Sports Medicine
https://doi.org/10.1007/s40279-023-01934-w

REVIEW ARTICLE

Optimising the Early-Stage Rehabilitation Process Post-ACL Reconstruction

Matthew Buckthorpe[1,2] · Alli Gokeler[3] · Lee Herrington[4] · Mick Hughes[5] · Alberto Grassi[6] · Ross Wadey[1] · Stephen Patterson[1] · Alessandro Compagnin[2] · Giovanni La Rosa[2] · Francesco Della Villa[2]

Accepted: 1 September 2023

Abstract

Outcomes following anterior cruciate ligament reconstruction (ACLR) need improving, with poor return-to-sport rates and a high risk of secondary re-injury. There is a need to improve rehabilitation strategies post-ACLR, if we can support enhanced patient outcomes. This paper discusses how to optimise the early-stage rehabilitation process post-ACLR. Early-stage rehabilitation is the vital foundation on which successful rehabilitation post-ACLR can occur. Without high-quality early-stage (and pre-operative) rehabilitation, patients often do not overcome major aspects of dysfunction, which limits knee function and the ability to transition through subsequent stages of rehabilitation optimally. We highlight six main dimensions during the early stage: (1) pain and swelling; (2) knee joint range of motion; (3) arthrogenic muscle inhibition and muscle strength; (4) movement quality/neuromuscular control during activities of daily living (5) psycho-social-cultural and environmental factors and (6) physical fitness preservation. The six *do not share equal importance* and the extent of time commitment devoted to each will depend on the individual patient. The paper provides recommendations on how to implement these into practice, discussing training planning and programming, and suggests specific screening to monitor work and when the athlete can progress to the next stage (e.g. mid-stage rehabilitation entry criteria).

1 Introduction

Anterior cruciate ligament (ACL) rupture is a debilitating injury and subsequent ACL reconstruction (ACLR) results in long lay-off times for both recreational-level (typically > 12 months) [1] and elite-level (~ 8 months, but typically ranges from 6 to 12 months) [2–4] athletes, with less-than-optimal outcomes. Although surgery is thought to restore the passive stability of the knee [5], leading to good patient-reported outcomes in the short to medium term [6], only around 80% of recreational ACLR patients return to some type of sporting activity, with only 65% returning to their pre-injury sporting level [7]. Oveall, the secondary ACL injury risk is around 15% [8]. However, a third of young athletes will reinjure their ACL within the first 2 years after return-to-sport (RTS) [9–11], representing a 30- to 40-fold increased risk of re-injury upon RTS, compared with matched controls [8], which is clearly unacceptable. For elite-level athletes, the RTS rates are much higher (83–100%) [2–4, 12], but elite athletes often RTS at lower performance levels [13–15], have a high re-injury risk [2, 16] and report substantially reduced career length [2, 4]. For example, only 65% of elite male footballers are still playing at the same level 3 years post-ACLR [4], whilst 62% of female players quit football 2 years after RTS post-ACLR, with the most common reason for quitting being sustaining a new knee injury [17]. A particular challenge post-ACLR is the increased risk of early onset of knee osteoarthritis (OA) [18], which would impact long-term knee health, and expected career length. Early RTS at low functional levels has been shown to accelerate the onset of knee OA features [18, 19]. To optimise functional outcomes (RTS, return to performance and re-injury prevention), there is a need to optimise rehabilitation processes and practices across all levels of sport/activity.

One issue in clinical practice is the large disconnect between research and practice, thought to be due to ineffective implementation of evidence-based findings [20, 21]. Practitioners need to engage with, study, translate and implement research into practice. However, most practitioners working with injured athletes are often generalists (treating

Extended author information available on the last page of the article

Published online: 03 October 2023

Key Points

Outcomes post-anterior cruciate ligament reconstruction are sub-optimal and to improve outcomes we need to optimise our rehabilitation processes and practices.

Without high-quality early-stage (and pre-operative) rehabilitation, patients often do not overcome major aspects of dysfunction, which limits knee function and the ability to transition through subsequent stages of rehabilitation optimally.

We highlight six main dimensions during the early stage: (1) pain and swelling; (2) knee joint range of motion; (3) arthrogenic muscle inhibition and muscle strength; (4) movement quality/neuromuscular control during activities of daily living; (5) psycho-social-cultural and environmental factors; and (6) physical fitness preservation.

Appropriate planning and programming are required to effectively target these dimensions and implement strategies into practice.

a range of musculoskeletal injuries), and so, cannot develop sufficient expertise [22]. If we are to truly impact individual patients across the globe, a stronger focus on research implementation, as well as addressing barriers and facilitators to research implementation (e.g. a 9- to 12-month rehabilitation and a sufficient number of supervised treatments are not always implemented because of insurance coverage) [22], is needed from researchers (and research practitioners, who treat or have treated a large volume of patients) to translate efficacious rehabilitative and preventive methods into practice on behalf of the practitioners [23–26].

Recent approaches have been made to provide practitioners with guidance on rehabilitation processes and practices post-ACLR, including papers on optimising the mid- and late-stage rehabilitation and RTS processes [27–30]. It is felt that these are key areas to address within conventional rehabilitation approaches. However, without high-quality early-stage (and pre-operative) rehabilitation, patients often do not overcome major aspects of dysfunction that limit knee function and the ability to transition through mid- and subsequent late-stages of rehabilitation optimally [31–34]. Thus, optimal early-stage rehabilitation appears essential for developing the key qualities required for a successful mid- and late-stage rehabilitation. There is a lack of published recommendations on 'how to optimise' early-stage rehabilitation processes and outcomes. Therefore, we wrote this paper to accompany previously published reviews in this journal around optimising mid- [29] and late-stage rehabilitation and RTS [28] training and testing processes. This paper provides what we feel is a missing piece to support the optimisation of the whole pathway post-ACLR. The author team is made up individuals across multiple disciplines including the physiotherapist, sports medicine physician, surgeon, rehabilitation specialist, sports scientist and strength and conditioning specialist, sport psychologist, and sport and exercise physiologist, all with specific experience and/or expertise in researching and/or treating ACL patients. All authors contributed to the paper but with a topic expert assigned to each of the specific areas given the breadth of the subject matter. A comprehensive literature search was conducted across all topics in writing the specific sections.

2 The Functional Recovery Process

It is important to have a well-structured functional recovery process in place post-ACLR, and a clear understanding of where the early stage of rehabilitation fits within the overall functional recovery framework. Prior to discussing early-stage rehabilitation, it is essential to briefly cover pre-operative rehabilitation. Knee function prior to surgery is important in expected and final outcomes post-ACLR [35–37]. Patients with full knee extension, absent or trace swelling, and no knee extension lag on straight leg raise preoperatively have better post-surgical outcomes [38]. Full knee extension is a requirement for normal gait [39] and achieving preoperative full knee extension ROM reduces the chance for postoperative complications, such as arthrofibrosis [40, 41]. McHugh et al. [41] found that patients with pre-operative knee extension loss were five times more likely to have extension loss issues post-surgery. Patients with better pre-operative quadriceps activation demonstrated greater post-operative activation, whilst patients with better pre-operative strength also demonstrated better post-operative strength [42]. A deficit in knee extensor strength of 20% or more pre-surgery predicts a significant strength deficit until 2 years post-ACLR [36]. Alongside our recommendations for early-stage rehabilitation post-ACLR, we advise a period of pre-operative rehabilitation (not time based but function based where possible). The research available indicates that pre-operative rehabilitation (a 5- to 6-week programme focusing on restoration of muscle strength, quadriceps hypertrophy and hop performance) results in superior knee function post-operatively [37, 43–46]. Moreover, this pre-operative rehabilitation can be valuable in identifying copers (athletes who resume prior levels of activity without dynamic instability following ACL rupture) and non-copers (athletes who continue to have episodes of dynamic instability despite progressive rehabilitation) [47]. Interestingly, nearly half (45%) of non-copers became copers following a ten-session, 5-week neuromuscular and strength training programme post-ACL injury [48]. Furthermore, athletes who were potential copers following neuromuscular and strength training were more likely to succeed 2 years later regardless of whether they had ACLR [48], strongly supporting the addition of strength and neuromuscular training post-ACL injury, prior to ACLR.

Immediately post-ACLR, is what we define as the 'early-stage' and the focus of this paper. The main objectives of the stage are to overcome the effects of surgery (and the injury) and prepare for entry to mid-stage rehabilitation. Mid-stage rehabilitation has three key objectives; to restore muscle strength, movement quality and fitness to a sufficient level to be prepared for entry to the late-stage and RTS framework. Late-stage rehabilitation focuses on restoring fitness, neuromuscular and movement performance and RTS training, defined as a continuum of sport-specific on-field rehabilitation, return to training, return to competition and finally return to performance (Fig. 1) [49]. For an optimal recovery process, it is important to have clear goals and priorities, and a clear understanding of when an athlete is ready for surgery and able to satisfactorily commence each stage of rehabilitation. This paper respects the importance of being optimally prepared for surgery, identifying the best surgical option for the individual patient and the impact of differing surgical techniques on the physical quality requirements for optimising early post-ACLR recovery.

3 Important Early-Stage Dimensions

The main clinical considerations for early-stage rehabilitation can be grouped into six categories: (1) pain and swelling; (2) joint range of motion (ROM); (3) arthrogenic muscle inhibition (AMI) and muscle strength; (4) movement quality/neuromuscular control during activities of daily living (5) psycho-social-cultural and environmental factors and (6) physical fitness preservation (Fig. 2). This section addresses each of these considerations separately, highlighting the relevant literature.

3.1 Pain and Swelling

Post-ACLR, there is often considerable pain, swelling and potentially other signs of inflammation. This inflammatory process creates a catabolic joint environment and should be clinically managed by the treating team not only for acute outcomes, but also for the late sequelae [50]. Pain and swelling (two common signs of inflammation) affect joint proprioception [51, 52] and result in AMI [53, 54] and so, should be addressed early post-ACLR. Swelling can mechanically prevent full joint ROM, with changes in swelling being frequently associated with irritation of intra-articular structures and articular disorders in clinically active knees [55].

It is recommended to utilise a range of treatment modalities to address pain and swelling as part of early-stage rehabilitation. Use of cryotherapy (ice), compression and elevation are standard practices as part of acute injury management [56, 57] and are applied early post-ACLR to reduce joint inflammation and pain [57–59]. Incorporating active ROM exercises (e.g. stationary cycling, in pool ROM tasks and active isotonic exercises assisted, against gravity, or with band or elastic resistance) may also be initiated early to increase the venous blood return and reduce swelling, as well as supporting recovery of knee ROM (see Electronic Supplementary Material [ESM]).

Beyond these general aspects, frequent medical consultations (in the authors experience at least every 10–15 days) are suggested to monitor the patient and recognise and address potential post-ACLR complications (see Table 1 for an overview of post-operative complications). In the case of excessive swelling and pain (alongside other signs of inflammation such as *rubor* and *calor*), the medical consultation should be urgently organised. *Haemarthrosis, excessive swelling and recurrent synovitis* are not uncommon complications post-ACLR [60] and should be managed by the medical team with the use of knee compression, anti-inflammatory drugs and aspiration of excessive intra-articular swelling. In the presence of worsening symptoms, it is critical to rule out the presence of *infection*, particularly of *septic arthritis*, which although rare, is a devastating condition post-ACLR. The clinician should be aware that the prevalence of septic arthritis in a general population post-ACLR is around 0.37–0.45% [61, 62], but higher in professional athletes and following additional procedures, such as lateral extra-articular tenodesis [62]. When assessing/monitoring pain and swelling, it is important to consider the surgical procedure. For example, hamstring graft harvesting could produce muscle bleeding and ecchymosis in the posterior thigh and posterior

Fig. 1 Functional recovery process involving progression of five stages including pre-operative, early-middle- and late-stage rehabilitation and return to sport (RTS) training

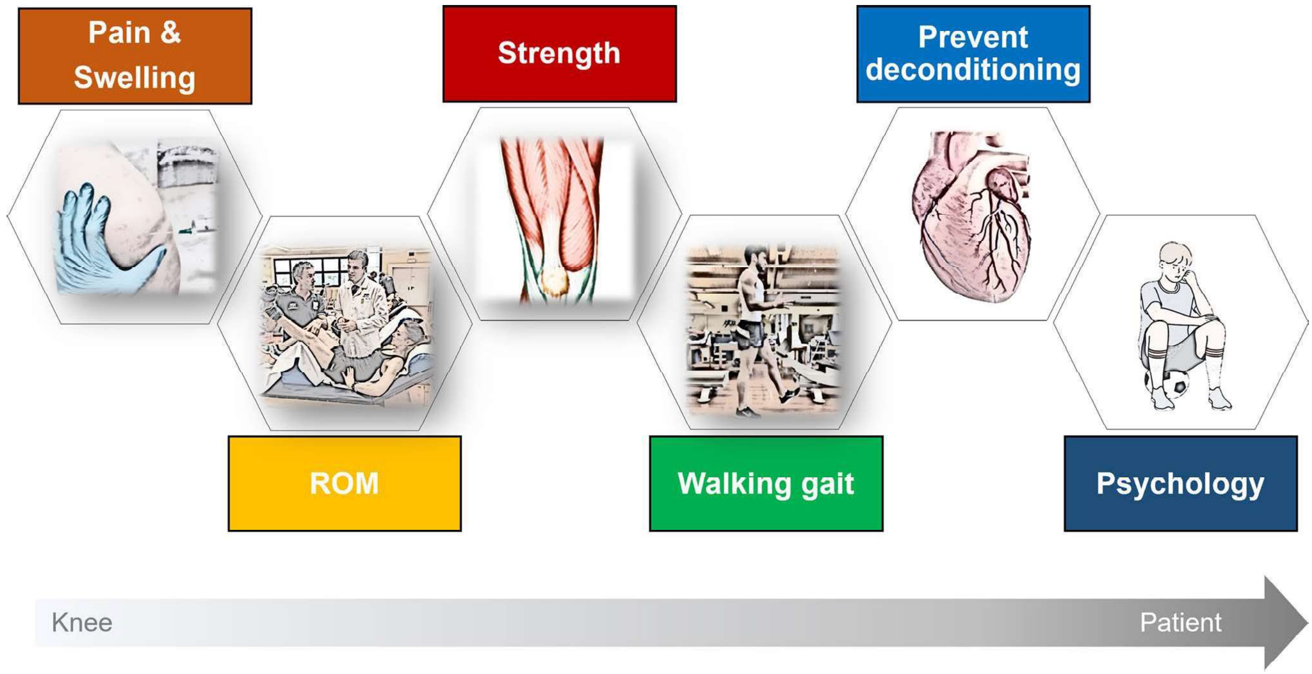

Fig. 2 Proposed six important dimensions in early-stage rehabilitation following anterior cruciate ligament reconstruction. From left to right there is an increased focus on the patient, and reduced focus on the knee. *ROM* range of motion

knee, or swelling on the calf, which could be considered a normal post-operative course to some extent. Long multi-ligament surgery could produce fluid extravasation and whole thigh oedema. Meniscal repair with all-inside sutures is generally more painful than standard ACLR and could create recurrent swelling.

Clinicians should also be aware of the medications that the patient is taking post-ACLR. Use of venous thromboembolism chemical prophylaxis is currently debated and commonly used post-ACLR [63], even if there is no complete consensus [64]. Venous thromboembolism is a serious complication post-ACLR and can be suspected in the case of severe lower limb swelling in patients with well-known risk factors. In the case of complications, it is critical to act as soon as possible.

Pain and swelling should be monitored to support rehabilitation progression. Pain can be monitored using a 11-point numeric rating scale (0, absence of pain, 10, worst imaginable pain). A numeric rating scale pain value of 0–2 (knee specific) has been recommended as a criterion for transition to higher intensity rehabilitation (e.g. mid-stage rehabilitation [29]). Tolerance of higher pain in non-specific areas (e.g. due to scar tissue) and harvest site pain may be acceptable and may need careful differentiation when questioning the patient about their pain experience. We suggest a maximum numeric rating scale score of 4/10 during rehabilitation sessions based on patellofemoral joint (PFJ) pain and tendon research [65–68] and anecdotal experience. As pain perception is an individual experience, it may be useful in the early-stage of rehabilitation to anchor these pain scores to physical tasks that are undertaken regularly (e.g. sitting from standing and/or rising from a chair, when walking a set number of steps, or ascending or descending the stairs). These scores for specific tasks can then be compared to understand if pain is increasing or decreasing in relation to those specific tasks and changes in rehabilitation loading can be made accordingly.

Swelling should be recorded regularly, preferably daily through the early-stage. The Stroke test [69] and knee circumference measurements [70] can be used (see ESM), together with soreness rules proposed by Adams et al. [71]. Measurement of knee circumference at the patella has been shown to have strong intra-tester reliability and good sensitivity to change [70] and the Stroke test has been shown to be a reliable indicator [69]. The knee circumference measurement is a simple easy-to-use and interpret test and can be performed by the patients themselves (see ESM). Changes of greater than 1 cm in knee circumference at the patella are thought clinically significant [70], indicating the levels of load applied were causes of joint stress. This may be especially useful if considered over the course of a day, with one measure being taken on first rising in the morning and the other at cessation of activity at the end of the day [72]. When an increase in swelling and soreness occurs, it is essential to adjust the programme and educate the patient on load management. Anecdotally, it is the patient's activity

Table 1 Complications that the clinician may face during the early stage of rehabilitation post-ACLR

Clinical signs and symptoms	How to react, Step 1	How to react, Step 2
Deficit of passive knee extension at week 3 post-ACLR	Medical attention within 1 week, set up a programme of *increased intensity on knee extension ROM recovery* of 3 weeks then re-evaluate. Educate the patient regarding the non-deleterious role of passive forced extension on the ACL graft. Consider bracing a locked-in extension or using a drop-out cast [216]	If progression is positive, continue the recovery programme. If no or minimal progression, consider the execution of MRI and surgical options (mobilisation under anaesthesia or arthroscopic debridement) after 3–4 months
Persistent moderate knee swelling and signs of inflammation	Medical attention within 1 week. *Start medical therapy (e.g. anti-inflammatory) and conservative treatment (e.g. neoprene brace).* Re-evaluate in 1–2 weeks. Evaluate aspiration of the intra-articular fluid. Consider an optimisation of the load progression (in and outside the rehabilitation clinic)	If progression is positive (decreased swelling), continue the recovery programme. If no or minimal progression after several months and no post-operative infection, consider arthroscopic debridement. Always consider the complexity of the surgery (meniscal repair or other ligament reconstruction)
Surgical leg swelling, redness and soreness	*Immediate medical attention to rule out DVT* with Doppler ultrasound of the lower leg. In the clinical reasoning, consider if the patient is (or is not) receiving prophylactic therapy (very common practice)	If the ultrasound results are positive for DVT immediately start medical therapy (anticoagulant therapy according to medical prescription)
Appearance of severe knee swelling, fever and other systemic symptoms Important warning sign when swelling is increasing and not decreasing	*Immediate medical attention to rule out septic arthritis. Immediately start medical therapy (antibiotic therapy).* Aspiration, assessment of synovial fluid aspect, culture of intra-articular fluid and WBC count in the synovial fluid. Blood WBC, CRP and ESR are useful but not specific	If good clinical response to medical therapy, re-start the programme. If no response to medical therapy, evaluate surgical options (e.g. single or multiple arthroscopic lavage with or without hardware and graft removal) followed by targeted antibiotic treatment
Delayed wound healing and superficial wound infection	Based on the wound location, decrease the mechanical stress on the skin due to movement. Avoid the wound getting wet. Delay pool rehabilitation until complete skin closure or even 1 week after. Apply Steri-Strips to approximate skin margins	If no progression after 4–6 weeks post-operatively or in the case of increasing skin opening or purulent liquid leakage from the wound, consider surgical options (wound debridement, intra-operative culture, skin closure and antibiotic therapy)

ACLR anterior cruciate ligament reconstruction, *CRP* C-reactive protein, *ESR* erythrocyte sedimentation rate, *DVT* deep vein thrombosis, *MRI* magnetic resonance imaging, *WBC* white blood cell outside the clinic, as opposed to rehabilitation activity in the clinic, that results in an overload, and tracking activity status is important (e.g. step count, activity log).

3.2 Knee Joint Range of Motion

Recovery of knee joint extension and flexion ROM are important aspects of early-stage rehabilitation and if not satisfactorily attained can adversely affect subjective and objective outcome markers in late-stage rehabilitation [71], with early knee extension loss being strongly related to medium-term loss [33]. Normal or optimal gait biomechanics cannot occur without appropriate joint ROM [39], with full knee extension an essential criterion to meet to safely progress the patient off their crutches post-ACLR [29]. Extension loss results in abnormal joint arthrokinematics at both the tibiofemoral and PFJ, and results in abnormal articular cartilage contact pressures and quadriceps inhibition [73, 74]. Patients who experienced an extension deficit post-ACLR have been reported to have a five-fold higher risk of developing anterior knee pain [75]. Failure to regain full extension by 3 weeks post-ACLR is an important predictive factor for subsequent cyclops lesions or arthrofibrosis [76]. In this context, it is key to act immediately and seek medical attention (again, we suggest frequent medical consultations in the early stage). It is also important to educate the patient regarding the non-harmful role on the ACL graft of passive extension stretching. In the case of a real biological and mechanical joint condition, it is suggested to also evaluate a surgical solution, especially if the deficit persists beyond 3 months (Table 2).

Sufficient knee flexion ROM (110–120°) should also be achieved by the end of the early stage (4–6 weeks) [71], with this ROM required for the patient to commence stationary cycling [72] and treadmill running [29]. Knee flexion ROM recovery should be progressive and not aggressive and may be guided by the presence of associated surgical procedures that may suggest more caution (e.g. meniscal repair). ROM exercises to facilitate knee flexion and extension should generally begin immediately post-ACLR. Early joint motion is beneficial for avoiding capsular contractions and reducing swelling and pain, and an early full passive and active extension would appear to have no adverse effect on joint laxity [57, 77]. Additionally, anterior knee pain incidence and the risk for a cyclops lesion can be reduced through early movement and stimulation of knee hyperextension [76, 78]. Use of techniques such as active and passive ROM exercises are essential (see ESM). Hydrotherapy could support the improvement in both joint swelling and passive and active joint ROM [79].

3.3 Muscle Activation and Strength

3.3.1 Knee Extensors/Quadriceps

One of the main priorities of rehabilitation post-ACLR is the restoration of knee extensor muscle strength [29, 80]. Residual deficits in knee extensor muscle size and strength post-ACLR are associated with reduced knee function [81, 82] and are a key barrier to functional progression [83]. Knee extensor weakness is also associated with a range of important complications such as altered biomechanics during gait [84] and higher load functional tasks [85], decreased dynamic stability [86], persistent knee pain [87], increased risk of knee OA [18] and poorer RTS outcomes [9]. It is imperative to minimise the extent of knee extensor weakness during the early-stage post-ACLR. For this reason, post-operative rehabilitation should start as soon as possible. Commonly reported deficits of ~ 40–60% in maximal isometric voluntary force versus the uninjured limb have been reported 4–6 weeks post-ACLR [88, 89]. Knee extensor maximal and explosive strength 6-weeks post-ACLR has been shown to predict hop and jump performance 6-months post-ACLR [90]. The greater the deficits in strength at the end of the early stage, the harder it will be to recover strength during the mid- and subsequent late stages, which will influence RTS and long-term outcomes [9, 83, 85, 91]. The degree of quadriceps strength deficit at the end of early-stage rehabilitation will be associated with pre-surgery strength deficits [35, 42, 46], graft choice [larger deficits in those with bone-patella-tendon-bone or quadriceps tendon vs other graft types (e.g. hamstring tendon autograft)] [92, 93], and the extent of pain and swelling/inflammation [86, 94] neuromuscular inhibition/AMI [86, 95] and muscle atrophy [95] post-ACLR.

Rehabilitation activity is an important and controllable factor in early-stage outcomes [96] and incorporating strategies to overcome AMI and quadriceps lag as well as minimising strength loss, and associated determinants of strength loss (e.g. neural inhibition and morphological alterations such as muscle atrophy of specific muscle fibres) is essential. Understanding exercise selection and programme design principles is also essential to achieve optimal loading. However, following injury and subsequent ACLR, disruption to joint homeostasis (e.g. pain, swelling, laxity) causes alterations in neural control. Loss of mechanoreceptors from the ACL is thought to disrupt the ligamentous-muscular reflex between the ACL and the quadriceps, leading to an inability to actively recruit high-threshold motor units during voluntary quadriceps contractions. This phenomenon by which uninjured muscle becomes reflexively inhibited because of the injury to the joint it surrounds is termed AMI [97]. AMI is hypothesised to be present post-ACLR and contribute to the ever-present post-traumatic knee extensor strength deficit

Table 2 Recommended supplementary strategies to support a reduction in arthrogenic muscle inhibition and/or enhanced stimuli for muscle strength (and associated underlying mechanisms) enhancements at lower relative joint loading during the early stage of rehabilitation after anterior cruciate ligament reconstruction

Strategy/adjunct	Description and evidential support
Focal joint cooling (BEFORE the session!)	Application of ice on the knee joint may serve to temporarily decrease AMI [54, 94] and facilitate increased quadriceps activation [217, 218], by altering sensory input from nociceptors and thermoreceptors. Hart et al. [219] showed how 20–30 min of ice prior to quadriceps strengthening exercises resulted in superior strength gains vs strength or ice alone, in patients post-ACLR. This is an important finding as clinicians typically use ice after, not before exercise
TENS	The greatest effect of TENS appears as a supplement to active exercise with an effect to minimise AMI and promote quadriceps recruitment [220, 221]. High-frequency sensory TENS applied to the anterior aspect of the knee before and during exercise has been shown to improve quadriceps central activation and strength over a 45-min period and following 2 weeks of use [222]
Hamstring fatigue prior to quadriceps exercises	While cortical drive to the quadriceps is lower post-ACLR [223] the hamstrings maybe facilitated [224]. Higher co-activation of the hamstrings will not only reduce the net force output of the knee extensors, but through the process of reciprocal muscle inhibition will reduce the volitional drive to the quadriceps muscle [225]. A single bout of hamstring fatiguing exercise (vibration) has been used to decrease antagonist-agonist coactivation, while increasing quadriceps central activation [226] and maybe a useful strategy prior to quadriceps exercises
NMES	There is level 1 evidence that use of NMES in addition to standard physical therapy appears to significantly improve quadriceps strength and physical function in the early post-ACLR period vs standard physical therapy alone [227]. The use of NMES has been shown to add no or minimal additional value beyond that of an eccentrically based rehabilitation protocol post-ACLR [228] but would appear to be an effective tool during the early to mid-stages post-ACLR, when patients cannot tolerate heavy eccentric loading. NMES allows for the direct activation of the motor axon and could allow for the direct recruitment of the inhibited motoneurons. NMES has been shown to lead to higher recruitment of type II muscle fibres when compared with voluntary contractions of a similar intensity [229–231], in part due to a reversal [232] of the logical motor unit recruitment process (e.g. smallest to largest) [233]
BFR training	Although a novel concept, studies combining low-intensity NMES with BFR have found increases in muscle size and strength [234, 235] and preservation of muscle size during periods of unloading [236]. The use of NMES and BFR in the first few weeks' post-ACLR does not involve transmission of large forces through the tibiofemoral joint, thus posing a low risk of damaging the graft or exacerbating any cartilage, meniscal or bone injuries. Thus, the current evidence suggests that BFR and NMES may evoke greater strength and muscle mass adaptations in human muscles than NMES alone and could be used in the initial weeks post-ACLR (days 3–21). BFR with RT can elicit muscle hypertrophy and strength adaptations in load-compromised populations using light external loads of 20–30% 1RM [237, 238], which may be comparable in magnitude to heavy-load RT [239, 240]. Level 1 evidence suggests that BFR RT can elicit greater hypertrophy and strength adaptations in ACLR patients than matched load training without BFR [241]. Furthermore, BFR RT provides a greater reduction in pain and swelling and improves patient physical function to a greater extent than high-load RT, without detrimental effects on muscle hypertrophy and strength improvements [242]. Importantly, knee pain during training was significantly lower with BFR RT and 24 h post-training [243]. It is recommended to start the addition of BFR RT 2–3 weeks post-surgery following a criterion-driven approach [242]
Cross-education training	Cross-education, which is the increase in muscle force on the untrained side after RT of the contralateral homologous limb muscle [213, 214], has been shown to accelerate the recovery of the injured limb's strength post-ACLR [215]. High-intensity eccentric training of the contralateral limb may be more effective than concentric training, in terms of this cross-education benefit [216]. The mechanism behind cross-education training is thought to be due to enhanced neural activation/decreased pre-synaptic inhibition, which can facilitate an increased activation of the injured limb [244, 245]. Deficits in knee extensor strength, prevalent in the injured limb are also present in the contralateral uninjured limb [246–248]. Strength training of the contralateral limb is an effective strategy to support the maintenance of strength on the contralateral limb to serve as an appropriate reference value for the injured limb as part of the limb symmetry index [28]. Our advice is to include high-intensity, low-volume eccentric (or concentric/isometric, where eccentric is not feasible) strengthening of the contralateral limb to preserve muscle strength and support neural adaptations to in part overcome AMI in the injured limb

ACLR anterior cruciate ligament reconstruction, *AMI* arthrogenic muscle inhibition, *BFR* blood flow restriction training, *CET* cross-education training, *NMES* neuromuscular electrical stimulation, *RT* resistance training, *TENS* transcutaneous nerve electrical stimulation

[98–101]. Often, there is limited consideration of the notion that if a patient fails to overcome AMI, they will be unable to optimally restore muscle mass and strength. AMI can limit the extent of neuromuscular activation required to bring about improvements in quadriceps function from voluntary resistance training, thereby limiting the value of any conventional strength and conditioning programme.

A further significant challenge for rehabilitation specialists is designing resistance training programmes that facilitate positive training adaptations, whilst being mindful of biological healing constraints and tissue capacity [102, 103]. It is important to understand the potential loading of various tasks on the new ACL graft, both to protect it from excessive loads that could lead to graft attenuation or even failure throughout the functional recovery process [104, 105] and to provide sufficient load to encourage graft strengthening. The tensile capacity of the ACL ligament is considered to be about 2000 N for male individuals [106] and 1300 N for female individuals [107], although the ACL graft and the graft fixation sites are likely to be significantly weaker than their eventual ultimate strength [108–110]. The inserted tendon graft undergoes healing and metaplasia referred to as the 'ligamentisation' process [104, 111] in the months post-ACLR. The new ACL graft will eventually display similar tensile capacities to the native ACL, but this can take 2 years [108–110]. Immediately post-ACLR, the graft fixation sites require time for incorporation into the surrounding bone and during the first 6–12 weeks post-ACLR, the graft is vulnerable to fixation loosening and overstretching from excessive tensile loading due to early necrosis and graft-bone interface healing [104, 112, 113]. An additional key consideration with knee extensor strengthening post-ACLR is minimising PFJ stress, given the high prevalence of patients who go on to develop patellofemoral pain syndrome post-ACLR [114]. Being too aggressive (maximum loading/effort or high force exercise, e.g. heavy-load [3–5 RM] full range knee extensions) in the early stage can be deleterious to the integrity of the ACL graft/fixations sites post-operatively and lead to patellofemoral pain syndrome [115].

Any quadriceps strengthening approach must be aligned with the other dimensions of activity. Given the deleterious effects of pain, swelling and AMI on muscle activation and force generation, addressing pain, swelling and AMI (considering quadriceps lag as an indicator) is key prior to structured strengthening. Furthermore, considering the load limitations on the knee, specifically the new ACL graft, the incorporation sites and the PFJ, any voluntary resistance training during the early stage should be performed with supplementary strategies as adjuncts. These supplementary strategies should support a reduction in AMI, and/or allow for enhanced stimuli (muscle force/mechanical loading, neuromuscular activation, metabolic by-products) for adaptations at lower loading of the aforementioned knee structures (e.g. ACL graft, incorporation sites and PFJ). An in-depth focus on these strategies goes beyond this text but a brief description and evidential support can be found in Table 2 and advice on implementation in the ESM.

Utilisation of resistance training as part of a planned programme is essential to optimal loading and functional recovery post-ACLR. Exercise selection and programming can be challenging during the early-stage, and a fear of utilising quadriceps strengthening approaches often leads to deficits in quadriceps function, which make the rehabilitation journey as a whole more challenging. As stated previously, incorporating safe and optimal loading in the early stage is imperative to minimise the extent of knee extensor weakness during the early-stage post-ACLR. In the subsequent paragraphs in this section, we make recommendations as to appropriate exercise selection and programming principles during the early stage for preservation and early recovery of quadriceps muscle function and knee extensor strength.

In terms of exercise selection during the earlystage, we recommend using isolated and/or non-weight-bearing tasks (e.g. leg press/knee extension) as opposed to functional exercises (e.g. squatting/deadlifts), at least for the purposes of strengthening (and the associated neural and morphological adaptations). Patients will likely still have considerable neural inhibition of the quadriceps (AMI), altering technique and intra- and inter-muscular coordination [116, 117]. That is not to say basic functional tasks (e.g. bilateral squatting) cannot be taught during this stage as part of early movement restoration.

Isolated strength tasks should include both closed kinetic chain (CKC) [e.g. leg press] and open kinetic chain (OKC) [e.g. knee extension isoinertial/isokinetic machine] exercises. OKC exercises in particular isolate the muscle in question and limit the involvement of other muscle groups, thereby ensuring higher and more complete activation and fatigue of the target muscle. Knee extensions are thought critical for restoring quadriceps strength, as well as being key for assessing readiness to RTS post-ACLR [118]. A relatively recent systematic review analysed ten randomised trials and found no evidence of a difference in anterior tibial laxity between those who performed OKC versus CKC exercises post-ACLR [119]. However, there remains a common fear with the use of OKC that they result in loosening the healing graft due to a high strain on the graft. Importantly, with every step during walking, strain on the ACL is two to three times higher than that during full ROM knee extensions with a + 3-kg load [104, 120]. As such, relatively low load OKC knee extensions are safe for the ACL/knee. Importantly, although we encourage the use of OKC exercises, even during the early stage, we also encourage some caution. During isoinertial knee extensions, there is no or minimal hamstring muscle co-activation [121], which can leave the ACL more vulnerable to unopposed anterior shear forces on the graft, if high loads are used. For structured strengthening of the knee extensors during the early (and mid-) stage and particularly when the patient can begin use to use heavier loads (e.g. 10–15 kg), we suggest restricting the ROM to limit ACL and PFJ loading. The quadriceps muscle forces required to extend the knee is three to four times higher near a full knee extension (than at deeper knee flexion angles) [121]. Furthermore, the resultant ACL strain and PFJ reaction and compressive forces will be higher with a lower patellofemoral contact surface area nearer a full extension (from 50° of knee flexion to 0° degrees of knee flexion/full extension) [104, 122], all at lower relative loads that can be lifted through full ROM. ACL strain is minimal (0.0% peak strain) and PFJ reaction forces are dramatically reduced when OKC quadriceps contractions are performed at 60–90° of knee flexion [104, 115, 123]. Thus, restricted ROM (e.g. 45–90°) knee extensions, will allow for higher loads to be lifted at lower relative ACL and PFJ loading [104, 114, 122–125] and thus, makes sense. To reiterate, we still recommend using full ROM loaded knee extensions to support enhanced strength and activation (particularly at extended knee angles), but anecdotally believe heavier loaded restricted ROM knee extensions are superior.

A key consideration with early-stage strengthening is the level of loading/intensities during strength tasks. There is little discussion on programming variables for strength recovery for injured athletes, with most of the literature on exercise selection (OKC vs CKC). Whilst there is a dose–response relationship between intensity and strength gains, with higher loads/intensities associated with greater improvement in maximal strength [126–128], high loads are contraindicated early post-ACLR, as the knee is load compromised, likely in pain, with swelling and accompanying AMI. Thus, lower loads/intensities are recommended and can still promote improvements in quadriceps function. Lower loads performed to fatigue (e.g. 4–6 sets of 20 RM with minimal recovery [e.g. 30–60 s] between sets) will predominantly target adaptations related to muscle endurance and work capacity and lead to muscle hypertrophy via metabolic stimuli/adaptations [129]. Taking the working set close to volitional fatigue can facilitate more complete activation of the motor unit pool, thereby facilitating activation of higher threshold type II motor units [129]. As an athlete becomes stronger and overcomes pain, swelling and AMI, higher intensities can and should be used, in a progressive manner, as part of a periodised resistance training programme [80].

In general, we suggest the adoption of a multi-modal approach to early-stage quadriceps muscle preservation and recovery is necessary. Initially, addressing pain, swelling and consequential AMI is essential. Focused quadriceps strengthening should only occur when patients have minimal pain (0–2) and swelling and sufficient quadriceps activation (no lag on straight leg raise). Use of neuromuscular electrical stimulation and/or passive blood flow restriction in the initial weeks performed alongside transcutaneous nerve electrical stimulation and early introduction of isometrics is recommended [80]. These isometrics should be performed at restricted ROM (60° and/between 90° knee flexion), with repetitive sustained holds (e.g. 5 × 45 s [2 min rest between each repetition]) 1–2 times per day (based on anecdotal experience and lower limb tendon pain research) [66, 130–132]. Full ROM (0–90°) OKC knee extensions against gravity/low loads (e.g. 1–3 kg) can be performed once able to comfortably achieve a 90° knee flexion angle. We suggest the use of restricted ROM loaded knee extensions from 4 weeks post-ACLR (providing the clinical milestone have been attained) [through to 12 weeks post-operatively) using slow knee extensions (3 s up [concentrically], 3 s down [eccentrically]) with 15–25 RM loads (increasing intensity in an incremental manner from 4 through to 12 weeks) [96] in conjunction with a comprehensive CKC plan (see ESM).

We also recommend assessing knee extensor muscle strength (and where possible morphological and neural aspects of neuromuscular function) as part of the transition to mid-stage rehabilitation. This should involve assessing isometric knee extensor strength, using a dynamometer (ideally an isokinetic or isometric bespoke build dynamometer/portable dynamometer) [132] at/or between 60–90° knee flexion [104, 115, 123, 133] (see ESM), with strength reported as absolute force/torque, normalised to body mass, and as a limb symmetry/quadriceps index. Furthermore, monitoring knee extensor workloads (e.g. sessional, and weekly reporting of repetition load and intensity, volume, rating of perceived exertion) and the knee's response to such loading (pain, swelling via knee circumference) is recommended throughout the stage (and subsequent stages).

3.3.2 Knee Flexors/Hamstrings

Large deficits in knee flexor strength are apparent early post-ACLR (40–50% at 4 weeks, [89]) with deficits of 0–20% still common at the time of RTS, and even years post-ACLR [134–138]. Although deficits in knee flexor strength are typically less than those for the knee extensors [139, 140], even small deficits in knee flexor strength can be detrimental to injury risk upon RTS [91]. Hamstring strength recovery is harder and more complicated in those with a hamstring graft (HG) [92] because of selective muscle inhibition and atrophy (10–28%) of the grafted semitendinosus muscle [141–144], which may compromise strength recovery [141]. In essence, ACLR with an HG should be treated as ACLR plus a severe hamstring strain, with a periodised resistance training programme similar to that utilised for the knee extensors adopted [80, 145] for the hamstring muscles. It is typically recommended that specific strengthening of the knee flexors be delayed for 6–8 weeks post-ACLR with an HG to allow healing [104, 146, 147]. But an acute hamstring injury however severe would not be left this long unloaded. Therefore, Buckthorpe et al. [145] advise using isometric/concentric exercises of low intensity at short-medium muscle lengths during the early stage, which we advocate here, and which would be expected to support more optimal recovery. It is important during the early stage though, to avoid strenuous activities that may potentially result in damage to the hamstring donor site (e.g. removing shoes with the contralateral foot/leg, fast deep water running in the swimming pool). Thus, controlled isolated exercises at a low intensity to promote muscle reactivation and muscle volume preservation are recommended (see ESM).

We recommend assessing knee flexor strength as part of criterion-based rehabilitation. Whilst hamstring strength would not be a significant barrier to progression, as with the knee extensors, failure to overcome hamstring muscle inhibition post-ACLR with HG can be problematic. Patients should be able to initially flex the knee to 90° while standing (prior to adding load to this task as tolerated) and undertake a bilateral straight leg bridge (heels on a 30-cm-high box) for 10 repetitions to a neutral hip extension [72] (see ESM). We also recommend assessing isometric knee flexor strength at either 60° or 90° (matching whatever is chosen for the knee extensors) using a dynamometer, aiming to achieve a limb symmetry index > 60% (see ESM).

3.3.3 Other Muscle Groups

Typically, early-stage post-ACLR programmes focus exclusively on resolving knee mechanics. However, it is important also that rehabilitation be focused both distally and proximally to the knee joint. Deficits in ankle plantar flexor strength and muscle strength about the lumbo-pelvic-hip region can occur and impact neuromuscular performance and movement quality [29].

The triceps surae muscles are important contributors to muscle force generation and load acceptance during activities such as walking, jogging/running and jump-landing [148, 149]. The resolution of plantar flexor strength appears to be much easier than with other muscle groups (e.g. quadriceps/hamstrings, hip musculature). Whilst some work suggests small deficits in plantar flexor strength [150] and muscle size [151], others have indicated relatively early restoration of plantar flexion strength post-ACLR [152, 153]. Early targeted work on the plantar flexors is important to ensure minimal deficits in maximal strength as patients commence a return to running and landing activity, which typically begins towards the end of the mid-stage/start of the late stage (single limb load acceptance) of rehabilitation [28, 29, 72] (see ESM).

Hip muscle strength weakness is also common post-ACLR [154]. Reduced activation of the hip abductors and external rotators (e.g. gluteus medius and maximus) may be a risk factor for ACL injury [155] and patellofemoral pain [156, 157] and be present in those with ACLR. The gluteus maximus is thought to become 'inhibited' (defined as reduced activation or delayed onset) after lower limb injury because of pain [158, 159] and is an important muscle alongside other gluteal muscles (gluteus medius and gluteus minimus) in preventing dynamic knee valgus during high-load closed chain tasks [160, 161]. We recommend including non-weight bearing hip (see ESM) and lumbo-pelvic ('core', see ESM) muscle strengthening alongside knee extensor strengthening. There is strong evidence that patients with patellofemoral pain have deficits in hip abduction, extension, and external rotation strength [162] and that hip muscle strengthening is effective in reducing the intensity of pain and improving functional capabilities in patients with patellofemoral pain [163–166].

3.4 Movement Quality/Neuromuscular Control During Activities of Daily Living

Alterations in movement quality (e.g. the ability to control the limb, maintaining balance and optimal kinematics during movement) [28] are apparent during various functional tasks including walking, jogging/running, jump-landing and sport-specific movements post-ACLR [34, 117, 167–171] and are associated with an elevated risk of re-injury [170], and early-onset development of knee OA [172, 173]. It is now becoming accepted that a key theme of rehabilitation post-ACLR is the assessment and treatment of aberrant movement patterns during functional tasks [28–30, 174]. However, movement retraining is still typically seen as a late-stage rehabilitation factor.

Failure to sufficiently resolve movement quality during basic functional tasks (when compared to highly complex sporting actions such as cutting mechanics) early post-ACLR can have a marked impact on movement quality during late-stage rehabilitation and at the time of and after RTS. For example, Sigward et al. [34] found that aberrant knee moments during gait at 4 weeks were significantly related to knee moments during running at 4 months. Similarly, limb loading asymmetries have been reported in patients 1–12 months post-ACLR during bilateral squats [32, 34, 175] with asymmetries at 1 month found to be an independent predictor of limb asymmetries during a vertical jump landing at the time of RTS [32].

When assessing and training movement quality, it is important to understand what movement quality is and which factors may affect performance [174]. Altered movement quality is thought to be due to multiple factors. The classic contention has been that these alterations are thought to be due to biomechanical and basic neuromuscular deficits such as muscle imbalances/weakness (e.g. knee extensor weakness [85]). We contend that the current standard of care needs to consider the underlying neural processes that generate movement (i.e. neuromechanics) in addition to focusing on the final output of the nervous system in the form of biomechanics (kinetics and kinematics). This is especially relevant as recent data indicate an ACL injury is not an isolated joint injury that only affects stability and elicits biomechanical impairments, but it is also an injury that induces neurophysiological effects on sensorimotor control [176–178]. Disruption to the native ACL leads to laxity of the knee and can alter somatosensory activity. The resultant decrease in joint position sense and kinaesthesia, along with nociceptor activity associated with pain and swelling, may potentially impair movement quality [179]. As such, it appears essential to incorporate holistic movement re-training programmes, which address not only the biomechanical and neuromuscular factors, but also the sensorimotor and neurocognitive factors, and to initiate these early post-ACLR.

We recommend including both land- and water-based gait, balance and foundation movement (e.g. bilateral squat, step-ups in the pool) re-training during the early stage, which should include specific technique coaching and movement practice, ideally with some biofeedback on limb loading strategies (asymmetries in ground reaction forces) and kinematics employing an external focus of attention [180]. The walking gait re-education programme should include optimal use of crutches, teaching good control in knee extension–flexion ROM and hip adduction during the stance phase, and dynamic stability as well as selective movement retraining exercises to support the motor re-training process (e.g. standing marches in place, with optimal lumbar pelvic control and hip, knee and ankle flexion) [ESM]. Specific functional tasks can be included earlier in the pool [79], as the buoyancy properties of water support effective reductions in body weight and thus lower relative joint loading, overcoming to some degree the strength deficits post-ACLR (see ESM).

A key decision post-ACLR is when patients are ready to 'leave the crutches'. Patients under assessment should have sufficiently normalised gait (ideally, video analysis of walking gait on treadmill), be able to achieve full active knee extension, have control of swelling and no 'joint overload' (e.g. clinical increase of swelling [> 1 cm, at the patella], or pain [+ 1 point]) and no quadriceps lag on an active straight leg raise [29, 72]. We recommend assessing the bilateral squat technique and limb loading as part of early-stage criterion-based rehabilitation. The goal should be achieving good technique and limb loading (< 20% deficit) with a bilateral squat to 90°.

3.5 Psycho-Social-Cultural and Environmental Considerations

Numerous psychological, social, cultural and environmental factors have been identified to influence patients' experiences of and engagement in rehabilitation, which can impact cognitive, affective, functional and physical sport injury rehabilitation outcomes post-ACLR [181]. Synthesis of the evidence base at this early stage of recovery [182–184] shows that the main challenges that athletes experience and strive to overcome are: (a) comprehending and understanding the meaning of their ACL injury, (b) being incapacitated and (c) building a working alliance with their therapist.

During early-stage rehabilitation, athletes endeavour to *make sense* of their experience (e.g. Why me? Why now?), seeking information to understand the *nature* of the injury (e.g. Why did it happen to me?), as well as comprehend and understand the *meaning* of their injury [185, 186] in the context of their lives (e.g. identity) and current playing situation (e.g. timing of the injury during the season and its impact on their season and team). The early stage is emotionally challenging, in which patients often experience shock, anger, anxiety, depression, fear, sense of loss, helplessness, frustration, and psychological and existential pain [187, 188]. Athletes are often left to navigate these emotions themselves because they are isolated at home because of the injury, the cultural norms of sport encourage athletes to suppress negative injury-related emotions rather than disclose and talk about them, or their sporting clubs/rehabilitation clinics do not have the space, resources or processes in place to enable athletes to mentally rehabilitate from injury [189, 190]. As a result, a common strategy used by athletes is to try to avoid thinking about their injury and to suppress injury-related emotions. Although this strategy has been identified to work for some in the short term [191], it has been identified to be an unsustainable strategy in the longer term and can often lead to emotional outbursts that can negatively impact rehabilitation [190, 192]. To overcome this to some degree, sporting organisations/rehabilitation clinics should provide pathways for injured athletes to receive emotional support to help them regulate their emotions [193], such as counselling [194]. Support providers can listen to athletes' concerns, offer emotional comfort by expressing empathy and encouragement, and, if appropriate, challenge emotions to help athletes rationalise or distance themselves from them [195, 196]. An important consideration here for support providers is to understand the person and not just the injury [183]. By attending to the person, this can often create a climate where athletes are more likely to disclose their emotions as well as enable the support provider to contextualise athletes' responses (e.g. *why* they are experiencing certain emotions). In the absence of this support, 'self-help' strategies such as written emotional disclosure [197] learning from former injured athletes' stories using narrative videos [198] have been shown to enable athletes to make sense of their injury experience. It is important though to recognise that some athletes might need a clinical referral if they are experiencing a mental illness, which is common post-injury [199, 200].

A second challenge for patients is being physically incapacitated, limiting their ability to perform activities of daily living and restricting their mobility [195, 201]. Tangible support has been shown to be effective in helping athletes to address the everyday demands injured athletes find challenging [202], including transportation to medical appointments, shopping, cooking and housework, which can directly and/or indirectly support rehabilitation [183]. The main providers of tangible support appear to be teammates, family and friends; in particular, people with whom the injured athlete lives or has regular contact, and who are willing and able to provide the necessary assistance [195]. However, there are two challenges here. First, athletes are sometimes unaware of the support network available to them (e.g. their thoughts might be clouded with emotions) and second, they do not want to ask for help (e.g. they see asking for help as a sign of weakness). To help athletes recognise their social support network (i.e. who is available and what support they can offer), one strategy is to use *relational mapping*, where athletes draw their network of support providers, which can not only help to raise their awareness, but also challenge the misperception that they have limited practical support available to them. In addition, sporting clubs/rehabilitation clinics and support providers also need to challenge the stigma around asking for help, reframing it as a strength and not a weakness [183]. It is important though to also acknowledge that not all athletes will require or welcome tangible social support (e.g. those who are trying to preserve their independence). For these athletes, too much support or support from those from whom it is not welcome can be considered unhelpful, particularly if it poses a threat to their self-esteem [195].

Effective communication and a strong patient–therapist (therapeutic) alliance have been shown to be associated with improved rehabilitation outcomes following a musculoskeletal injury [182]. An “alliance” is often used to describe relationships in which a therapist and an injured athlete mutually collaborate to help manage the injury by creating a climate of trust, forging an emotional bond, and agreeing upon goals and treatment options [203]. For example, several researchers have examined how therapists can strengthen their relationship with injured athletes, including establishing and building rapport [204], educating athletes about their injury and the rehabilitation process [205], and being a primary source of social support [195]. If a trusting relationship does develop, this has been identified as promoting rehabilitation adherence [206], which can lead to desirable rehabilitation outcomes [207]. Training programmes to enhance communication are available for physiotherapists and for athletes [182].

3.6 Physical Fitness Preservation

Successful RTS requires not only resolving physical impairments at the knee, but also restoring neuromuscular function, sports-specific movement quality and sport-specific readiness (fitness, technical training, load readiness and psychological readiness) [49, 208, 209]. To achieve this, we need to think about ‘return to performance’ throughout the functional recovery process [49, 210], even early post-ACLR. The long rehabilitation and RTS process can offer an opportunity to develop an athlete’s physical fitness to higher levels than pre-injury, providing it is appropriately planned. From the limited evidence, patients including professional football players demonstrate reduced cardiovascular (CV) fitness 6-months post-ACLR [211], suggesting a need to focus on fitness preservation/recovery. Loss of CV fitness post-ACLR will result in lower baseline fitness levels as an athlete enters mid- and late-stage rehabilitation. Appropriately planned safe fitness preservation/re-conditioning in the early stage can be a benefit to the professional player with sufficient time, also offering psychological benefits (e.g. ability to focus on other factors than the injury).

A key aspect of early-stage fitness preservation/reconditioning is acknowledging that this is not the main priority and it should not compromise early joint/functional recovery. Key elements of early-stage re-conditioning entail minimising CV fitness deficits, preventing loss of adjacent joint and contralateral limb muscle mass/strength using contralateral strength training, which may also support resolution of the respective injured limb’s muscle group through the cross-education effect [212–215], and preventing increases in body fat. There are a wide variety of methods, including nutritional control, non-weight-bearing CV conditioning and adjacent joint, contralateral limb and upper body strengthening, which should be appropriately programmed (see ESM). A key consideration is selecting appropriate training modalities and exercise stimuli for the energy system (aerobic, glycolytic, alactic) maintenance/development, both locally at the muscle level (e.g. muscle-specific adaptations) and centrally (e.g. cardiopulmonary adaptations).

4 Recommendations for Activity Planning

We recommend incorporating a holistic bio-psycho-social approach, targeting six main areas during the early stage including: (i) pain and swelling; (ii) joint ROM; (iii) AMI and muscle strength; (iv) movement quality/neuromuscular control during activities of daily living; (v) psycho-social-cultural and environmental factors and (vi) fitness preservation during the early stage of rehabilitation post-ACLR. In addition, certain factors should be considered when rehabilitating patients with different graft types [68], as well as concomitant injuries such as meniscal injury, chondral defects/

injury (e.g. bone bruise) or multi-ligament injuries [68]. The individual focus according to graft types becomes critical in the early stage. Additional details may be found in Table 3.

Programme planning is essential in rehabilitation and RTS post-ACLR. When designing the early-stage programme, it is important to focus on the goals/priorities and allocate training time according to these different training goals. The six key dimensions do not hold equal importance in the early stage (e.g. fitness reconditioning should never be prioritised over joint ROM recovery and pain resolution). Each dimension is also not exclusive of one another and ensuring a balanced but specific programme is important. For example, addressing pain and swelling is important to facilitate appropriate active joint ROM whilst satisfactory gait cannot occur without sufficient knee extension [39]. The exact work and allocated time on each training goal and in each environment (e.g. home, rehabilitation gym or hydrotherapy pool) depend on the individual, their goals and actual time/financial commitment. It is important to create a priority list for all patients and ensure that the most important objectives are achieved (e.g. pain resolution, ROM recovery, quadriceps activation and strength preservation, and sufficient walking gait to leave the crutches and resume activities of daily living). We typically suggest focussing more on addressing pain, swelling and passive joint ROM restrictions, whilst addressing quadriceps AMI and preserving quadriceps muscle volume (with supplementary modalities such as blood flow restriction, neuromuscular electrical stimulation, cross-education) in the initial weeks, followed by a stronger focus on active ROM, gait/motor pattern recovery and quadriceps strengthening (as well as physical fitness preservation for professionals) in the subsequent weeks. Hydrotherapy typically commences when the patient is safe to enter the water, around 2–3 weeks post-ACLR. The main contraindications to its use in this stage are wound healing and the risk of infection; thus stitches must be removed, and surgery scars should be free from the signs of inflammation [79]. Hydrotherapy can be a valuable rehabilitation

Table 3 Typical concomitant procedures associated with ACL reconstruction and specific considerations

Concomitant procedure	Considerations
Lateral meniscus repair	Usually, repairable lateral meniscal tears involve the posterior root or are radial tears of the meniscal body. As such, weight bearing can be deleterious as it increases the hoop stress on the repair site. Delayed weight bearing should be considered, alongside specific recommendations on ROM recovery and caution with movements involving tibial rotation
Medial meniscus repair	Medial meniscus repair, despite entailing a higher failure rate, is less critical than lateral meniscus repair. Longitudinal tears, ramp repairs and even bucket handle repairs tolerate weight-bearing activities well in full extension, as they create compression at the repair site. Specific recommendations on ROM recovery should be implemented in the case of complex bucket handle repair to avoid meniscal displacement (although less critical than in lateral meniscus repair)
Antero-lateral procedure (e.g. lateral tenodesis; modified Lemaire; antero-lateral ligament reconstruction)	It is important to study the procedure well and consider the additional morbidity due to the extra-articular procedure. Some procedures could produce graft tension and pain with the knee in extension and prevent full knee extension ROM recovery
Medial collateral ligament surgery	Medial collateral ligament procedures, especially with wide approaches can be painful and create adhesions. Usually, the procedures are stable during ROM, meaning early mobilisation should be encouraged to avoid stiffness. Early weight bearing is not recommended as it could produce valgus overload on the repair/reconstruction (the medial collateral ligament is the main restraint in the knee to valgus loading)
Posterior lateral corner surgery	Specific recommendations regarding ROM recovery should be prescribed. Early weight bearing is not recommended as it could produce varus overload on the repair\ reconstruction. Avoid posterior tibial translation and external rotation during passive manoeuvres
Chondral or osteochondral procedure	It is important to prescribe specific recommendations in regard to ROM recovery, especially for regenerative techniques (e.g. ACI and MACI). The regenerative procedures dictate the recovery plan, with amendments to the typical ACL rehabilitation journey. It is important to consider the position of the lesion (e.g. tibio-femoral or patello-femoral, medial or lateral) and think biomechanically considering the specific loading of the site during rehabilitation tasks. It is critical to manage the joint loading well in these patients, with more caution and planned progressive loading. However, the most performed cartilage procedures in the setting of ACL reconstructions involve microfractures on the medial or lateral femoral condyle and in these cases only delayed weight bearing is required as a treatment consideration

ACI autologous chondrocyte implantation, *ACL* anterior cruciate ligament, *MACI* matrix-induced chondrocyte implantation, *ROM* range of motion

Table 4 Recommended criteria for progression from the early to mid-stage of the anterior cruciate ligament rehabilitation programme. Each outcome measure, the specific test and goal as well as the justification for this criterion are presented

Outcome measure	Test	Goal	Reason for meeting criteria
Pain	Numeric rating scale of pain	0–2 (knee specific) Tolerance to higher pain (0–4) in a non-specific area may be acceptable (e.g. because to scar tissue)	Pain along with swelling has a profound effect on joint proprioception [51, 52] as well as resulting in neuromuscular inhibition via the AMI process and resultant muscle atrophy and weakness [249–252]
Swelling	Stroke test [69] Zero: no wave produced on downstroke Trace: small wave on medial side with downstroke 1 +: large bulge on medial side with downstroke 2 +: swelling spontaneously returns to medial side after upstroke 3 +: so much fluid that it is not possible to move the swelling out of the medial aspect of the knee (see ESM)	Zero to trace swelling	Changes in knee joint swelling are frequently associated with irritation of intra-articular structures and articular disorders in clinically active knees [55]. Swelling can result in AMI, cause pain and prevent an optimal range of motion. It is also typically a sign of joint overload and a joint reaction to loading. If the knee is swollen, it will not respond to higher loading and will also prevent optimal recruitment of the knee extensor muscles, limiting the ability to progress resistance training
Passive knee extension	Prone hang test [253] Subjects lie prone on a treatment bed with the lower legs off the end allowing full passive knee extension. The heel height difference is measured (approximately 1 cm = 1°) [see ESM]	Straight knee (0°) with a view to achieving full knee extension (vs other side) by the end of the mid-stage [29]	Restoring joint range of motion is a vital aspect of the rehabilitation process. Even small losses of knee extension (3–5%) appear to adversely affect subjective and objective outcome markers later in the rehabilitation phase [71]
Passive knee flexion	Supine or prone with long arm goniometer [254] (see ESM)	At least > 120° of knee flexion [72]	Restoration of joint mobility is critical for the recovery of normal or optimal gait biomechanics and proprioception. Normal or optimal gait biomechanics cannot occur without normal or optimal accessory (spin, glide) and physiological (extension, flexion) joint motion [39]
Quadriceps recruitment	Full quadriceps activation [72] (see ESM)	Ability to sufficiently recruit the quadriceps (no lag on single straight leg raises through 10 repetitions) [72]	Quadriceps inhibition can prevent recovery of quadriceps muscle strength and the safe and expedient progression of rehabilitation [94, 255]. Persistent quadriceps lag on a single leg raise has been shown to indicate an inability to actively extend the knee fully. If this is not achieved by week 5 post-ACLR, this would be considered a predisposing factor for significant quadriceps weakness at 6-months post-ACLR [256]

Table 4 (continued)

Outcome measure	Test	Goal	Reason for meeting criteria
Walking gait	Visual assessment of walking gait, ideally on treadmill (see ESM)	Sufficiently normalised gait without aid [72]	Abnormal gait patterns have been associated with joint weakness [257], low patient satisfaction with outcome after surgery [258], decreased functional performance [259] and post-operative complications including knee osteoarthritis [260]. Abnormal gait patterns often become further exacerbated as the athlete returns to running [261]. Thus, re-establishing normal gait early, as well as safely, after ACLR is a key priority
Target criteria ('nice to haves' but will not stop transition to mid-stage rehabilitation)			
Movement quality (foundation task)	Bilateral squat to 90° [262] (see ESM)	Ability to squat to 90° with appropriate kinematic alignment (no major weight shift) and sufficient loading symmetry between limbs (< 20% asymmetry between limbs)	The bilateral squat is a foundation exercise that is important to achieve prior to progressing to a loaded squat work in the mid-stage of rehabilitation for the purposes of strengthening as well as subsequent commencement of bilateral landing, jumping and plyometric tasks. Some patients after ACLR failed to symmetrically load their legs during squatting up to 12 months post-operatively and this was related to poor functional outcomes [175]. Asymmetries in squat limb loading at 1 month were found to be an independent predictor of limb asymmetries during a vertical jump landing at the time of return-to-sport [32]
Knee extensor strength	Isometric strength testing Maximal voluntary isometric contractions of the knee extensors at 60/90°. Four repetitions of 3–5 s with 1 min's rest between efforts (see ESM)	Limited research, but we suggest LSI > 60%	Knee extensor deficits range from 40 to 60% at around 4–6 weeks post-ACLR [89]. The greater the extent of knee extensor strength at the end of the early stage, the harder it will be to recover strength during the mid-stage of rehabilitation. Failure to recover knee extensor strength is common post-ACLR and linked to worse outcomes. Thus, overcoming quadriceps AMI and preserving quadriceps function limiting the extent of knee extensor strength through effective rehabilitation in the early stage is important. Setting criteria for knee extensor strength makes the objective tangible. Although there is limited evidence, an LSI of > 60% is recommended here

Table 4 (continued)

Outcome measure	Test	Goal	Reason for meeting criteria
Knee flexor strength	Isometric strength testing Maximal voluntary isometric contractions of the knee flexors at 60/90° (matching the angle chosen for knee extensors). Four repetitions of 3–5 s with 1 min's rest between efforts (see ESM)	Limited research but we suggest LSI > 60%	Large deficits in knee flexor strength are apparent early post-ACLR (40–50% at 4 weeks, [89]). Whilst hamstring strength would not be a significant barrier to progression, as with the knee extensors, failure to overcome hamstring muscle inhibition post-ACLR with a hamstring graft can be problematic

ACLR anterior cruciate ligament reconstruction, *AMI* arthrogenic muscle inhibition, *LSI* limb symmetry index

tool for rehabilitation post-ACLR but should be seen as a *supplementary service* to in-clinic/gym (and home) based rehabilitation.

There is likely no perfect micro-cycle planning system for early-stage ACL rehabilitation. The specific week's activity (between-session) and within-session design (e.g. planning the ordering of treatment and rehabilitation activity) will depend on the patient; whether they can attend the clinic regularly, how far from the clinic they live and how much supervised rehabilitation they can have (based on finances and/or insurance and life factors). Across the author team, different approaches to micro-cycle planning are evident. A key theme across the group's philosophy is the need for daily work, early commencement of rehabilitation post-ACLR, and regular communication between the patient and clinical team (surgeon, sports medicine physician and/or sports physiotherapist). Professionals will typically embark on more demanding, often full-time programmes (e.g. double, or multiple short sessions throughout each day) addressing all key dimensions of early-stage rehabilitation. Without the same financial support and resources as professional athletes, recreational athletes will generally undertake less frequent and simpler programmes (e.g. focused on the one or two key priorities for that specific week). Recreational athletes typically present to a rehabilitation clinic 1–2 weeks post-ACLR and usually attend regularly (generally 1–3 × per week) during this early-stage to monitor and progress their early rehabilitation exercises, as well perform home-based exercises to support. Education is essential for both recreational and professional athletes. Providing education and autonomy can aid in better self-management in the face of less supervised rehabilitation sessions, particularly for recreational athletes/the general population.

As well as on-going daily and weekly monitoring, it is important to have specific criteria or 'targets' to achieve by the end of the early-stage. As with our suggestions for other stages [28, 29] when establishing criterion-based rehabilitation, it is important to understand the 'must haves' versus the 'nice to haves'. Table 4 presents our recommended criteria, based on both evidence from the literature, as well as substantial clinical experience of the author team.

5 Conclusions

Early-stage rehabilitation is the vital foundation on which successful rehabilitation post-ACLR can be based. We highlight six main dimensions during the early stage: (1) pain and swelling; (2) knee joint ROM; (3) AMI and muscle strength; (4) movement quality/neuromuscular control during activities of daily living; (5) psycho-social-cultural and environmental factors; and (6) physical fitness preservation.

The six *do not share equal importance* and the extent of time commitment devoted to each will depend on the individual patient. We recommend planning the rehabilitation activity, considering the bio-psycho-social model, and incorporating regular monitoring and specific screening for a criterion-based assessment.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s40279-023-01934-w.

Declarations

Funding No sources of funding were used to assist in the preparation of this article.

Conflicts of Interest Matthew Buckthorpe, Alli Gokeler, Lee Herrington, Mick Hughes, Alberto Grassi, Ross Wadey, Stephen Patterson, Alessandro Compagnin, Giovanni La Rosa and Francesco Della Villa have no conflicts of interest that are directly relevant to the content of this article.

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Availability of Data and Material Not applicable.

Code Availability Not applicable.

Authors' Contributions MB conceived the idea for the paper and wrote the first version of the manuscript. MB, MH, AC and GLR produced the supplementary video content. All authors have been involved in drafting the manuscript or revising it critically for important intellectual content. All authors read and approved the final version of the manuscript.

References

1. Ardern CL, Webster KE, Taylor NF, et al. Return to preinjury level of competitive sport after anterior cruciate ligament reconstruction surgery: two-thirds of patients have not returned by 12 months after surgery. Am J Sports Med. 2011;39:538–43.
2. Della Villa F, Hägglund M, Della Villa S, et al. High rate of second ACL injury following ACL reconstruction in male professional footballers: an updated longitudinal analysis from 118 players in the UEFA Elite Club Injury Study. Br J Sports Med. 2021;55:1350–7.
3. Lai CC, Ardern CL, Feller JA, Webster KE. Eighty-three per cent of elite athletes return to preinjury sport after anterior cruciate ligament reconstruction: a systematic review with meta-analysis of return to sport rates, graft rupture rates and performance outcomes. Br J Sports Med. 2018;52(2):128–38.
4. Waldén M, Hägglund M, Magnusson H, Ekstrand J. ACL injuries in men's professional football: a 15-year prospective study on time trends and return-to-play rates reveals only 65% of players still play at the top level 3 years after ACL rupture. Br J Sports Med. 2016;50(12):744–50.
5. Desai N, Björnsson H, Musahl V, et al. Anatomic single- versus double-bundle ACL reconstruction: a meta-analysis. Knee Surg Sports Traumatol Arthrosc. 2014;22(5):1009–23.
6. Salmon LJ, Heath E, Akrawi H, et al. 20-Year outcomes of anterior cruciate ligament reconstruction with hamstring tendon autograft: the catastrophic effect of age and posterior tibial slope. Am J Sports Med. 2018;46(3):531–43.
7. Ardern CL, Taylor NF, Feller JA, et al. Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. Br J Sports Med. 2014;48:1543–52.
8. Wiggins AJ, Granhi RK, Schneider DK, et al. Risk of secondary injury in younger athletes after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. Am J Sports Med. 2016;44(7):1861–76.
9. Grindem H, Snyder-Mackler L, Moksnes H, et al. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. Br J Sports Med. 2016;50:804–8.
10. Paterno MV, Rauh MJ, Schmitt LC, et al. Incidence of second ACL injuries 2 years after primary ACL reconstruction and return to sport. Am J Sports Med. 2014;42(7):1567–73.
11. Webster KE, Feller JA. Exploring the high reinjury rate in younger patients undergoing anterior cruciate ligament reconstruction. Am J Sports Med. 2016;44(11):2827–32.
12. Zaffagnini S, Grassi A, Marcheggiani Muccioli GM, et al. Return to sport after anterior cruciate ligament reconstruction in professional soccer players. Knee. 2014;21(3):731–5.
13. Arundale AJH, Silvers-Granelli HJ, Snyder-Mackler L. Career length and injury incidence after anterior cruciate ligament reconstruction in major league soccer players. Orthop J Sports Med. 2018;6(1):232. https://doi.org/10.1177/2325967117750825.
14. Barth KA, Lawton CD, Touhey DC, et al. The negative impact of anterior cruciate ligament reconstruction in professional male footballers. Knee. 2019;26:142–8.
15. Niederer D, Engeroff T, Wilke J, et al. Return to play, performance, and career duration after anterior cruciate ligament rupture: a case-control study in the five biggest football nations in Europe. Scand J Med Sci Sports. 2018;28:2226–33.
16. Lai CCH, Feller JA, Webster KE. Fifteen-year audit of anterior cruciate ligament reconstructions in the Australian Football League from 1999 to 2013: return to play and subsequent ACL injury. Am J Sports Med. 2018;46(14):3353–60.
17. Fältström A, Kvist J, Hägglund M. High risk of new knee injuries in female soccer players after primary anterior cruciate ligament reconstruction at 5- to 10-year follow-up. Am J Sports Med. 2021;49(13):3479–87.
18. Culvenor AG, Patterson BE, Guermazi A, et al. Accelerated return to sport after anterior cruciate ligament reconstruction and early knee osteoarthritis features at 1 year: an exploratory study. Phys Med Rehabil. 2018;10(4):349–56.
19. Patterson B, Culvenor AG, Barton CJ, et al. Poor functional performance 1 year after ACL reconstruction increases the risk of early osteoarthritis progression. Br J Sports Med. 2020;54:546–55.
20. Andrade R, Pereira R, van Cingel R, Staal JB, Espregueira-Mendes J. How should clinicians rehabilitate patients after ACL reconstruction? A systematic review of clinical practice guidelines (CPGs) with a focus on quality appraisal (AGREE II). Br J Sports Med. 2020;54(9):512–9.
21. Hanson DW, Finch CF, Allegrante JP, et al. Closing the gap between injury prevention research and community safety promotion practice: revisiting the public health model. Public Health Rep. 2012;127(2):147–55.

22. Fausett WA, Reid DA, Larmer PJ. Current perspectives of New Zealand physiotherapists on rehabilitation and return to sport following anterior cruciate ligament reconstruction: a survey. Phys Ther Sport. 2022;53:166–72.
23. Finch CF. A new framework for research leading to sports injury prevention. J Sci Med Sport. 2006;9:3–9.
24. Timpka T, Ekstrand J, Svanström L. From sports injury prevention to safety promotion in sports. Sports Med. 2006;36:733–45.
25. Verhagen E. If athletes will not adopt preventive measures, effective measures must adopt athletes. Curr Sports Med Rep. 2012;11:7–8.
26. Verhagen E, Voogt N, Bruinsma A, Finch CF. A knowledge transfer scheme to bridge the gap between science and practice: an integration of existing research frameworks into a tool for practice. Br J Sports Med. 2014;48:698–701.
27. Bien DP, Dubuque TJ. Considerations for late stage ACL rehabilitation and return to sport to limit re-injury risk and maximize athletic performance. Int J Sports Phys Ther. 2015;10(2):256–71.
28. Buckthorpe M. Optimising the late-stage rehabilitation and return-to-sport training and testing process after ACL reconstruction. Sports Med. 2019;49(7):1043–58.
29. Buckthorpe M, Della VF. Optimising the "mid-stage" training and testing process after ACL reconstruction. Sports Med. 2020;50(4):657–78.
30. Dingenen B, Gokeler A. Optimization of the return-to-sport paradigm after anterior cruciate ligament reconstruction: a critical step back to move forward. Sports Med. 2017;47(8):1487–500.
31. Hannon JP, Wang-Price S, Goto S, et al. Twelve-week quadriceps strength as a predictor of quadriceps strength at time of return to sport testing following bone-patellar tendon-bone autograft anterior cruciate ligament reconstruction. Int J Sports Phys Ther. 2021;16(3):681–8.
32. Labanca L, Laudani L, Menotti F, et al. Asymmetrical lower extremity loading early after anterior cruciate ligament reconstruction is a significant predictor of asymmetrical loading at the time of return to sport. Am J Phys Med Rehabil. 2016;95(4):248–55.
33. Noll S, Garrison JC, Bothwell J, Conway JE. Knee Extension range of motion at 4 weeks is related to knee extension loss at 12 weeks after anterior cruciate ligament reconstruction. Orthop J Sports Med. 2015;3(5):2325967115583632. https://doi.org/10.1177/2325967115583632.
34. Sigward SM, Lin P, Pratt K. Knee loading asymmetries during gait and running in early rehabilitation following anterior cruciate ligament reconstruction: a longitudinal study. Clin Biomech. 2016;32:249–54.
35. de Jong SN, van Caspel DR, van Haeff MJ, et al. Functional assessment and muscle strength before and after reconstruction of chronic anterior cruciate ligament lesions. Arthroscopy. 2007;23:21–8.
36. Eitzen I, Holm I, Risberg MA. Preoperative quadriceps strength is a significant predictor of knee function two years after anterior cruciate ligament reconstruction. Br J Sports Med. 2009;43(5):371–6.
37. Eitzen I, Moksnes H, Snyder-Mackler L, Risberg MA. A progressive 5-week exercise therapy program leads to significant improvement in knee function early after anterior cruciate ligament injury. J Orthop Sports Phys Ther. 2010;40(11):705–21.
38. Shelbourne KD, Wilckens JH, Mollabashy A, DeCarlo M. Arthrofibrosis in acute anterior cruciate ligament reconstruction: the effect of timing of reconstruction and rehabilitation. Am J Sports Med. 1991;19(4):332–6.
39. Clark NC. The role of physiotherapy in rehabilitation of soft tissue injuries of the knee. Orthop Trauma. 2015;29(1):48–56.
40. Månsson O, Kartus J, Sernert N. Pre-operative factors predicting good outcome in terms of health-related quality of life after ACL reconstruction. Scand J Med Sci Sports. 2013;23(1):15–22.
41. McHugh MP, Tyler TF, Gleim GW, Nicholas SJ. Preoperative indicators of motion loss and weakness following anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 1998;27:407–11.
42. Lepley LK, Palmieri-Smith RM. Pre-operative quadriceps activation is related to post-operative activation, not strength, in patient's post-ACL reconstruction. Knee Surg Sports Traumatol Arthrosc. 2016;24:236–46.
43. de Valk EJ, Moen MH, Winters M, et al. Preoperative patient and injury factors of successful rehabilitation after anterior cruciate ligament reconstruction with single-bundle techniques. Arthrosc. 2013;29:1879–95.
44. Failla MJ, Logerstedt DS, Grindem H, et al. Does extended preoperative rehabilitation influence outcomes 2 years after ACL reconstruction? A comparative effectiveness study between the MOON and Delaware-Oslo ACL cohorts. Am J Sports Med. 2016;44(10):2608–14.
45. Grindem H, Granen LP, Risberg MA, et al. How does combined preoperative and postoperative rehabilitation programme influence the outcome of ACL reconstruction two years after surgery? A comparison between patients in the Delaware-Oslo ACL Cohort and the Norwegian National Knee Ligament Registry. Br J Sports Med. 2015;49:385–9.
46. Shaarani SR, O'Hare C, Quinn A, et al. Effect of prehabilitation on the outcome of anterior cruciate ligament reconstruction. Am J Sports Med. 2013;41:2117–27.
47. Eastlack ME, Axe MJ, Snyder-Mackler L. Laxity, instability, and functional outcome after ACL injury: copers versus noncopers. Med Sci Sports Exerc. 1999;31(2):210–5.
48. Thoma LM, Grindem H, Logerstedt D, et al. Coper classification early after anterior cruciate ligament rupture changes with progressive neuromuscular and strength training and is associated with 2-year success: The Delaware-Oslo ACL Cohort Study. Am J Sports Med. 2019;47(4):807–14.
49. Buckthorpe M, Frizziero A, Roi GS. Update on functional recovery process for the injured athlete: return to sport continuum redefined. Br J Sports Med. 2019;53(5):265–7.
50. Lattermann C, Jacobs CA, Proffitt Bunnell M, et al. A multicenter study of early anti-inflammatory treatment in patients with acute anterior cruciate Ligament tear. Am J Sports Med. 2017;45(2):325–33.
51. Baxendale RH, Ferrell WR. Disturbances of proprioception at the human knee resulting from acute joint distension. J Physiol. 1987;392:60.
52. Matre D, Arendt-Neilsen L, Knardahl S. Effects of localization and intensity of experimental muscle pain on ankle joint proprioception. Eur J Pain. 2002;6(4):245–60.
53. Lepley AS, Lepley LK. Mechanisms of arthrogenic muscle inhibition. J Sport Rehabil. 2021;31(6):707–16.
54. Norte G, Rush J, Sherman D. Arthrogenic muscle inhibition: best evidence, mechanisms, and theory for treating the unseen in clinical rehabilitation. J Sport Rehabil. 2021;31(6):717–35.
55. Hurley M. The effects of joint damage on muscle function, proprioception and rehabilitation. Man Ther. 1997;2:11–7.
56. Bleakley C, McDonough S, MacAuley D. The use of ice in the treatment of acute soft-tissue injury: a systematic review of randomized controlled trials. Am J Sports Med. 2004;32(1):251–61.
57. Kotsifaki R, Korakakis V, King E, et al. Aspetar clinical practice guideline on rehabilitation after anterior cruciate ligament reconstruction. Br J Sports Med. 2023;57:500–14.
58. Bleakley CM, Glasgow P, MacAuley DC. PRICE needs updating, should we call the POLICE? Br J Sports Med. 2012;46:220–1.

59. Raynor MC, Pietrobon R, Guller U, Higgins LD. Cryotherapy after ACL reconstruction: a meta-analysis. J Knee Surg. 2005;18(2):123–9. https://doi.org/10.1055/s-0030-1248169.
60. Bahl V, Goyal A, Jain V, Joshi D, Chaudhary D. Effect of haemarthrosis on the rehabilitation of anterior cruciate ligament reconstruction: single bundle versus double bundle. J Orthop Surg Res. 2013;8:5. https://doi.org/10.1186/1749-799X-8-5.
61. Calvo R, Figueroa D, Anastasiadis Z, et al. Septic arthritis in ACL reconstruction surgery with hamstring autografts: eleven years of experience. Knee. 2014;21(3):717–20.
62. Sonnery-Cottet B, Archbold P, Zayni R, et al. Prevalence of septic arthritis after anterior cruciate ligament reconstruction among professional athletes. Am J Sports Med. 2011;39(11):2371–6.
63. Keller RA, Moutzouros V, Dines JS, Bush-Joseph CA, Limpisvasti O. Deep Venous Thrombosis prophylaxis in anterior cruciate ligament reconstructive surgery: what is the current state of practice? Sports Health. 2018;10(2):156–9.
64. Ekdahl V, Stålman A, Forssblad M, et al. There is no general use of thromboprophylaxis and prolonged antibiotic prophylaxis in anterior cruciate ligament reconstruction: a nation-wide survey of ACL surgeons in Sweden. Knee Surg Sports Traumatol Arthrosc. 2020;28(8):2535–42.
65. Esculier JF, Bouyer LJ, Dubois B, et al. Is combining gait retraining or an exercise programme with education better than education alone in treating runners with patellofemoral pain? A randomised clinical trial. Br J Sports Med. 2018;52(10):659–66.
66. Rio E, van Ark M, Docking S, et al. Isometric contractions are more analgesic than isotonic contractions for patellar tendon pain: an in-season randomized clinical Ttial. Clin J Sport Med. 2017;27(3):253–9.
67. Silbernagel KG, Crossley KM. A proposed return-to-sport program for patients with midportion Achilles tendinopathy: rationale and implementation. J Orthop Sports Phys Ther. 2015;45(11):876–86.
68. Silbernagel KG, Thomeé R, Eriksson BI, Karlsson J. Continued sports activity, using a pain-monitoring model, during rehabilitation in patients with Achilles tendinopathy: a randomized controlled study. Am J Sports Med. 2007;35(6):897–906.
69. Sturgill LP, Synder-Mackler L, Manal TJ, Axe MJ. Interrater reliability of a clinical scale to assess knee joint effusion. J Orthop Sports Phys Ther. 2009;39(12):845–9.
70. Jakobsen T, Christensen M, Christensen S, et al. Reliability of knee joint range of motion and circumference measurements after total knee arthroplasty: does tester experience matter. Physiother Res Int. 2010;15:126–34.
71. Adams D, Logerstedt DS, Hunter-Giordano A, et al. Current concepts for anterior cruciate ligament reconstruction: a criterion based rehabilitation progression. J Orthop Sports Phys Ther. 2012;42(7):601–14.
72. Herrington L, Myer G, Horsley I. Task based rehabilitation protocol for elite athletes following anterior cruciate ligament reconstruction: a clinical commentary. Phys Ther Sport. 2013;14(4):188–98.
73. Harner CD, Irrgang JJ, Paul J, Dearwater S, Fu FH. Loss of motion after anterior cruciate ligament reconstruction. Am J Sports Med. 1992;20(5):499–506.
74. Shelbourne KD, Gray T. Minimum 10-year results after anterior cruciate ligament reconstruction: how the loss of normal knee motion compounds other factors related to the development of osteoarthritis after surgery. Am J Sports Med. 2009;37(3):471–80.
75. Marques FDS, Barbosa PHB, Alves PR, et al. Anterior knee pain after anterior cruciate ligament reconstruction. Orthop J Sports Med. 2020;8(10):2325967120961082. https://doi.org/10.1177/2325967120961082.
76. Pinto FG, Thaunat M, Daggett M, et al. Hamstring contracture after ACL reconstruction is associated with an increased risk of cyclops syndrome. Orthop J Sports Med. 2017;5(1):2325967116684121. https://doi.org/10.1177/2325967116684121.
77. Isberg J, Faxén E, Brandsson S, et al. Early active extension after anterior cruciate ligament reconstruction does not result in increased laxity of the knee. Knee Surg Sports Traumatol Arthrosc. 2006;14(11):1108–15.
78. Shelbourne KD, Trumper RV. Preventing anterior knee pain after anterior cruciate ligament reconstruction. Am J Sports Med. 1997;25:41–7.
79. Buckthorpe M, Pirotti E, Della VF. Benefits and use of aquatic therapy during rehabilitation after ACL reconstruction-a clinical commentary. Int J Sports Phys Ther. 2019;14(6):978–93.
80. Buckthorpe M, La Rosa G, Villa FD. Restoring knee extensor strength after anterior cruciate ligament reconstruction: a clinical commentary. Int J Sports Phys Ther. 2019;14(1):159–72.
81. Bodkin S, Goetschius J, Hertel J, Hart J. Relationships of muscle function and subjective knee function in patients after ACL reconstruction. Orthop J Sports Med. 2017;5:2325967117719041. https://doi.org/10.1177/232596711771904.
82. Zwolski C, Schmitt LC, Quatman-Yates C, et al. The influence of quadriceps strength asymmetry on patient-reported function at time of return to sport after anterior cruciate ligament reconstruction. Am J Sports Med. 2015;43:2242–9.
83. Snyder-Mackler L, Delitto A, Bailey SL, et al. Strength of the quadriceps femoris muscle and functional recovery after reconstruction of the anterior cruciate ligament: a prospective, randomized clinical trial of electrical stimulation. J Bone Joint Surg Am. 1995;77:1166–73.
84. Lewek M, Rudolph K, Axe M, Snyder-Mackler L. The effect of insufficient quadriceps strength on gait after anterior cruciate ligament reconstruction. Clin Biomech (Bristol, Avon). 2002;17(1):56–63.
85. Palmieri-Smith RM, Lepley LK. Quadriceps strength asymmetry following ACL reconstruction alters knee joint biomechanics and functional performance at time of return to activity. Am J Sports Med. 2015;43:1662–9.
86. Felson DT, Niu J, McClennan C, et al. Knee buckling: prevalence, risk factors, and associated limitations in function. Ann Intern Med. 2007;147:534–40.
87. Amin S, Baker K, Niu J, et al. Quadriceps strength and the risk of cartilage loss and symptom progression in knee osteoarthritis. Arthritis Rheum. 2009;60:189–98.
88. Drechsler WI, Cramp MC, Scott OM. Changes in muscle strength and EMG median frequency after anterior cruciate ligament reconstruction. Eur J Appl Physiol. 2006;98(6):613–23.
89. Harput G, Kilinc HE, Ozer HE, et al. Quadriceps and hamstring strength recovery during early neuromuscular rehabilitation after ACL hamstring-tendon autograft reconstruction. J Sport Rehabil. 2015;24(4):398–404.
90. Pua YH, Mentiplay BF, Clark RA, Ho JY. Associations among quadriceps strength and rate of torque development 6 weeks post anterior cruciate ligament reconstruction and future hop and vertical jump performance: a prospective cohort study. J Orthop Sports Phys Ther. 2017;47(11):845–52.
91. Kyritsis P, Bahr R, Landreau P, Miladi R, Witvrouw E. Likelihood of ACL graft rupture: not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture. Br J Sports Med. 2016;50:946–51.
92. Johnston PT, Feller JA, McClelland JA, Webster KE. Strength deficits and flexion range of motion following primary anterior cruciate ligament reconstruction differ between quadriceps and hamstring autografts. J ISAKOS. 2021;6(2):88–93.

93. Lepley LK. Deficits in quadriceps strength and patient-oriented outcomes at return to activity after ACL reconstruction: a review of the current literature. Sports Health. 2015;7(3):231–8.
94. Hopkins JT, Ingersoll CD, Edwards JE, et al. Cryotherapy and TENS decrease arthrogenic muscle inhibition of the vastus medialis following knee joint effusion. J Athl Train. 2002;37:25–32.
95. Williams GN, Snyder-Mackler L, Barrance PJ, et al. Quadriceps femoris muscle morphology and function after ACL injury: a differential response in copers versus non-copers. J Biomech. 2005;38:685–93.
96. Welling W, Benjaminse A, Lemmink K, Dingenen B, Gokeler A. Progressive strength training restores quadriceps and hamstring muscle strength within 7 months after ACL reconstruction in amateur male soccer players. Phys Ther Sport. 2019;40:10–8.
97. Hopkins JT, Ingersoll CD. Arthrogenic muscle inhibition: a limiting factor in joint rehabilitation. J Sport Rehabil. 2000;9(2):135–59.
98. Hurley MV, Jones DW, Wilson D, et al. Rehabilitation of quadriceps inhibition due to isolated rupture of the anterior cruciate ligament. J Orthop Rheumatol. 1992;5:145–55.
99. Snyder-Mackler L, Delitto A, Stralka S, et al. Use of electrical stimulation to enhance recovery of quadriceps femoris muscle force production in patients following anterior cruciate ligament reconstruction. Phys Ther. 1994;74:901–7.
100. Urbach D, Nebelung W, Weiler HT, et al. Bilateral deficit of voluntary quadriceps muscle activation after unilateral ACL tear. Med Sci Sports Exerc. 1999;31:1691–6.
101. Urbach D, Nebelung W, Becker R, et al. Effects of reconstruction of the anterior cruciate ligament on voluntary activation of quadriceps femoris a prospective twitch interpolation study. J Bone Joint Surg Br. 2001;83:1104–10.
102. Lorenz D, Morrison S. Current concepts in periodization of strength and conditioning for the sports physiotherapist. Int J Sports Phys Ther. 2015;10:734–47.
103. Lorenz DS, Reiman MP, Walker JC. Periodization: current review and suggested implementation for athletic rehabilitation. Sports Health. 2010;2:509–18.
104. Escamilla RF, Macleod TD, Wilk KE, et al. Anterior cruciate ligament strain and tensile forces for weight-bearing and non-weight-bearing exercises: a guide to exercise selection. J Orthop Sports Phys Ther. 2012;42(3):208–20.
105. Grodski M, Marks R. Exercises following anterior cruciate ligament reconstructive surgery: biomechanical considerations and efficacy of current approaches. Res Sports Med. 2008;16(2):75–96.
106. Woo SL, Hollis JM, Adams DJ, et al. Tensile properties of the human femur-anterior cruciate ligament-tibia complex: the effects of specimen age and orientation. Am J Sports Med. 1991;19:217–25.
107. Chandrashekar N, Mansouri H, Slauterbeck J, Hashemi J. Sex-based differences in the tensile properties of the human anterior cruciate ligament. J Biomech. 2006;39(16):2943–50.
108. Nagelli CV, Hewett TE. Should return to sport be delayed until 2 years after anterior cruciate ligament reconstruction? Biological and functional considerations. Sports Med. 2017;47(2):221–32.
109. Vogl TJ, Schmitt J, Lubrich J, et al. Reconstructed anterior cruciate ligaments using patellar tendon ligament grafts: diagnostic value of contrast-enhanced MRI in a 2-year follow-up regimen. Eur Radiol. 2001;11(8):1450–6.
110. Zaffagnini S, De Pasquale V, Marchesini Reggiani L, et al. Neoligamentization process of BPTB used for ACL graft: histological evaluation from 6 months to 10 years. Knee. 2007;14(2):87–93.
111. Amiel D, Kleiner JB, Roux RD, Harwood FL, Akeson WH. The phenomenon of "ligamentization": anterior cruciate ligament reconstruction with autogenous patellar tendon. J Orthop Res. 1986;4:162–72.
112. Claes S, Verdonk P, Forsyth R, Bellemans J. The, "ligamentization" process in anterior cruciate ligament reconstruction: what happens to the human graft? A systematic review of the literature. Am J Sports Med. 2011;39:2476–83.
113. Morrissey MC, Hudson ZL, Drechsler WI, et al. Effects of open versus closed kinetic chain training on knee laxity in the early period after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2000;8:343–8.
114. Culvenor AG, Collins NJ, Vicenzino B, et al. Predictors and effects of patellofemoral pain following hamstring-tendon ACL reconstruction. J Sci Med Sport. 2016;19:518–23.
115. Luque-Seron JA, Medina-Porqueres I. Anterior cruciate ligament strain in vivo: a systematic review. Sports Health. 2016;8:451–5.
116. Salem GJ, Salinas R, Harding FV. Bilateral kinematic and kinetic analysis of the squat exercise after anterior cruciate ligament reconstruction. Arch Phys Med Rehabil. 2003;84:1211–6.
117. Sigward SM, Chan MM, Lin PE, et al. Compensatory strategies that reduce knee extensor demand during a bilateral squat change from 3 to 5 months following anterior cruciate ligament reconstruction. J Orthop Sport Phys Ther. 2018;48(9):713–8.
118. Noehren B, Snyder-Mackler L. Who's afraid of the Big Bad Wolf? Open-chain exercises after anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 2020;50(9):473–5.
119. Perriman A, Leahy E, Semciw AI. The effect of open- versus closed-kinetic-chain exercises on anterior tibial laxity, strength, and function following anterior cruciate ligament reconstruction: a systematic review and meta-analysis. J Orthop Sports Phys Ther. 2018;48:552–66.
120. Englander ZA, Garrett WE, Spritzer CE, DeFrate LE. In vivo attachment site to attachment site length and strain of the ACL and its bundles during the full gait cycle measured by MRI and high-speed biplanar radiography. J Biomech. 2020;98: 109443. https://doi.org/10.1016/j.jbiomech.2019.109443.
121. Wilk KE, Escamilla RF, Fleisig GS, et al. A comparison of tibiofemoral joint forces and electromyographic activity during open and closed kinetic chain exercises. Am J Sports Med. 1996;24(4):518–27.
122. Steinkamp LA, Dillingham MF, Markel MD, et al. Biomechanical considerations in patellofemoral joint rehabilitation. Am J Sports Med. 1993;21:438–44.
123. Fleming BC, Oksendahl H, Beynnon BD. Open- or closed-kinetic chain exercises after anterior cruciate ligament reconstruction? Exerc Sport Sci Rev. 2005;33:134–40.
124. Culvenor AG, Øiestad BE, Holm I, et al. Anterior knee pain following anterior cruciate ligament reconstruction does not increase the risk of patellofemoral osteoarthritis at 15- and 20-year follow-ups. Osteoarthr Cartil. 2017;25:30–3.
125. Escamilla RF, Fleisig GS, Zheng N, et al. Biomechanics of the knee during closed kinetic chain and open kinetic chain exercises. Med Sci Sports Exerc. 1998;30:556–9.
126. Anderson T, Kearney JT. Effects of three resistance training programs on muscular strength and absolute and relative endurance. Res Q Exerc Sport. 1982;53:1–7.
127. Campos GE, Luecke TJ, Wendeln HK, et al. Muscular adaptations in response to three different resistance-training regimens: specificity of repetition maximum training zones. Eur J Appl Physiol. 2002;88(1–2):50–60.
128. Harber MP, Fry AC, Rubin MR, et al. Skeletal muscle and hormonal adaptations to circuit weight training in untrained men. Scand J Med Sci Sports. 2004;14:176–85.
129. Burd NA, West DW, Staples AW, et al. Low-load high volume resistance exercise stimulates muscle protein synthesis more than low volume resistance exercise in young men. PLoS ONE.

2010;5(8): e12033. https://doi.org/10.1371/journal.pone.0012033.

130. Rio E, Kidgell D, Purdam C, et al. Isometric exercise induces analgesia and reduces inhibition in patellar tendinopathy. Br J Sports Med. 2015;49(19):1277–83.
131. Rio E, Kidgell D, Moseley GL, et al. Tendon neuroplastic training: changing the way we think about tendon rehabilitation: a narrative review. Br J Sports Med. 2016;50(4):209–15.
132. Toonstra J, Mattacola CG. Test-retest reliability and validity of isometric knee-flexion and -extension measurement using 3 methods of assessing muscle strength. J Sport Rehabil. 2013. https://doi.org/10.1123/jsr.2013.TR7.
133. Kannus P, Beynnon B. Peak torque occurrence in the range of motion during isokinetic extension and flexion of the knee. Int J Sports Med. 1993;14(8):422–6.
134. Ardern CL, Webster KE, Taylor NF, et al. Hamstring strength recovery after hamstring tendon harvest for anterior cruciate ligament reconstruction: a comparison between graft types. Arthroscopy. 2010;26(4):462–9.
135. Nomura Y, Kuramochi R, Kukubayashi T. Evaluation of hamstring muscle strength and morphology after anterior cruciate ligament reconstruction. Scand J Med Sci Sports. 2015;25(3):301–7.
136. Tengman E, Brax Olofsson L, Stensdotter AK, et al. Anterior cruciate ligament injury after more than 20 years. II. Concentric and eccentric knee muscle strength. Scand J Med Sci Sports. 2014;24(6):e501–9.
137. Timmins RG, Bourne MN, Shield AJ, et al. Biceps femoris architecture and strength in athletes with a previous anterior cruciate ligament reconstruction. Med Sci Sports Exerc. 2016;48:337–45.
138. Vairo GL. Knee flexor strength and endurance profiles after ipsilateral hamstring tendons anterior cruciate ligament reconstruction. Arch Phys Med Rehabil. 2014;95(3):552–61.
139. Cristiani R, Mikkelsen C, Forssblad M, et al. Only one patient out of five achieves symmetrical knee function 6 months after primary anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2019;27(11):3461–70.
140. Kim HJ, Lee JH, Ahn SE, et al. Influence of anterior cruciate ligament tear on thigh muscle strength and hamstring-to-quadriceps ratio: a meta-analysis. PLoS ONE. 2016;11(1): e0146234. https://doi.org/10.1371/journal.pone.0146234.
141. Bourne MN, Bruder AM, Mentiplay BF. Eccentric knee flexor weakness in elite female footballers 1–10 years following anterior cruciate ligament reconstruction. Phys Ther Sport. 2019;37:144–9.
142. Irie K, Tomatsu T. Atrophy of semitendinosus and gracilis and flexor mechanism function after hamstring tendon harvest for anterior cruciate ligament reconstruction. Orthopedics. 2002;25:491–5.
143. Snow BJ, Wilcox JJ, Burks RT, Greis PE. Evaluation of muscle size and fatty infiltration with MRI nine to eleven years following hamstring harvest for ACL reconstruction. J Bone Jt Surg Am. 2012;94:1274–82.
144. Williams GN, Synder-Mackler L, Barrance PJ, et al. Muscle and tendon morphology after reconstruction of the anterior cruciate ligament with autologous semitendinosus-gracilis graft. J Bone Jt Surg Am. 2004;86(9):1936–46.
145. Buckthorpe M, Danelon F, La Rosa G, et al. Recommendations for hamstring function recovery after ACL reconstruction. Sports Med. 2021;51(4):607–24.
146. Carofino B, Fulkerson J. Medial hamstring tendon regeneration following harvest for anterior cruciate ligament reconstruction: fact, myth and clinical application. Arthroscopy. 2005;21:1257–65.
147. Ristanis S, Tsepis E, Giotis D, et al. Electromechanical delay of the knee flexor muscles is impaired after harvesting hamstring tendons for anterior cruciate ligament reconstruction. Am J Sports Med. 2009;37(11):2179–86.
148. Dorn TW, Schache AG, Pandy MG. Muscular strategy shift in human running: dependence of running speed on hip and ankle muscle performance. J Exp Biol. 2012;215(11):1944–56. https://doi.org/10.1242/jeb.064527.
149. Fong CM, Blackburn JT, Norcross MF, McGrath M, Padua DA. Ankle-dorsiflexion range of motion and landing biomechanics. J Athl Train. 2011;46(1):5–10.
150. Schlumberger A. Strength of ankle muscles in high level athletes after knee surgery. 3rd International Conference on Strength Training; 13–17 November 2002; Budapest.
151. Hasegawa S, Kobayashi M, Arai R, et al. Effect of early implementation of electrical muscle stimulation to prevent muscle atrophy and weakness in patients after anterior cruciate ligament reconstruction. J Electromyogr Kinesiol. 2011;21(4):622–30.
152. Karanikas K, Arampatzis A, Bruggemann GP. Motor task and muscle strength followed different adaptation patterns after anterior cruciate ligament reconstruction. Eur J Phys Rehabil Med. 2009;45(1):37–45.
153. Thomas AC, Villwock M, Wojtys EM, Palmieri-Smith RM. Lower extremity muscle strength after anterior cruciate ligament injury and reconstruction. J Athl Train. 2013;48(5):610–20.
154. Petersen W, Taheri P, Forkel P, Zantop T. Return to play following ACL reconstruction: a systematic review about strength deficits. Arch Orthop Trauma Surg. 2014;134:1417–28.
155. Khayambashi K, Ghoddosi N, Straub RK, Powers CM. Hip muscle strength predicts non-contact anterior cruciate ligament injury in male and female athletes: a prospective study. Am J Sports Med. 2016;44(2):355–61.
156. Davis IS, Powers CM. Patellafemoral pain syndrome: proximal, distal and local factors, an international retreat. April 30–May 2, 2009, Fells Point, Baltimore, MD. J Orthop Sports Phys Ther. 2010;40(3):1–16.
157. Powers CM. The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. J Orthop Sports Phys Ther. 2010;40(2):42–51.
158. Buckthorpe M, Stride M, Della VF. Gluteus maximus dysfunction: its relevance to athletic performance and injury and how to treat it: a clinical commentary. Int J Sports Phys Ther. 2019;14(4):655–69.
159. Bullock-Saxton JE, Janda V, Bullock MI. The influence of ankle sprain injury on muscle activation during hip extension. Int J Sports Med. 1994;15:130–4.
160. Lafond D, Normand MC, Gosselin G. Rapport force. J Can Chiropract Assoc. 1998;42(2):90–100.
161. Vakos JP, Nitz AJ, Threlkeld AJ, et al. Electromyographic activity of selected trunk and hip muscles during a squat lift. Spine. 1994;19(6):687–95.
162. Prins MR, van der Wurff P. Females with patellofemoral pain syndrome have weak hip muscles: a systematic review. Aust J Physiother. 2009;55:9–15.
163. Collins NJ, Barton CJ, van Middelkoop M, et al. 2018 Consensus statement on exercise therapy and physical interventions (orthoses, taping and manual therapy) to treat patellofemoral pain: recommendations from the 5th International Patellofemoral Pain Research Retreat, Gold Coast, Australia, 2017. Br J Sports Med. 2018;52(18):1170–8.
164. Lack S, Neal B, De Oliveira SD, Barton C. How to manage patellofemoral pain: understanding the multifactorial nature and treatment options. Phys Ther Sport. 2018;32:155–66.

165. Santos TRT, Oliveira BA, Ocarino JM, et al. Effectiveness of hip muscle strengthening in patellofemoral pain syndrome patients: a systematic review. Braz J Phys Ther. 2015;19:167–76.
166. Willy RW, Hoglund LT, Barton CJ, et al. Patellofemoral pain. J Orthop Sports Phys Ther. 2019;49(9):1–95.
167. Decker MJ, Torry MR, Noonan TJ, et al. Landing adaptations after ACL reconstruction. Med Sci Sports Exerc. 2002;34(9):1408–13.
168. de Fontenay BP, Argaud S, Blache Y, et al. Motion alterations after anterior cruciate ligament reconstruction: comparison of the injured and uninjured lower limbs during a single-legged jump. J Athl Train. 2014;49(3):311–6.
169. Lee SP, Chow JW, Tillman MD. Persons with reconstructed ACL exhibit altered knee mechanics during high speed manoeuvres. In J Sports Med. 2014;35(6):528–33.
170. Paterno MV, Schmitt LC, Ford KR, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament after anterior cruciate ligament reconstruction and return to sport. Am J Sports Med. 2010;38(10):1968–78.
171. Sterns KM, Pollard CD. Abnormal frontal plane knee mechanics during sidestep cutting in female soccer athletes after anterior cruciate ligament reconstruction and return to sport. Am J Sports Med. 2013;41(4):918–23.
172. Chaudhari AM, Briant PL, Bevill SL, Koo S, Andriacchi TP. Knee kinematics, cartilage morphology, and osteoarthritis after ACL injury. Med Sci Sports Exerc. 2008;40(2):215–22.
173. Oiestad BE, Holm I, Aune AK, et al. Knee function and prevalence of knee osteoarthritis after anterior cruciate ligament reconstruction: a prospective study with 10 to 15 years of follow-up. Am J Sports Med. 2010;38(11):2201–10.
174. Buckthorpe M. Recommendations for movement re-training after ACL reconstruction. Sports Med. 2021;51(8):1601–8.
175. Neitzel JA, Kernozek TW, Davies GJ. Loading response following anterior cruciate ligament reconstruction during the parallel squat exercise. Clin Biomech (Bristol, Avon). 2002;17(7):551–4.
176. Grooms D, Appelbaum G, Onate J. Neuroplasticity following anterior cruciate ligament injury: a framework for visual-motor training approaches in rehabilitation. J Orthop Sports Phys Ther. 2015;45(5):381–93.
177. Grooms DR, Page SJ, Nichols-Larsen DS, et al. Neuroplasticity associated with anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 2017;47(3):180–9.
178. Kapreli E, Athanasopoulos S, Gliatis J, et al. Anterior cruciate ligament deficiency causes brain plasticity: a functional MRI study. Am J Sports Med. 2009;37(12):2419–26.
179. Kapreli E, Athanasopoulos S. The anterior cruciate ligament deficiency as a model of brain plasticity. Med Hypotheses. 2006;67:645–50.
180. Gokeler A, Neuhaus D, Benjaminse A, et al. Principles of motor learning to support neuroplasticity after ACL injury: implications for optimizing performance and reducing risk of second ACL injury. Sports Med. 2019;49(6):853–65.
181. Wadey R. Sport injury psychology: cultural, relational, and methodological considerations. London: Routledge; 2021.
182. Brewer BW, Redmond CJ. Psychology of sport injury. Champaign: Human Kinetics; 2017.
183. Wadey R, Evans L. Working with injured athletes: research and practice. In: Hanton S, Mellalieu SD, editors. Professional practice in sport psychology: a review. London: Routledge; 2011. p. 107–32.
184. Gledhill A, Forsdyke D. The psychology of sports injury: from risk to retirement. London: Routledge; 2021.
185. Everard C, Wadey R, Howells K. Storying sports injury experiences of elite track athletes: a narrative analysis. Psychol Sport Exerc. 2021;56: 102007. https://doi.org/10.1016/j.psychsport.2021.102007.
186. Sparkes A. Athletic identity: an Achilles' heel to the survival of self. Qual Health Res. 2016;8(5):644–64.
187. Atkinson M. Pain and injury: from the unidimensional to the multidimensional. In: Wadey R, editor. Sport injury psychology: cultural, relational, and methodological considerations. London: Routledge; 2020. p. 61–73.
188. Tamminen K, Dunn R, Gairdner S. Time to re-evaluate injured athletes' emotional responses. In: Wadey R, editor. Sport injury psychology: cultural, relational, and methodological considerations. London: Routledge; 2020. p. 96–107.
189. Mankad A, Gordon S, Wallman K. Perceptions of emotional climate among injured athletes. J Clin Sport Psych. 2009;3(1):1–14.
190. Salim J, Wadey R, Diss C. Examining hardiness, coping and stress-related growth following sport injury. J Appl Sport Psychol. 2015;28:154–69.
191. Carson F, Polman RCJ. The facilitative nature of avoidance coping within sports injury rehabilitation. Scand J Med Sci Sports. 2010;20(2):235–40.
192. Wadey R, Evans L, Hanton S, Sarkar M, Oliver H. Can preinjury adversity affect postinjury responses? A 5-year prospective, multi-study analysis. Front Psychol. 2019;10:1411. https://doi.org/10.3389/fpsyg.2019.01411.
193. Gervis M, Pickford H, Hau T, Fruth M. A review of the psychological support mechanisms available for long-term injured footballers in the UK throughout their rehabilitation. Sci Med Football. 2020;4(1):22–9.
194. Rock JA, Jones MV. A preliminary investigation into the use of counselling skills in support of rehabilitation from sport injury. J Sport Rehabil. 2002;11(4):284–304.
195. Bianco T. Social support and recovery from sport injury: elite skiers share their experiences. Res Q Exerc Sport. 2001;72:376–88.
196. Cecil S. Less control, more flexibility: using acceptance and commitment therapy with injured athletes. In: Wadey R, editor. Sport injury psychology: cultural, relational, and methodological considerations. London: Routledge; 2020. p. 197–206.
197. Salim J, Wadey R. Can emotional disclosure promote sport injury-related growth? J Appl Sport Psychol. 2018;30(4):367–87.
198. Everard C, Wadey R, Howells K, Day M. Construction and communication of evidence-based video narrative in elite sport: knowledge translation of sport injury experiences. J Appl Sport Psychol. 2022. https://doi.org/10.1080/10413200.2022.2140225.
199. Gervis M, Pickford H, Hau T. Professional Footballers' Association Counselors' perceptions of the role long-term injury plays in mental health issues presented by current and former players. J Clin Sport Psychol. 2019;13(3):451–68.
200. Souter G, Lewis R, Serrant L. Men, mental health and elite sport: a narrative review. Sports Med Open. 2018;4:57. https://doi.org/10.1186/s40798-018-0175-7.
201. Carson F, Polman RCJ. ACL injury rehabilitation: a psychological case study of a professional rugby union player. J Clin Sport Psychol. 2008;2:71–90.
202. Griffin LJ, Moll T, Williams T, Evans L. Rehabilitation from sport injury: a social support perspective. In: Zenko Z, Jones L, editors. Essentials of exercise and sport psychology: an open access textbook. Society of Transparency, Openness, and Replication of Kinesiology; 2021: p. 734–78
203. Kerai S. Physiotherapist-injured athlete relationship: toward a cultural and relational understanding. In: Wadey R, editor. Sport injury psychology: cultural, relational, and methodological interpretations. London: Routledge; 2020. p. 108–19.
204. Bejar MP, Raabe J, Zakrajsek RA, Fisher LA, Clement D. Athletic trainers' influence on national collegiate athletic associates

division I athletes' base psychological needs during sport injury rehabilitation. J Athl Train. 2019;54(3):245–54.
205. Clement D, Arvinen-Barrow M, Fetty T. Psychosocial responses during different phases of sport injury rehabilitation: a qualitative study. J Athl Train. 2015;50(1):95–104.
206. Niven A. Rehabilitation adherence in sport injury: sport physiotherapists' perceptions. J Sport Rehabil. 2007;16(2):93–110.
207. Brewer BW. The role of psychological factors in sport injury rehabilitation outcomes. Int Rev Sport Exerc Psychol. 2010;3:40–61.
208. Buckthorpe M, Della Villa F, Della Villa S, Roi GS. On-field rehabilitation part 1: 4 pillars of high-quality on-field rehabilitation are restoring movement quality, physical conditioning, restoring sport-specific skills, and progressively developing chronic training load. J Orthop Sports Phys Ther. 2019;49(8):565–9.
209. Buckthorpe M, Della Villa F, Della Villa S, Roi GS. On-field rehabilitation part 2: a 5-stage program for the soccer player focused on linear movements, multidirectional movements, soccer-specific skills, soccer-specific movements, and modified practice. J Orthop Sports Phys Ther. 2019;49(8):570–5.
210. Ardern CL, Glasgow P, Schneiders A, et al. 2016 consensus statement on return to sport from the first world congress in sports physical therapy. Bern Br J Sports Med. 2016;50:853–64.
211. Almeida AM, Santos Silva PR, Pedrinelli A, Hernandez AJ. Aerobic fitness in professional soccer players after anterior cruciate ligament reconstruction. PLoS ONE. 2018;13(3): e0194432.
212. Carrol TJ, Herbert RD, Munn J, et al. Contralateral effects of unilateral strength training: evidence and possible mechanisms. J Appl Physiol. 2006;101:1514–22.
213. Harput G, Ulusoy B, Tildiz TI, et al. Cross-education improves quadriceps strength recovery after ACL reconstruction: a randomized controlled trial. Knee Surg Traumatol Arthrosc. 2019;27(1):68–75.
214. Minshull C, Gallacher P, Roberts S, et al. Contralateral strength training attenuates muscle performance loss following anterior cruciate ligament (ACL) reconstruction: a randomised-controlled trial. Eur J Appl Physiol. 2021;121(12):3551–9.
215. Tseng WC, Nosaka K, Tseng KW, Chou TY, Chen TC. Contralateral effects by unilateral eccentric versus concentric resistance training. Med Sci Sports Exerc. 2020;52(2):474–83.
216. Logerstedt D, Sennett BJ. Case series utilizing drop-out casting for the treatment of knee joint extension motion loss following anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 2007;37(7):404–11.
217. Rice D, McNair PJ, Dalbeth N. Effects of cryotherapy on arthrogenic muscle inhibition using an experimental model of knee swelling. Arthritis Rheum. 2009;61(1):78–83.
218. Kuenze CM, Kelly AR, Jun HP, Eltoukhy M. Unilateral quadriceps strengthening with disinhibitory cryotherapy and quadriceps symmetry after anterior cruciate ligament reconstruction. J Athl Train. 2017;52(11):1010–8.
219. Hart JM, Kuenze CM, Diduch DR, Ingersoll CD. Quadriceps muscle function after rehabilitation with cryotherapy in patients with anterior cruciate ligament reconstruction. J Athl Train. 2014;49(6):733–9.
220. Stokes M, Shakespeare D, Sherman K, et al. Transcutaneous nerve stimulation and post-meniscectomy quadriceps inhibition. Int J Rehabil Res. 1985;8:248.
221. Arvidsson I, Eriksson E. Postoperative TENS pain relief after knee surgery: objective evaluation. Orthopedics. 1986;9:1346–51.
222. Harkey MS, Gribble PA, Pietrosimone BG. Disinhibitory interventions and voluntary quadriceps activation: a systematic review. J Athl Train. 2023;49(3):411–21.
223. Rush JL, Glaviano NR, Norte GE. Assessment of quadriceps corticomotor and spinal-reflexive excitability in individuals with a history of anterior cruciate ligament reconstruction: a systematic review and meta-analysis. Sport Med. 2021;51:961–90.
224. Sherman DA, Glaviano NR, Norte GE. Hamstrings neuromuscular function after anterior cruciate ligament reconstruction: a systematic review and meta-Analysis. Sport Med. 2021;51:1751–69.
225. Sahrmann S. Diagnosis and treatment of movement impairment syndromes. Oxford: Elsevier Health Sciences; 2013.
226. Yu S, Lowe T, Griffin L, Dong XN. Single bout of vibration-induced hamstrings fatigue reduces quadriceps inhibition and coactivation of knee muscles after anterior cruciate ligament (ACL) reconstruction. J Electromyogr Kinesiol. 2020;55:10246. https://doi.org/10.1016/j.jelekin.2020.102464.
227. Hauger AV, Reiman MP, Bjordal JM, et al. Neuromuscular electrical stimulation is effective in strengthening the quadriceps muscle after anterior cruciate ligament surgery. Knee Surg Sports Traumatol Arthrosc. 2018;26:399–410.
228. Lepley LK, Wojtys EM, Palmieri-Smith RM. Combination of eccentric exercise and neuromuscular electrical stimulation to improve quadriceps function post-ACL reconstruction. Knee. 2015;22(3):270–7.
229. Binder-Macleod SA, Halden EE, Jungles KA. Efects of stimulation intensity on the physiological responses of human motor units. Med Sci Sports Exerc. 1995;27:556–65.
230. Cabric M, Appel HJ, Resic A. Fine structural changes in electrostimulated human skeletal muscle. Evidence for predominant effects on fast muscle fibres. Eur J Appl Physiol Occup Physiol. 1987;57:1–5.
231. Trimble MH, Enoka RM. Mechanism underlying the training effects associated with neuromuscular electrical stimulation. Phys Ther. 1991;71:273–80.
232. Bickel CS, Gregory CM, Dean JC. Motor unit recruitment during neuromuscular electrical stimulation: a critical appraisal. Eur J Appl Physiol. 2011;111:2399–407.
233. Henneman E, Clamann HP, Gillies JD, Skinner RD. Rank order of motoneurons within a pool: law of combination. J Neurophysiol. 1974;37:1338–49.
234. Gorgey AS, Timmons MK, Dolbow DR, et al. Electrical stimulation and blood flow restriction increase wrist extensor cross-sectional area and flow meditated dilatation following spinal cord injury. Eur J Appl Physiol. 2016;116:1231–44.
235. Natsume T, Ozaki H, Saito AI, et al. Effects of electrostimulation with blood flow restriction on muscle size and strength. Med Sci Sports Exerc. 2015;47:2621–7.
236. Slysz JT, Boston M, King R, et al. Blood flow restriction combined with electrical stimulation attenuates thigh muscle disuse atrophy. Med Sci Sports Exerc. 2021;53(5):1033–40.
237. Hughes L, Paton B, Rosenblatt B, Gissane C, Patterson SD. Blood flow restriction training in clinical musculoskeletal rehabilitation: a systematic review and meta-analysis. Br J Sports Med. 2017;51(13):1003–11.
238. Patterson SD, Hughes L, Warmington S, et al. Blood flow restriction exercise: considerations of methodology, application, and safety. Front Physiol. 2019;10:533. https://doi.org/10.3389/fphys.2019.00533.
239. Giles L, Webster KE, Mcclelland J, Cook JL. Quadriceps strengthening with and without blood flow restriction in the treatment of patellofemoral pain: a double-blind randomised trial. Br J Sports Med. 2017;51(23):1688–94.
240. Ladlow P, Coppack RJ, Dharm-Datta S, et al. Low-load resistance training with blood flow restriction improves clinical outcomes in musculoskeletal rehabilitation: a single-blind

randomized controlled trial. Front Physiol. 2018;9:1269. https://doi.org/10.3389/fphys.2018.01269.
241. Ohta H, Kurosawa H, Ikeda H, et al. Low-load resistance muscular training with moderate restriction of blood flow after anterior cruciate ligament reconstruction. Acta Orthop Scand. 2003;74(1):62–8.
242. Hughes L, Rosenblatt B, Haddad F, et al. Comparing the effectiveness of blood flow restriction and traditional heavy load resistance training in the post-surgery rehabilitation of anterior cruciate ligament reconstruction patients: a UK National Health Service randomised controlled trial. Sports Med. 2019;49(11):1787–805.
243. Hughes L, Patterson SD, Haddad F, et al. Examination of the comfort and pain experienced with blood flow restriction training during post-surgery rehabilitation of anterior cruciate ligament reconstruction patients: a UK National Health Service trial. Phys Ther Sport. 2019;39:90–8.
244. Carr LJ, Harrison LM, Stephens JA. Evidence for bilateral innervation of certain homologous motoneurone pools in man. J Physiol. 1994;475(2):217–27.
245. Zhou S. Chronic neural adaptations to unilateral exercise: mechanisms of cross education. Exerc Sport Sci Rev. 2000;28(4):177–84.
246. Chung KS, Ha JK, Yeom CH, et al. Are muscle strength and function of the uninjured lower limb weakened after anterior cruciate ligament injury? Two-year follow up after reconstruction. Am J Sports Med. 2015;43:3101–21.
247. Lepley AS, Gribble PA, Thomas AC, et al. Quadriceps neural alterations in anterior cruciate ligament reconstructed patients: a 6-month longitudinal investigation. Scand J Med Sci Sports. 2015;25(6):828–39.
248. Zult T, Gokeler A, van Raay JJ, et al. An anterior cruciate ligament injury does not affect the neuromuscular function of the non-injured leg except for dynamic balance and voluntary quadriceps activation. Knee Surg Sports Traumatol Arthrosc. 2017;25:172–83.
249. Graven-Nielsen T, Lund H, Arendt-Nielsen L, et al. Inhibition of maximal voluntary contraction force by experimental muscle pain: a centrally mediated mechanism. Muscle Nerve. 2002;26(5):708–12.
250. Henriksen M, Rosager S, Aaboe J, et al. Experimental knee pain reduces muscle strength. J Pain. 2011;12(4):460–7.
251. Palmieri-Smith RM, Kreinbrink J, AshtonMiller JA, Wojtys EM. Quadriceps inhibition induced by an experimental knee joint effusion affects knee joint mechanics during a single-legged drop landing. Am J Sports Med. 2007;35(8):1269–75.
252. Stokes M, Young A. The contribution of reflex inhibition to arthrogenous muscle weakness. Clin Sci. 1984;67(1):7–14.
253. Sachs RA, Daniel DM, Stone ML, Garfein RF. Patellofemoral problems after anterior cruciate ligament reconstruction. Am J Sports Med. 1989;16(6):760–5.
254. Norkin CC, White DJ. Measurement of joint motion: a guide to goniometry. 5th ed. Philadelphia: F.A. Davis Company; 2017.
255. Lynch A, Logerstedt D, Axe M, Snyder-Mackler L. Quadriceps activation failure after anterior cruciate ligament rupture is not mediated by knee joint efusion. J Orthop Sports Phys Ther. 2012;42:502–10.
256. Potter H, Foo L. Magnetic resonance imaging of joint arthroplasty. Orthop Clin North Am. 2006;37:361–73.
257. Bush-Joseph C, Hurwitz D, Patel R, et al. Dynamic function after anterior cruciate ligament reconstruction with autologous patella tendon. Am J Sports Med. 2001;29:36–41.
258. Kocher M, Steadman J, Briggs K, Sterett W, Hawkins R. Relationship between objective assessment of ligament stability and subjective assessment of symptoms and function after anterior cruciate ligament reconstruction. Am J Sports Med. 2004;32:629–34.
259. Decker M, Torry M, Noonan T, Sterett W, Steadman J. Gait retraining after anterior cruciate ligament reconstruction. Arch Phys Med Rehabil. 2004;85:848–56.
260. Dye S, Staubli H, Biedert R, Vaupel G. The mosaic of pathophysiology causing patellofemoral pain: therapeutic implications. Oper Tech Sports Med. 1999;7:46–54.
261. Myer G, Brent J, Ford K, Hewett T. A pilot study to determine the effect of trunk and hip focused neuromuscular training on hip and knee isokinetic strength. Br J Sports Med. 2008;42:614–9.
262. Crossley KM, Zhang WJ, Schache AG, et al. Performance on the single-leg squat task indicates hip abductor muscle function. Am J Sports Med. 2011;39(4):866–73.

Authors and Affiliations

Matthew Buckthorpe[1,2] · Alli Gokeler[3] · Lee Herrington[4] · Mick Hughes[5] · Alberto Grassi[6] · Ross Wadey[1] · Stephen Patterson[1] · Alessandro Compagnin[2] · Giovanni La Rosa[2] · Francesco Della Villa[2]

✉ Matthew Buckthorpe
matthew.buckthorpe@stmarys.ac.uk

1 Faculty of Sport, Technology and Health Sciences, St Mary's University, London TW1 4SX, Twickenham, UK

2 Education and Research Department, Isokinetic Medical Group, FIFA Medical Centre of Excellence, Bologna, Italy

3 Exercise Science and Neuroscience, Department Exercise & Health, Faculty of Science, Paderborn University, Paderborn, Germany

4 Centre for Human Sciences Research, University of Salford, Salford, UK

5 North Queensland Physiotherapy Centre, Townsville, QLD, Australia

6 II Clinica Ortopedica, IRCCS Istituto Ortopedico Rizzoli, Bologna, Italy