Benjaminse, et al., 2017; Welling et al., 2018)

LSI = limb symmetry index, °/s = degrees per second, PT/BW = peak torque/body weight, H/Q ratio = hamstring/quadriceps ratio.

Extracted from Welling et al. (2019)

Initial phase commenced 2 weeks after ACLR.

Training frequency: 2-3 supervised sessions per week

Phase 1: Focussed on swelling and pain control, restoring full knee extension range of movement and quadriceps activation.

Phase 2: Muscular endurance. Exercises included step ups, leg raises, leg press. Exercises were progressed and/or added depending on 24-hour reaction of knee (pain and swelling). General duration 10-14 weeks.

Phase 3: Normalise strength symmetry and muscular strength. Muscular strength and endurance exercises were performed in this phase. Unilateral and bilateral, and open and closed kinetic chain resistance exercises were performed. Balance and jumping/landing technique exercises were also performed, and running was commenced. General duration 12-14 weeks.

Phase 4: Address remaining knee extension and flexion strength deficits. Continued monitoring of knee joint response (pain and swelling) and training adjusted as necessary. Ongoing muscular endurance exercises performed. Participants were instructed to perform concentric phase of exercise “as fast as possible”. For specific eccentric exercises participants were instructed to perform exercise “as slow as possible”. Continued training of balance, running, jumping and landing technique.

An isokinetic strength test was performed at 10 months post-ACLR and any further strength deficits were addressed by further tailoring individual’s resistance training protocol.

Rehabilitation then focussed on on-field rehabilitation (sports specific) and return to sport.

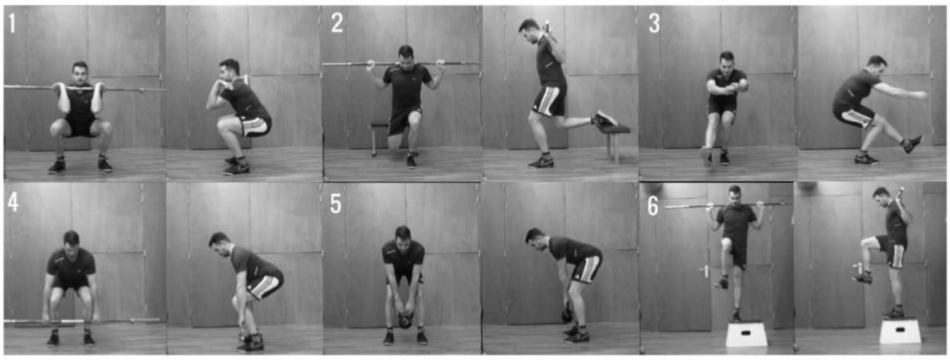


Fig. 3. Six examples of one-legged and two-legged closed kinetic chain exercises performed during the strength training. 1 = front squat, 2 = split squat, 3 = pistol squat, 4 = dead lift, 5 = good morning, 6 = step up.

Appendix E

Sports Injury Rehabilitation Adherence Scale (SIRAS)

1. Circle the number that best indicates the intensity with which this patient completed the rehabilitation exercises during today's appointment:

   Minimum effort 1 2 3 4 5 Maximum effort

2. During today's appointment, how frequently did this patient follow your instructions and advice?

   Never 1 2 3 4 5 Always

3. How receptive was this patient to changes in the rehabilitation programme during today's appointment?

   Very unreceptive 1 2 3 4 5 Very receptive

The SIRAS can also be used with reference to adherence tendencies in general by using the present tense (without reference to ' today's appointment'). Originally published in Brewer BW, Van Raalte JL, Petitpas AJ, Sklar JH, Pohlman MH, Krushell RJ, et al. Preliminary psychometric evaluation of a measure of adherence to clinic-based sport injury rehabilitation. Phys Ther Sport 2000;1:68–74.

Extracted from Kold, Brewer, Pizzari, Schoo, and Garret (2007)