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REVIEW ARTICLE

Optimising the 'Mid-Stage' Training and Testing Process After ACL Reconstruction

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Abstract

Outcomes following anterior cruciate ligament (ACL) reconstruction need improving, with poor return-to-sport rates and high risk of secondary re-injury. There is a need to improve rehabilitation strategies after ACL reconstruction, if we can support enhanced patient outcomes. This paper discusses how to optimise the mid-stage rehabilitation process after ACL reconstruction. Mid-stage is a difficult and vitally important stage of the functional recovery process and provides the foundation on which to commence late-stage rehabilitation training. Often many aspects of mid-stage rehabilitation (e.g. knee extensors isolated muscle strength) are not actually restored prior to return-to-sport. In addition, if we are to allow time for optimal late-stage rehabilitation and return-to-sport training, we need to optimise the mid-stage rehabilitation approach and complete it in a timely manner. This paper forms a key part of a strategy to optimise the ACL rehabilitation approach and considers factors more specific to mid-stage rehabilitation characterised in 3 areas: (1) muscle strength: muscle and joint specific, in particular at the knee level, with the knee extensors and flexors and distally with the triceps surae and proximally with the lumbo-pelvic-hip complex, as well as closed kinetic chain strength; (2) altered basic motor patterning (movement quality) and (3) fitness re-conditioning. In addition, 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 is able to progress to the next stage (e.g. late-stage rehabilitation criteria).

1 Introduction

Despite being perhaps the most discussed rehabilitation topic, there is by no means a consensus on the best way to rehabilitate a patient after anterior cruciate ligament reconstruction (ACLR). It is well established that outcomes after ACLR are not perfect. Although, on one side, patient-reported outcomes are often good in the short to medium term after ACLR [1], a large proportion (35–45%) of competitive athletes do not return to competitive sport [2, 3]. Even 1 in 5 (18%) professional/elite athletes does not return to competitive sport after ACLR [4]. Of those who do return-to-sport (RTS), 15% can expect a secondary ACL injury, with nearly 1 in 3 (around 30%) young recreational and elite athletes experiencing a re-injury, usually within the first 2 years after RTS [5–9].

Recently, meeting RTS criteria prior to RTS has been shown to reduce the risk of re-injury by 75–84% [5, 10]. However, within the Kyritsis et al. [10] paper, 12 of the 26 players with a second ACL injury actually met the RTS criteria, while 28 of the 132 players with no second ACL injury did not pass RTS criteria. This highlights a lack of specificity and sensitivity for RTS criteria to identify high risk athletes. Recently, we focused on optimisation of late-stage rehabilitation and RTS after ACLR and proposed additional criteria, more stringent and reflective of factors which may be linked with re-injury risk and athletic performance [11]. However, given the fact that only 26% of patients meet current criteria at 6 months after ACLR [12], making the criteria harder is unlikely to solve the problem. Recent suggestions have been to delay RTS until at least 9 months to reduce the risk of secondary injury [5]. This is because the first 6–12 months after RTS is the period of the highest risk

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Key Points

Outcomes after ACL reconstruction are sub-optimal and to improve outcomes we need to optimise our rehabilitation processes and practices

Many factors which could be characterised as more 'mid-stage rehabilitation markers' are typically not restored or not done so in a timely fashion after ACL reconstruction, which may compromise entry into a late-stage rehabilitation programme

The primary goals of mid-stage rehabilitation should be to address deficits associated with neuromuscular function, including muscle/joint specific strength imbalance resolution and closed kinetic chain strength, as well as basic motor re-patterning. In addition, for athletes a key element of the programme should contain fitness re-conditioning to avoid detraining and support an optimised physical fitness by the time of return-to-sport

Appropriate planning and programming is required to be able to incorporate all training aspects effectively. The programme should be periodised incorporating load management strategies.

[8, 13] and there was a 52% reduction in knee re-injury risk for each month RTS was delayed up to 9 months in a single study [5]. However, even at 9 months one study showed that only 11% of their ACLR patients actually met RTS criteria [14]. One approach would be to delay RTS even further, with a suggestion to 2 years [15]. Delaying RTS of course allows more time to achieve the necessary functionality; however, this is only effective if this time is filled with high-quality rehabilitation. It would appear more logical to optimise our rehabilitation strategies after ACLR.

Recent approaches have been done to optimise pre-operative rehabilitation [16, 17], late-stage rehabilitation [11, 18–20] and update the RTS frameworks [11, 21, 22]. However, it appears that factors more associated with mid-stage rehabilitation are typically not resolved after ACLR. In particular, there appears difficulty to be in restoring knee extensor muscle strength in a timely fashion [14, 23]. Without high quality early and mid-stage rehabilitation, patients often do not overcome major aspects of dysfunction which limits knee function and ability to transition through late-stage rehabilitation and RTS training optimally. So, getting mid-stage rehabilitation right is essential to optimising patient outcomes after ACLR.

There is a lack of published recommendations on 'how to optimise' mid-stage rehabilitation. Therefore, we wrote this paper to accompany our previous work which addressed late-stage rehabilitation and RTS training and testing after ACLR [11], to transition towards the optimisation of the whole pathway after ACLR. In particular, we discuss important factors specific to the mid-stage rehabilitation and provide recommendations on how to optimise this work, as well as outline screening tests and specific criteria to achieve to effectively prepare for entry into the 'late-stage rehabilitation and RTS programme' [11]. It is hoped this will support practitioners working directly with patients after ACLR.

2 The Functional Recovery Process

It is important to have a well-structured functional recovery process in place, and clear understanding of where mid-stage rehabilitation fits within the overall approach. There is no gold standard ACL rehabilitation approach, but having criterion-based rehabilitation through stages or phases is regarded as best practice [24]. The functional recovery process can be broadly separated into pre-operative, early-, mid- and late-stage rehabilitation and RTS training (Fig. 1).

Pre-operative rehabilitation aims to prepare the athlete for surgery, normalising knee function through minimising knee joint effusion, gaining full quadriceps activation and normal gait [25]. Research shows that prehabilitation (5–6-week programme focusing on restoration of muscle strength, quadriceps hypertrophy and hop performance) results in superior knee function post ACLR [26–28]. The early stage is focused on resolving pain and swelling, recovering sufficient knee joint range of motion, recovery of activities of daily living including the ability to walk without crutches, and minimisation of muscle atrophy [25]. Late-stage rehabilitation focuses on optimising neuromuscular and movement performance and RTS training, defined as a continuum of sport-specific on-field rehabilitation, return to training, return to play and finally return to performance [22]. Mid-stage rehabilitation of course fits between early- and late-stage rehabilitation and is the focus of this paper. For an optimal mid-stage rehabilitation, it is important to have clear goals and priorities, but also a clear understanding of when an athlete is ready to both start (see Table 1 for criteria to commence mid-stage rehabilitation) and finish mid-stage rehabilitation.

3 Important 'Mid-stage' Rehabilitation Considerations

The main considerations for mid-stage rehabilitation can be grouped into three categories: (1) muscle strength, (2) movement quality and (3) fitness re-conditioning (Fig. 2).

Of course, the stage also considers knee factors such as joint range of motion, effusion/swelling control, pain management and joint stability, as well as considering the psychology of the athlete (e.g. motivation, apprehension, etc.). Knee factors are though the predominant focus of earlier stage rehabilitation, and like psychology are then running themes throughout the functional recovery process after ACLR.

3.1 Muscle Strength

3.1.1 Knee Extensor Strength

The key priority of mid-stage rehabilitation is the restoration of knee extensor muscle strength in a timely fashion. Injury and surgery result in large deficits of quadriceps muscle volume, neural activation and strength [29]. Residual deficits in knee extensor strength after ACLR are associated with poor biomechanics [30], reduced knee function [31, 32] and increased knee osteoarthritis risk [33], as well as elevated risk of knee re-injury [5]. Knee extensor strength by the end of mid-stage rehabilitation should be within 20% of the contralateral limb, which provides the muscular strength foundation on which to commence late-stage rehabilitation [11, 34]. Deficits greater than 20% are associated with reduced knee function and movement compensations during high load activities (e.g. jumping and hopping) [30].

Extensive research indicates that most patients are unable to sufficiently restore quadriceps strength after ACLR [29, 35–37], with more than half of patients experiencing a deficit greater than 10% versus the contralateral uninjured limb at the time of RTS [14, 29, 37–39]. Failure to achieve less than a 20% difference versus the contralateral limb is common at 6-month post-ACLR [29].

Difficulties in restoring knee extensor strength appear due to arthrogenic muscle inhibition (AMI) present after injury and surgery, which remains and limits adaptations in knee extensor muscle volume and strength [29, 40]. AMI typically limits the ability to achieve desired neuromuscular activation and intensity levels for an optimal stimulus for strength training adaptations, and is often present bilaterally following unilateral ACLR and, in some cases, can be equivalent to the injured limb [41].

In the quest to recover knee extensor strength post-ACLR, it is essential to utilise effective programme planning, as well as additional modalities to in part overcome the effects of AMI and the load compromised joint to support the restoration of muscle size, voluntary activation and strength. One such modality is blood flow restrictive training, which can support more optimised muscle hypertrophy and strength gains during the mid-stage, as this allows resistance training in those load compromised athletes at lower loads [40, 42, 43]. It is also recommended to treat AMI and use a range of modalities to facilitate increased neuromuscular activation. Firstly, following the criteria to enter mid-stage rehabilitation is essential, to avoid loading a painful and irritable unprepared knee. In addition, managing pain and swelling is important, as they will negatively affect joint proprioception [44, 45], as well as result in neuromuscular inhibition via the AMI process [46–49]. Thirdly, incorporating a range of techniques early during the mid-stage to target AMI within the session and support increased neuromuscular activation during resistance training is recommended. Ice and transcutaneous electrical stimulation have been shown to temporarily reduce the AMI effects of swelling [50, 51]. Finally, the utilisation of neuromuscular electrical stimulation can support the recovery of knee extensor strength after ACLR [52], and allows for the direct activation of the motor axon, and could allow for the direct recruitment of the inhibited motoneurons. Muscle activation by means of neuromuscular electrical stimulation also allows for the recruitment of a greater proportion of type II muscle fibres when compared with voluntary contractions of a similar intensity [53–55] and, consequently, supporting more balanced recovery of muscle hypertrophy across all muscle fibres (e.g. avoiding preferential type I muscle hypertrophy in the presence of high-threshold motor unit inhibition).

We also recommend the inclusion of more 'isolated' open and closed chain knee extensor strengthening techniques (e.g. knee extension/leg press) as opposed to use of 'functional strengthening' (e.g. squatting, deadlifting, step-ups, lunges) during most of the mid-stage, but particularly in the earlier periods of the mid-stage [40]. Functional strength is the ability to produce force in situations in which muscles are commonly used, whilst isolated strength tasks (i.e. knee extension on the isokinetic machine) minimise the requirements for neural control to develop the muscle's 'capacity'

Fig. 1 The functional recovery process involving a criterion-based progression of five stages of pre-operative, early-, middle- and late-stage rehabilitation and return to sport training (RTS)

Table 1 Recommended criteria for progression from the early- to mid-stage of ACL rehabilitation programme

Outcome measure	Test	Goal	Reason for meeting criteria
Pain	Numeric rating scale of pain	0–2 (knee specific). Tolerance to higher pain in non-specific area may be acceptable (e.g. due to scar tissue)	Pain along with swelling has a profound effect on joint proprioception [44, 45] as well as result in neuromuscular inhibition via the AMI process and resultant muscle atrophy and weakness [46–49]
Effusion/swelling	Stroke test [163] Zero: No wave produced on downstroke Trace: Small wave on medial side with downstroke 1+: Large bulge on medial side with downstroke 2+: Effusion spontaneously returns to medial side after upstroke 3+: So much fluid that it is not possible to move the effusion out of the medial aspect of the knee	Zero to trace effusion	Changes in knee joint effusion are frequently associated with irritation of intra-articular structures and articular disorders in clinically active knees [167]. Swelling can result in AMI, cause pain and prevent 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 [168] 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°)	Straight knee (0°)	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 [34]
Passive knee flexion	Supine or prone with long arm goniometer [169]	At least 120° of knee flexion [25]	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 [170]
Quadriceps recruitment	Full quadriceps activation [25]	Ability to sufficiently recruit the quadriceps (no quadriceps sag on single leg raise through 10 repetitions) [25]	Quadriceps inhibition can prevent recovery of quadriceps muscle strength and the safe and expedient progression of rehabilitation [50, 171]. Persistent quadriceps lag on single leg raise has been shown to indicate an inability to actively fully extend the knee. If this is not achieved by week 5 post ACL reconstructive surgery, this would be considered a predisposing factor for significant quadriceps weakness at 6-months post-operation [164]
Walking gait	Visual assessment of walking gait	Sufficiently normalised gait without aid [25]	Abnormal gait patterns have been associated with joint weakness [172], low patient satisfaction with outcome after surgery [173] decreased functional performance [174] and post-operative complications including knee osteoarthritis [175]. Abnormal gait patterns often become further exacerbated as the athlete returns to running [161]. Thus, re-establishing normal gait early, as well as safely after ACLR is a key priority

Each outcome measure, the specific test and goal as well as the justification for these criteria are presented

AMI arthrogenic muscle inhibition

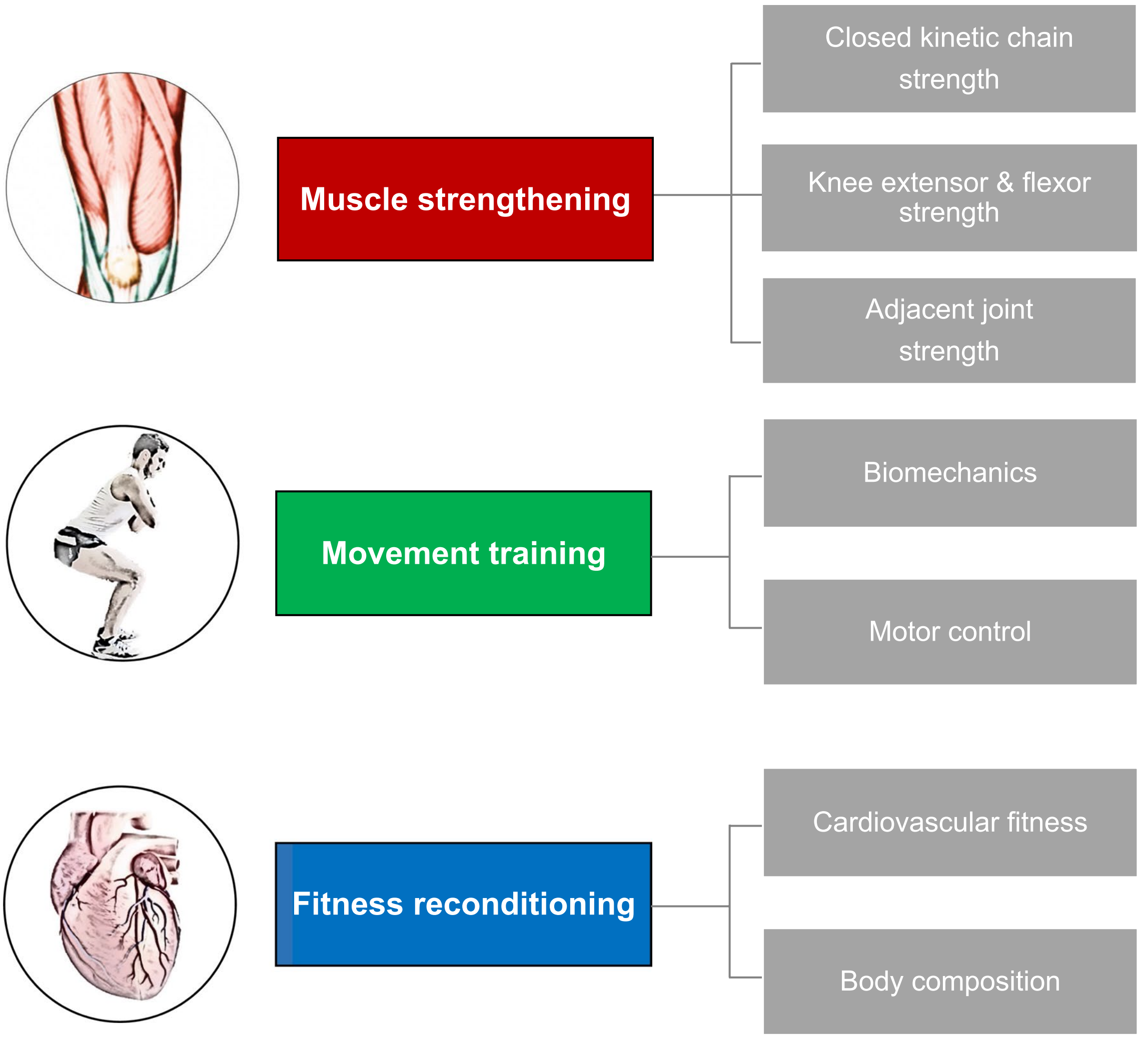

Fig. 2 A representation of the three important priorities of mid-stage rehabilitation training including muscle strengthening, movement training and fitness re-conditioning and the sub-sections

to produce force [56] and do not mimic the way in which the muscles function [57]. This is because when a patient has large knee extensor strength deficits, they will adopt movement patterns in which they 'cheat' and utilise the hip extensors instead of the knee extensors [58, 59]. Even when achieving the optimal kinematics (e.g. correcting the compensatory movement pattern of greater hip to knee flexion), there is still typically inhibition of the quadriceps, resulting in lower neuromuscular recruitment, which may result in insufficient stimulus for adaptation [58]. This may explain the large residual deficits in knee extensors strength reported in the literature after ACLR [14, 29, 36–38], even with elite level athletes [39]. This is not to say functional strengthening is not important during the mid-stage, as it is essential to develop both the isolated capacity of the muscle to produce force, as well as the intermuscular coordination to express this capacity during functional tasks [57, 60–62]. However, whilst there is a large quadriceps weakness and AMI, it is recommended to utilise to a much greater extent isolated strengthening than functional strengthening. More isolated open and closed kinetic chain exercises will reduce the task degrees of freedom and support the minimisation of cheat strategies, enabling more targeted work of the muscle group. This should also be accompanied as discussed with additional modalities (e.g. blood flow restrictive training, neuromuscular electrical stimulation). The balance of isolated to functional strengthening will then gradually change over time during the stage and reverse during the late-stage of rehabilitation (i.e. a stronger use of functional to isolated strengthening during the late-stage rehabilitation process) [11].

Although there are doubts about the safety of open kinetic chain exercises, this is arguably unsupported by substantial published evidence [63]. It is important though to avoid undue stress on the healing ACL graft through performing strengthening exercises at specific knee angles (e.g. 45°–90° open kinetic chain knee extension, [34, 64]) and carefully incorporating open kinetic chain strength exercise in general (and certain closed kinetic chain exercises).

One major issue in the mid-stage is that many clinicians often ignore the contralateral uninjured limb, training only the injured side. It is important to recognise that neuromuscular function deficits following ACLR are typically bilateral, in which the contralateral limb is weaker than its pre-operative values [23]. For example, only 29% of patients achieved a limb symmetry index (LSI) greater than 90%, when the reconstructed limb was compared to pre-surgery strength values at 6-month post-ACLR (note, pre-surgery, not pre-injury), whilst 57% were able to restore the injured limb's strength to within 10% of the uninjured limb (i.e. the conventional LSI) [23]. The contralateral limb often serves as a 'control limb' on which targets for the injured limb are based, both for progression through the functional recovery approach (e.g. LSI > 80% for progression to late-stage rehabilitation [11]), as well as for RTS (> 90–100% LSI depending upon the sport). Avoiding training the uninjured limb will likely result in an atrophy and strength loss, resulting in an earlier restoration of the LSI during the mid-stage (i.e. easier to achieve 80% LSI, as the target is effectively lower) and result in the patient being under-prepared to tolerate the higher loading demands of the subsequent programme (i.e. a sufficient LSI, but low levels of absolute strength). Furthermore, RTS without sufficient training of the uninjured limb will result in over-estimated knee function of the injured limb, and under-preparedness of both limbs, likely increasing the risk of re-injury for both sides. The high rates of ACL injury on the contralateral side after RTS following ACLR [65] are a particular concern.

Our advice is to include strength training for both limbs as part of the ACL functional recovery process. There is some evidence that training the contralateral limb can also result in strength gains for the injured limb, via the cross-education phenomenon [66–68]. The strength training approach to the contralateral limb should aim to preserve, not enhance, the strength and muscle size. Developing muscle size and strength of the contralateral limb beyond its pre-injury values will result in greater difficulties normalising LSI. However, maintaining strength on the uninjured side, recovering the desired LSI (strength of the injured limb versus the uninjured limb) as quickly as possible (mid- and late-stage), prior to then adopting a conditioning approach to both limbs (e.g. RTS training) is recommended. During the mid-stage, this would involve performing the same exercise on the uninjured as the injured limb, but doing so at higher intensities and much lower volumes. For example, 6 sets of leg press for the injured side at 12 repetition maximum (RM) would be complemented with 3–4 sets of 3–5RM for the uninjured side. Recent evidence suggests that high-intensity eccentric training of the contralateral limb may be more effective than concentric training, in terms of the cross-education benefit [69].

It is also recommended when measuring knee extensor strength as part of the functional recovery process, or prior to RTS to consider both the relative (e.g. LSI) and absolute strength of the injured limb. We recommend, based on both evidence [11, 14, 70] and clinical experience, an LSI of 80% knee extensor strength (compared to a 'preserved' contralateral limb) and > 2 Nm kg^{-1} peak torque on the isokinetic machine (90° s^{-1}) (80% of 2.5 Nm kg^{-1}) be achieved prior to progressing to the late-stage rehabilitation and RTS programme [11].

3.1.2 Knee Flexor Strength

Perhaps the second most important aspect of mid-stage rehabilitation is the recovery of knee flexor strength. Most studies [71–75], report hamstring strength deficits which can persist for many years after surgery, with deficits of between 0 and 20% at time of RTS [71–75]. Kyritsis et al. [10] showed a 10.6-fold greater risk of ACL re-injury after ACLR for every 10% decrease in knee flexor to extensor strength ratio of the injured limb in professional football players.

Hamstring strength recovery is particularly relevant in those who have ACLR with hamstring graft, as they appear to show selective muscle atrophy, with the semitendinosus of the surgically repaired limb being significantly smaller (10–28%) [76–79]. Semitendinosus atrophy from graft usage is not accompanied by compensatory gracilis hypertrophy [72], which may show up to a 30% deficit in muscle volume [77, 79]. This is often accompanied by reduced knee internal rotator strength [80]. It should be considered that semitendinosus tendon regeneration after ACLR may take approximately 18 months [81] and may not occur at all in 10–50% of patients [72, 78, 80]. Rehabilitation during this time and for individuals with no tendon regeneration would presumably not load the semitendinosus significantly and evidence indicates selective neuromuscular inhibition of semitendinosus during high force contractions [82], which likely results in insufficient stimulus following resistance training and persistent muscle size and strength deficits. This selective inhibition may require the semimembranosus to compensate to maintain optimal transverse plane control of the knee. After ACLR with hamstring graft, there is often compensatory biceps femoris hypertrophy [83], which results in a reduced internal to external knee rotation strength ratio [83] and likely contributes to the increased external tibial rotation seen during running in ACLR patients [84]. Thus, we recommend that the addition of hamstring exercises which elicit more selective medial hamstring muscle activation (e.g. Nordic hamstring curl [85], hamstring exercises performed with tibial internal rotations [86]) be incorporated to target potential residual deficit in medial hamstring muscle size and strength. A holistic approach to hamstring muscle strengthening [56, 87, 88], incorporating both knee and hip dominant exercises is also recommended for all patients. In those with hamstring graft, a periodised resistance programme similar to the knee extensors should be adopted, and knee flexor strengthening delayed for 6–8 weeks after surgery to allow healing of the harvested graft [64, 89, 90]. Hamstring strengthening should commence with isometric knee flexor exercises as well as low to moderate intensity hip extension exercises. Those without hamstring graft can be less cautious, respecting the load capacity of the knee as a whole. Higher intensity pain-free hamstring strengthening should be able to be commenced towards the end of the mid-stage, with at least an 80% LSI by the end of the mid-stage. After this, a stronger focus on high intensity, eccentric, high speed, longer muscle length and functional (e.g. higher speed running) strengthening should occur.

3.1.3 Adjacent Joint Strength

As well as the muscles about the knee, it is important that an aspect of mid-stage rehabilitation be focused both distally and proximally to the knee joint. Deficits in plantar flexor strength and muscle strength about the hip and lumbo-pelvic region can occur and impact neuromuscular performance and movement quality.

Firstly, a key muscle group to consider restoring after ACLR is the triceps surae. The soleus and gastrocnemius are important contributors to muscle force generation during running, particularly at speeds less than 7 m s^{-1} [91]. In addition, the ankle joint eccentrically accepts around 40–50% of the impact forces when landing [92]. The soleus muscle in particular acts as an agonist to the ACL, preventing anterior tibial translation, through restricting the shin moving anteriorly in relation the knee, by providing restraint to tibial advancement at the ankle [93, 94]. Schlumberger [95] reported an average of 8% deficit in calf muscle strength 6 months following ACLR, which may be higher when considering the contralateral strength deficits which are normally present after injury [23].

Additionally, a key aspect of ACL rehabilitation should be to address strength deficits of the lumbo-pelvic-hip musculature. Weakness of certain muscles in the region has been retrospectively or prospectively associated with lower limb and/or ACL injuries [96–103]. A systematic review by Petersen et al. [100] revealed deficits in hip muscle strength after ACLR. In particular, weakness or reduced activation of the hip abductors and external rotators (e.g. gluteus medius and maximus) may be a risk factor for ACL injury [98]. The gluteus maximus is thought to become 'inhibited' (defined as reduced activation or delayed onset) after lower limb injury [104, 105] 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 [106, 107]. In addition, weakness of the gluteal muscles can contribute to altered movement patterns which increase knee and ACL loading and are thought to be important risk factors for ACL injury. Weakness of gluteal muscles would be expected to lead to a more upright and laterally positioned trunk during high load movements, to position the centre of mass closer to the hip and thus reduce the requirements on the gluteal musculature. This would lead to the centre of mass position further away from the knee and thus higher loads on the knee in the sagittal plane, as well as lateral shifting of centre mass, achieving a resultant vector line lateral to the knee joint, causing a knee abduction moment [101]. Thus, we recommend a strong focus on addressing dysfunction of the gluteal muscles during mid-stage rehabilitation, as well as considering the trunk, pelvic and hip musculature in general (e.g. hip adductor strength, trunk muscle recruitment and endurance).

3.1.4 Closed Kinetic Chain Strength

As well as muscle/joint specific strength (e.g. knee extensors/flexors), it is also important to have good closed kinetic chain strength. The ability to perform functional tasks involves the ability of the neuromuscular system to develop force (e.g. strength) [108], during certain movements. Newtonian mechanics implies that movement acceleration is a function of force applied/body mass (force = mass × acceleration) and as such relative strength is theoretically important for optimal movement performance. In addition, there is good association between closed kinetic chain strength (e.g. isometric or dynamic squat strength) and athletic performance during sporting tasks such as jumping and sprint running and change of direction ability [109–111]. In the context of mid-stage rehabilitation, it is important to restore the necessary closed kinetic chain strength to support transition to more demanding functional tasks undertaken during the mid-stage (e.g. single leg squats, bilateral landing tasks) and ultimately to late-stage rehabilitation [11]. For example, bilateral landing, treadmill-based running and single limb plyometric tasks typically involve ground reaction forces of 1–1.5 [112], 2–3 [113] and 2–6 [112, 114, 115] times body mass, respectively. Therefore, developing and understanding the lower limbs ability to produce and accept force can provide the necessary foundation and understanding on when they may be ready to perform these potentially dangerous exercises after ACLR. Inability to produce or eccentrically dissipate these forces via the neuromuscular system (i.e. insufficient functional eccentric muscle strength of the lower limb) would result in movement compensations [30] and/or overreliance/acceptance of the passive restraints such as ligament, joint complexes and fascial system, potentially resulting in either chronic overload [116, 117] and/or acute injuries such as graft failure due to ligament fatigue [118, 119]. Having optimal task progressions according to both task complexity and loading parameters is recommended as too is developing sufficient closed kinetic chain strength to tolerate these tasks. It is recommended to be able to tolerate comfortably 1.5 times body mass single limb (e.g. leg press or single leg isometric squat, peak torque or predicted 1RM) before progression to late-stage rehabilitation. Increased focus on closed chain exercises to develop closed chain strength as well as knee extensors strength is needed again through a periodised resistance training programme within mid-stage rehabilitation.

3.2 Movement Quality

Multiple studies have identified altered movement quality (e.g. the ability to control the limb, maintaining balance and optimal kinematics during movement) in the involved limb of both male and female ACLR patients when compared to both their control limb and to uninjured controls during an array of functional exercises [120–123]. Disruption to the native ACL leads to mechanical instability of the knee and can alter neuromuscular control due to disrupted mechanoreceptors within the ligament [124] and altered somatosensory input and joint proprioception. The resultant decrease in joint position sense and kinaesthesia, along with nociceptor activity associated with pain and swelling, may potentially impair movement quality [125]. It appears that an ACL injury results in altered movement quality bilaterally, when compared to pre-injury movement quality [120]. Altered movement quality has been associated with increased risk for ipsilateral or contralateral secondary injury and the development of early onset of osteoarthritis of the knee joint [126–128]. Paterno et al. [128] linked altered movement quality prospectively with secondary ACL risk. The authors identified four predictive factors for secondary ACL risk in a group of young female athletes, including increased knee valgus, asymmetry in internal knee extensor moment, signal leg postural stability and opposite hip rotation moment as significant predictors of re-injury risk. In addition, Paterno et al. [129] demonstrated that those with deficits in postural control during functional type tasks (assessed using a single leg balance type task) were at heightened risk of secondary injury following ACLR. Thus, establishing symmetrical and optimal movement quality in basic motor patterning tasks is important to ensure the right movement foundation on which to retrain more demanding movement tasks. In addition, it is also important to restore/develop single control/balance and joint proprioception. Given the residual deficits in movement quality at the time of RTS, it would appear current rehabilitation programmes do not effectively target aberrant movement patterns sufficiently [129].

Altered movement quality is thought to be due to multiple factors including muscle imbalances/weakness (e.g. knee extensor weakness, [30]), altered posture (e.g. anterior tilted pelvis, [130, 131]), arthrokinetic dysfunction (e.g. reduced dorsi-flexor range of motion, [132]), altered reciprocal muscle inhibition and synergistic dominance [133, 134] and altered proprioception [135, 136]. Consequently, incorporating corrective exercises to address these factors is important to help establish more optimal movement quality. This would include a programme of re-activating and/or strengthening weak/inhibited muscles as well as muscle release techniques and flexibility training of over-active/tight muscles.

Patients may also move sub-optimally due to limiting understanding of the tasks (low knowledge of movement) or altered coordination during the task. So, practicing functional tasks (with optimal coaching strategies) and re-learning optimal technique are needed to reorganise skills following a period of neuromuscular/corrective training [62]. Motor learning is defined as the process of an individual's ability to acquire motor skills with a relatively permanent change in performance as a function of practice or experience [137]. Therefore, to gain expertise and induce a motor learning adaptation, a skill must be practiced repeatedly. We advise to incorporate optimal task progression based on both complexity and load for foundation motor pattern retraining. This should include a progression from bilateral to single leg tasks, with progression based on sufficient technique proficiency and strength development (Fig. 3).

It is important prior to adding load that the optimal technique is achieved, and that specific underlying dysfunction has been addressed to ensure more optimal movement quality and adaptation from the programme. Utilisation of coaching techniques and use of bio-feedback through video analysis to maximise cognitive understanding are highly recommended. Furthermore, incorporating strategies to maximise motor learning is encouraged including (1) adopting an external focus of attention; (2) implicit learning; (3) differential learning and (4) self-controlled learning and contextual interference [138].

3.3 Physical Fitness Re-conditioning

Successful RTS requires not only resolving impairments at the knee, but also restoring neuromuscular function, sports-specific movement quality and sport-specific readiness (fitness, technical training and load readiness) [22, 139, 140]. To achieve this, we need to think about *'return to performance'* throughout the functional recovery process [21, 22]. The rehabilitation and RTS process after ACLR are long (typically 6–9 months) [13] and offer an opportunity to develop an athlete's physical fitness to higher levels than before the injury, as long as it is appropriately planned. Additionally, there is also an opportunity to address physiological impairments which may have been limiting sport performance (e.g. muscle morphology/upper body strength), and increasing their susceptibility to injury or just previously unresolved aspects of function from previous injuries (e.g. chronic groin pain). Although late-stage rehabilitation and RTS training largely involve physical fitness re-conditioning [11], it is important that an athlete commences late-stage rehabilitation with a sufficient physical fitness profile to allow for intense training to achieve this higher level of athletic performance. As such, an aspect of mid-stage rehabilitation should be in avoiding detraining by incorporating *'physical fitness reconditioning'*. Evidence suggests that football players' cardiovascular (CV) fitness is lower at 6 months after ACLR than pre-injury values [141], indicating a need to better optimise the training of this important physical fitness parameter. This could in part be due to insufficient intensities in late-stage rehabilitation, but may also indicate an insufficient stimulus to preserve aerobic fitness during the earlier stages. Key fitness re-conditioning goals will depend on the athlete's sport, profile and previous injury history. But for most athletes incorporating specific sessions of re-conditioning that include a focus on body composition, upper body morphology and strength, and importantly CV conditioning, are recommended. This typically involves either incorporation of this work into their existing rehabilitation training or separate re-conditioning sessions, involving predominantly non-load-bearing upper body strength work (e.g. bench press, seated shoulder press, bench or seated rows, dips, pull-ups, etc.), low or no load CV training (e.g. deep water running in swimming pool, stationary bike, cross-trainer, alter-g, etc.) and additional corrective strengthening (e.g. extra 'lumbo-pelvic-hip strength session' focusing on areas of weakness).

4 Recommendations for Implementation

In designing the mid-stage approach, it is important to focus on the goals/priorities and allocate training time according to these different training goals. The exact work and allocated time on each training goal and in each environment depend on the individual, their goals and actual time commitment. In addition, certain factors should be considered when rehabilitating patients with different graft types [34], as well as concomitant injuries such as meniscal injury, chondral defects or multi-ligament injuries [34]. Mid-stage rehabilitation involves a big transition in terms of functional capacity of the injured athlete, in which they are transitioned from the point of being able to walk normally at the start of the stage to being required to be able to run with sufficiently normalised running mechanics towards the end of the stage.

It is essential to achieve optimal loading (defined as the load applied to structures that maximises physiological adaptation [142]), during the functional recovery process, which will be specific to the injured athlete and will change reflecting their functional capacity. In particular, the stimulus should target the specific training goal optimally (e.g. muscle endurance, hypertrophy, strength, power), whilst avoiding excessive loads which may adversely stress the healing joint/ligament [64] and/or patellofemoral joint. The knee is often load compromised throughout the mid-stage of rehabilitation

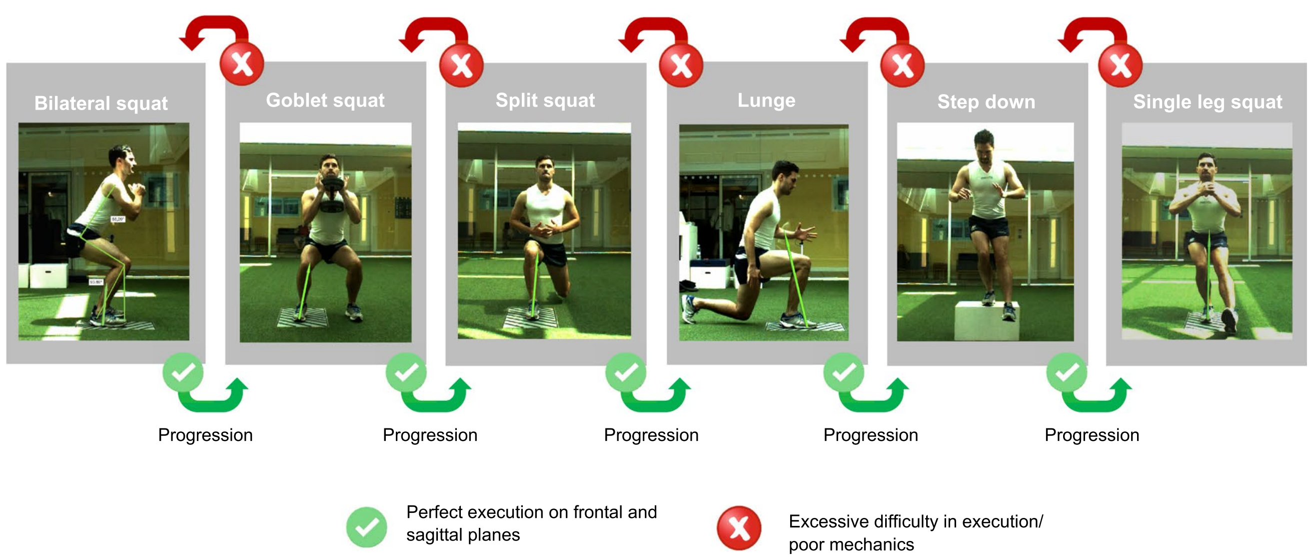

Fig. 3 A outline of our single leg squat task progression, beginning with bilateral unloaded squat, goblet squat, split squat, lunge, step up and finally single leg squat. Progression is based on movement quality and ability to handle additional loading during the task

and thus, cannot tolerate excessively high forces (e.g. very high-intensity resistance training, 85–90%+, 5RM). Excessive forces on a compromised knee joint would result in overload and pain and swelling and could potentially stretch or loosen the ACL graft [64, 143]. Thus, the functional recovery programme requires careful planning and well-designed progressions of increasing challenge.

Current evidence concerning training theory in uninjured individuals reports that strength adaptations are achieved across a range of training intensities (40–95% maximal intensity) [144]. It is typically recommended that 40–60% neuromuscular activation is needed at a minimum for a strengthening effect [145], although there is a dose–response relationship with greater gains in strength from exercise which elicit higher neuromuscular activation values [146–148]. The American College of Sports Medicine recommends loads of 60–70% 1RM for the development of muscle strength and 70–85% for hypertrophy [149]. Traditionally, it was believed that very high loads were necessary to bring about activation of all type II motor units based on the Henneman size principle [150] and achieve full and complete muscle hypertrophy (targeted at all motor units). However, it is suggested that more low-load training also recruits fast-twitch muscle fibres and can achieve muscle hypertrophy and strength gains, provided that the working set is continued close to volitional fatigue [151]. This would result in activation and fatigue of the respective motor units, with the addition of progressively larger motor units as the set progresses. As such, although not optimal for muscle hypertrophy, low load to fatigue can be used as a strategy for hypertrophy during the earlier stages of ACL rehabilitation, when the knee is load compromised. The efficacy of low to moderate load strengthening exercises (≤ 70% maximal intensity) for developing maximal eccentric strength and rate of force development is, however, questionable, thus requiring higher load training for full optimisation of neuromuscular function [152–155]. As such, there is a need to incorporate a periodised resistance training programme with increasing task difficulty. During the mid-stage, we recommend initially beginning with low- to moderate-intensity resistance (e.g. 12–20 RM), focused predominantly on muscle work capacity and hypertrophy [40], targeting metabolic stimuli for adaptation, as opposed to high mechanical stimulus or muscle damage, when the joint is highly load compromised [40]. There should then be a progressive increase in intensity and volume to support more optimised muscle hypertrophy and strength recovery, respecting the knee joint load tolerance. Very high intensities are often contraindicated in this stage, and more suited for late-stage rehabilitation, when the knee can tolerate higher loads [11].

In light of the above, we recommend splitting the mid-stage of rehabilitation in two separate halves/blocks of training, to allow specific work relative to the functional status of the athlete to be performed. The first half of activity recognises the load compromised athlete often with severe quadriceps weakness and dysfunction, unable to perform the majority of functional tasks on land (Table 2). During this stage, we recommend the use of lower intensities of resistance (e.g. 12–20RM), and a stronger focus on non-weight-bearing exercise (including lower limb and lumbo-pelvic-hip exercises) and machine-based strengthening tasks (e.g. leg press, knee extension). We recommend that this is accompanied by additional modalities to overcome the negative effects of AMI, allowing for higher neuromuscular activation (e.g. neuromuscular electrical stimulation), and/or supporting the accumulation of metabolic stimuli (e.g. blood flow restrictive training). Although this lacks task specificity and transference to functional exercises/movement [156], as described, it can often target a specific muscle group better in isolation. We still recommend the use of functional exercise during this time, but mostly with the goal of teaching optimal technique as well as improving intermuscular coordination [60, 61], as opposed to for enhancing muscle size and strength. During this first block of training, the athletes will be unable to perform the majority of functional tasks on land. As such, where possible we recommend utilising the hydrotherapy/swimming pool to practice functional movement tasks such as lunging, squatting, as well as deep water running (as well as the other benefits including active joint range of motion, gait and CV conditioning with deep water running). In water, the buoyancy force controls the downward (landing) movement of the body, thus generating higher upward (concentric) and lower downward (eccentric) forces. At the appropriate depths, there is also around a 45–60% reduction in body weight, allowing the earlier practice of functional tasks at lower loads. This would allow for a learning effect which can then be more applied on land, when the knee joint can tolerate higher loads (see supplementary video for examples of the exercises which can be performed in the pool as part of rehabilitation after ACLR).

During the second block of training, we encourage a progression to slightly higher intensities of strength training, typically 8–12 RM or 70–80% maximum for the injured limb [40]. Furthermore, including progressive land-based movement retraining and functional strengthening is now encouraged, as well as a combination of non-weight-bearing and weight-bearing lumbo-pelvic-hip exercises. The pool can again be used where available to allow for the inclusion of higher load movement activities such as single limb landing, as well as plyometric tasks. Plyometric type activity in water versus land appears to result in reduced joint inflammation and perceived pain [157, 158], but similar gains in concentric power development [114, 115]. This is typically though done only in those undertaking a pro-athlete programme in our clinics. Functional task progressions on land

Table 2 The important priorities of mid-stage rehabilitation, the specific training approach to target the priority and the approach specific to the half of the stage

Priorities	Training approach/goal	1st half of mid-stage	2nd half of mid-stage
Muscle strengthening			
Knee extensor strengthening	Resistance training to restore muscle endurance, work capacity, hypertrophy and strength (within 20% of the contralateral limb) of the quadriceps muscles	Low to moderate load OKC (initially at restricted range, 50°–90°) and CKC (predominantly isolated e.g. leg press) strengthening exercises (12–20 RM) focusing predominantly on muscle endurance and hypertrophy through metabolic stimuli. Supplementary use of NMES and BFRT	Moderate load strengthening (8–12 RM) in OKC and CKC (isolated [e.g. leg press] and functional [e.g. squat, lunge]) focused on muscle hypertrophy (and strength) through metabolic, mechanical stimuli and muscle damage mechanisms. Supplementary use of NMES and BFRT
Hamstring strength/activation	Restore hamstring strength (within 20% contralateral side or pre-injury values), reactivate and strength the medial hamstrings, restore muscle hypertrophy and knee control	Depending upon graft type—introduce hip dominant exercises, incorporate isometric knee dominant exercises at lower loads Incorporate rotational control and strengthening drills	Progress to isokinetic, isometric and concentric strengthening. Knee and hip dominant exercises at higher exercise intensities (8–12 RM)
Closed kinetic chain strength	Develop the strength of the kinetic chain to facilitate the ability to undertake functional exercises and more high load knee control in late-stage rehab	Introduce closed kinetic chain strengthening at low to moderate loads, leg press isometric and dynamically (12–15 RM)	CKC strengthening to develop leg press strength (8–12 RM) Use of functional training for both motor re-patterning and closed kinetic chain strength development
Calf muscle strengthening	Restore plantar flexor strength to facilitate optimal control and strength to support the knee and for propulsion during running and eccentric control in deceleration	Bed-based/seated plantar flexor strengthening and bilateral standing calf raises	Weight-bearing calf raises employing dynamic actions at 8–12 RM. Example, 4 sets of 10 single leg calf raises, with control eccentric lowering and optimal foot and ankle control
Gluteal muscles strengthening	Reactive and strengthening the gluteal muscles. The gluteus maximus in particular is prone to inhibition after injury	Non-weight-bearing muscle re-activation and endurance exercises (e.g. clam, BL bridge/hip thrust, side laying abduction)	Mix of WB and NWB exercises including single leg bridges, loaded hip thrusts (12 RM), standing clam with band, lateral band walks, standing hip extension drills, as well as closed chain triple extension drills (e.g. RDL, good morning, lunge)
NWB/isolated 'lumbo-pelvic strength endurance'	Reactive and integrate the local core muscle which may have become inhibited	Low load local stabiliser re-activation and neuromuscular control	Neuromuscular control in stance and during functional movements (e.g. pelvic and trunk control in load-bearing exercises)
Adductor muscle strengthening	Restore strength of the adductors to facilitate late-stage rehabilitation	Isometrics/squeezes to reactive and strengthening the adductors beginning with the knee bent avoiding long lever exercises in hamstring graft patients	Progress and include dynamic adductor strengthening (ECC, CON and ISO)
Hip flexor muscle strengthening	Restore hip flexor muscle balance and strength	Bed-based isolated superior hip flexor strengthening and leg lifts with optimal knee control	Weight-bearing and seated and loaded hip flexor strengthening with machines, manual and use of bands/isoinertial training
Movement quality			
Muscle release techniques	Manual therapy to target over-active and tight muscles as part of holistic approach to movement re-education, performed prior to stretching and neuromuscular activation/training	Stronger focus on manual therapy with bed-bed treatment, targeting RF, TFL, psoas, hip external rotators, lateral hamstring, VL, triceps surae	Shift towards preparatory foam rolling prior to land-based movement re-education sessions; massage on recovery days with professional athlete (pro-athlete schedule)

Table 2 (continued)

Priorities	Training approach/goal	1st half of mid-stage	2nd half of mid-stage
Muscle flexibility	Correct muscle length issues to ensure joint range of motion and muscle inflexibility do not compromise coordination and motor patterning	Use of hydrotherapy Strong focus on flexibility for joint range of motion Resolve muscle length asymmetries and muscle tension Ensure optimal muscle tension of hip flexors	Dynamic flexibility in the pool Push to achieve optimal mobility/flexibility at lumbo-pelvic region, knee and ankle (monitoring hip range of motion and dorsi-flexion R.O.M)
Balance and proprioception	Restore basic static and dynamic balance (instance) to provide foundation for more complex movement tasks	Bilateral and unilateral static and balance	Unilateral dynamic balance Unilateral landing control in the pool (> 1 m depth)
Movement retraining	Correct underlying deficits and retrain optimal basic motor patterning in tasks such as squat, lunge, hip hinge, step up and lunge. Progress to running gait re-education on treadmill	Largely use of the pool for motor pattern retraining, DWR and unilateral movement progressions (split squat, lunging squatting) Gait re-education and bilateral squats on land (limited motor training on land)	Landing drills in the pool Unilateral movement based progressions on land Bilateral loaded drills (goblet, front squat at low to moderate loads) Treadmill based running gait re-education
Physical fitness re-conditioning			
Aerobic conditioning in non- or low-load situations	Maintain aerobic fitness of the athlete to ensure a foundation of fitness on which to commence late-stage rehabilitation	Aerobic continuous moderate intensity on the bike and cross-trainer, introduction to moderate intensity DWR	Continuous and interval cardiovascular conditioning using cross-trainers, bike, and pool based DWR Introduction to alter-g running for conditioning
Upper body strength training	Incorporate UB strength training to develop athleticism and provide a good stimulus for recovery between lower limb rehabilitation sessions	Implement where possible on recovery days, lower priority, non-weight-bearing upper body strengthening (e.g. bench press, seated shoulder press, lat-pull down, etc.)	Include 2–4 times per week depending upon sport and goals generally as separate sessions. Varying stimulus depending on day (metabolic focus on LB recovery day), include standing lifts (e.g. shoulder press)

OKC open kinetic chain, *CKC* closed kinetic chain, *RM* repetition maximum, *NMES* neuromuscular electrical stimulation, *BFRT* blood flow restrictive training, *BL* bilateral, *WB* weight-bearing, *NMW* non-weight-bearing, *RDL* Romanian deadlift, *ECC* eccentric, *CON* concentric, *ISO* isometric, *RF* rectus femoris, *TFL* tensor fasciae latae, *VL* vastus lateralis, *R.O.M* range of motion, *DWR* deep water running, *UB* upper body, *LB* lower body, *lat* latissimus dorsi should include introduction to bilateral landing/jumping, as well as treadmill-based running re-education.

One important consideration is when and how to initiate treadmill-based running. Importantly, running is a high load task and requires substantial strength and neuromuscular control. Each step in running represents around 2–3 times body mass [113]. Effective implementation of running can serve as a useful training stimulus for developing strength and neuromuscular control, but it is important a patient is adequately prepared to commence running. In deciding when a patient is ready to return to running, most studies use time-based criteria, with the median time being 12 weeks [159]. The ability to perform specific tasks though like running is not related to healing times, but more specifically to function. Fewer than 1/5 studies reported clinical, strength or performance-based criteria for return to running, even though best evidence recommends performance-based criteria combined with time-based criteria to commence running activities following ACLR [159]. Most other criteria used beyond time are similar to the entry criteria for mid-stage rehabilitation (e.g. pain < 2, $> 120°$ or full knee flexion, zero or trace effusion and no instability of the knee/graft) [159] and so for clinicians this provides little indication of when they can actually introduce running. The other possible useful criteria are an isometric knee extension and flexion LSI of 70%, which should be adopted as this can provide some objective criteria to guide this decision-making process. These criteria though fail to understand a patients' closed kinetic chain strength, strength about the adjacent joints, as well as movement quality during basic movement tasks. In addition, a patient should be exposed to running gait re-education using running type activity at lower loads (e.g. deep water running or running on a trampoline and alter-G). They should then follow an introduction to running programme which should include a walk-run and then gradual increase in running speeds and time of running. We suggest achieving a single leg closed kinetic chain peak strength of at least 1.25 times body mass, an LSI for knee extensors and flexors of greater than 70% [159], as well as good single leg squat and bilateral landing movement quality as part of the return to run decision-making process. This provides the patient with guidance and targets, as opposed to time-based trial and error.

It is also important that mid-stage rehabilitation activity is effectively planned to ensure an optimal stimulus for adaptation, as well as sufficient load variation and recovery within and between weeks (e.g. periodisation). For recreational athletes, programme planning is often simpler, as they typically train a maximum of 2–3 times per week, and as such require a focus on priorities, as well as typically session replication. This would normally involve 2–3 days between sessions allowing sufficient recovery. Fitness reconditioning is less of a priority as they have much lower levels of physical fitness, which are easier to maintain and restore after injury and can normally be incorporated into their rehabilitation sessions in the gym. However, elite athletes have a much higher physical fitness profile, which needs to be maintained and requires a greater investment in re-conditioning to preserve [160]. They often have too many objectives to allow for effective planning in a single session design and require a greater volume of training with more carefully planned activity. As such, we typically plan a professional programme across 10 sessions, split across different environments depending on the stage (Tables 3, 4).

To support optimal progress through the programme, it is also important to objectively track that progress. It is recommended to include a series of regular monitoring as well as screening tests to track the progress of the athlete. This should be based around the objectives of the stage and assess knee status and response to training (e.g. pain, swelling, IKDC subjective form, etc.), strength, movement quality and physical fitness. Optimal rehabilitation progressions have to be in line with the biological healing and ability of the joint to withstand the loading demands. To achieve optimal loading, it is important to monitor the specific work and the knee's response to loading. Pain and swelling can be used to determine exercise-based progressions as these factors will relate to the loading stress experienced by the knee [161]. Measurement of knee circumference at the patella has been shown to be clinically relevant, with good reliability and sensitivity to change [162]. Changes greater than 1 cm were reported to be clinically significant, indicating possible exercise overload. Other techniques include assessing knee effusion via the stroke test [163]. Furthermore, regular measurement of joint range of motion can facilitate progression, and changes in range of motion may reflect the level of joint effusion [164]. Pain can be monitored using a 10-point numeric rating scale (0 no pain, 10 worst imaginable pain), which has been shown to be sensitive to changes in pain which affect function [165] with a reduction or increase by 1 point being regarded as the minimal clinically important change [166]. Furthermore, assessing/recording joint soreness during the warm up can support more optimised within session loading [34].

It is also important to have specific criteria or 'targets' to achieve by the end of the stage to allow for effective transition into the late-stage rehabilitation and RTS programme (where applicable). When establishing criterion-based rehabilitation it is important to understand the must haves versus nice to haves. Although certain aspects of function are important to be trained, they may not limit progression to late-stage rehabilitation. For example, CV training is important, as too is upper body strengthening for athletes; however, if these aspects are not specifically trained and developed within mid-stage rehabilitation, the patient can still satisfactorily progress to more intensive rehabilitation, they

Table 3 A breakdown of the typical week in the first half of mid-stage rehabilitation with a professional athlete

Time/session	Mon	Tues	Wed	Thurs	Fri	Sat	Sun
Session 1/AM	Gym: LB RT (muscle endurance loads/isometric strengthening) Additional modalities: NMES quads	Gym: LB RT (muscle endurance loads/isometric) Additional modalities: BFRT knee extension	Gym: recovery, non-weight-bearing conditioning and UB RT	Gym: LB RT (muscle endurance loads/isometric) Additional modalities: NMES	Gym - LB RT (muscle endurance loads dynamic/isometric strengthening) Additional modalities: BFRT leg press	Gym recovery, non-weight-bearing conditioning and UB RT	Off
Session 2/PM	Hydrotherapy	Hydrotherapy	Off	Hydrotherapy	Hydrotherapy	Off	Off

LB lower body, *RT* resistance training, *NMES* neuromuscular electrical stimulation, *BFRT* blood flow restrictive training, *UB* upper body

Table 4 A breakdown of the typical week in the second half of mid-stage rehabilitation with a professional athlete

Time/session	Mon	Tues	Wed	Thurs	Fri	Sat	Sun
Session 1/AM	Gym/MR—(LPH correctives and motor patterning/neuromuscular control)	Gym (massage, flexibility, general conditioning, UB RT)	Gym—(core/motor patterning/neuromuscular control)	Gym (massage, flexibility, general CV conditioning, UB RT)	Gym—(core/motor patterning/neuromuscular control)	Optional—Gym (massage, flexibility, general conditioning, UB RT)	Off
Session 2/PM	Gym—LB RT (rehab, mechanical stimulus/higher loading)	Hydrotherapy (movement and CV)	Gym—LB RT (rehab, metabolic stimulus/high volume fatiguing)	Hydrotherapy—(movement and CV)	Gym—LB RT (rehab, muscle damage/ECC strength training)	Off	Off

MR movement room, *LPH* lumbo-pelvic-hip, *UB* upper body, *RT* resistance training, *LB* lower body, *CV* cardiovascular, *ECC* eccentric

just do so at a lower level of physical fitness. However, failure to recover knee extensor strength or closed kinetic chain strength will negatively affect their ability to perform high load functional tasks, and potentially result in knee overload or even re-injury. Table 5 presents our recommended criteria, based on both evidence from the literature, as well as substantial clinical experience. The criteria are focused on understanding if patients have achieved a minimum level of knee function, muscle strength and neuromuscular control/movement quality to be prepared for entry into a late-stage rehabilitation and RTS programme [11].

5 Conclusions

There is a need to optimise the rehabilitation process after ACLR. This includes addressing the whole of the functional recovery process. This paper discussed important concepts relating to mid-stage rehabilitation after ACLR and should be considered alongside content on other stages (e.g. [11]). Mid-stage activity can be divided across (1) muscle strengthening, (2) movement training and (3) fitness re-conditioning. It is important to plan and prioritise the activity according to the individual, and the main priority should be the safe and optimal recovery of knee extensor and flexor muscle strength. The programme should be planned according to the functionality of the athlete, and we recommend splitting the programme into 2 halves, with a greater focus on isolated and non-weight-bearing corrective exercise during the first stage, with support from hydrotherapy and a more functional higher load land-based movement programme in the second half. Incorporating physical re-conditioning where possible can reduce the detraining effect and provide a stronger physical fitness foundation to commence more high-intensity late-stage rehabilitation, supporting the achievement of higher levels of athletic physical performance than before the injury.

Table 5 Recommended criteria for progression from the mid-stage to the late-stage of rehabilitation after anterior cruciate ligament reconstruction. Each outcome measure, the specific test and published reference are included, as well as the goal to achieve in order to transition to the next stage

Outcome measure	Test	Goal	Reason for inclusion
Knee effusion	*Stroke test* [163] and *Knee circumference measurements* [162] Changes of greater than 1 cm in knee circumference at the patella are clinically significant, indicating the levels of load applied were causes of joint stress	Zero effusion with minimal activity related effusion (< 1 cm change patella)	Changes in knee joint effusion are frequently associated with irritation of intra-articular structures and articular disorders in clinically active knees [167]. Swelling can result in AMI, cause pain and prevent optimal range of motion. It is also typically a sign of joint overload and a joint reaction to loading. The impact of loading can be measured and monitored by changes in knee circumference [167]. Thus, if the knee is reactive to mid-stage rehabilitation, it may not react well to more intense rehabilitative loading
Knee joint ROM	*As for mid-stage entry criteria*	Full	See Table 1
Knee extensor and flexor strength	Isokinetic testing [176]—alternating knee extensors and flexor concentrically at: $90°\ s^{-1}$ for 4 repetitions $180°\ s^{-1}$ for 20 repetitions	LSI > 80% for flexors and extensors and ideally a > 0.60 F/E ratio	Weakness in knee extensor strength will alter biomechanics, reduce functional performance, and is linked to elevated re-injury risk and poorer RTS outcomes [5, 30]. Achieving 80% is important prior to commencing high load (e.g. single leg deceleration, landing and plyometric) drills, as lower values may result in movement compensations and interfere with the movement retraining programme
Closed chain muscle strength	*Leg press strength test* [25] Leg press 90° knee flexion and seat at 45 degrees Maximal weight achieved for 8 RM test or *Isometric single leg squat* [110, 177] Single leg stance 60° knee flexion on force plate below a fixed bar as part of testing rig	At least 125% body mass for 8 reps or 1.5 × BM predicted 1 RM Peak force > 150% body mass	Having sufficient closed kinetic chain strength is important. Weakness will result in insufficient strength for acceptance and propulsion during landing and jumping tasks and may result in altered movement quality [30]
Gluteal muscle capacity	*Single leg bridge test (variation* [178]) Supine with knee angle at 90° flexion and feet on the floor and arms across the chest, lift up the hips from the floor to neutral hip flexion position and down again until buttocks touch the ground. Test conclude when subject cannot reach the height or gives up	Greater than 20 reps and within 5 of each side, with no cramping of hamstring or adductor magnus	Gluteal muscle weakness is associated with altered motor patterns specifically dynamic knee valgus [106, 107] and weakness of external rotation strength is a prospective risk factor for ACL injury [98]. Gluteus maximus is typically weaker after injury and re-activating and strengthening this muscle is important [104, 105]. Assessing muscle work capacity and activation is important. Cramping of the hamstrings or adductor magnus may indicate inhibition of gluteus maximus and synergistic dominance [179] which would need to be corrected prior to progression to more functional exercise

Table 5 (continued)

Outcome measure	Test	Goal	Reason for inclusion
Calf muscle capacity	*Single leg calf raises* [180] Subjects stand on one foot on the edge of the step and perform a calf raise through full range of motion. Calf raises are performed at 1 repetition every 2 s. The test concludes when subjects are unable to move through full range or slow below the cadence outlined above	Greater than 20 reps and within 5 repetitions versus other side	Calf muscle strength is important for acceptance and propulsion. The soleus muscle contributes the most muscle force production during running less than 7 m s^{-1} [91] and the ankle eccentrically accepts up to 50% of the impact forces from landing [92]. Reduced strength may limit absorption and possibly alter motion, resulting in reduced knee loading and compensatory patterns
Single leg balance	*Single leg balance in stance* [181] Subjects stand on one leg with other leg raised and arms crossed over the chest. The assessor uses a stopwatch to time how long stance is maintained on one leg with (a) eyes open, and (b) eyes closed Time ends when; Arms are used (uncrossed) Use of the raised foot (touches down or other leg) Movement of the stance foot 45 secs has elapsed (maximum time) Eyes opened and eyes closed trials	A (eyes open) 43 s B (eyes closed) 9 s (normative data for 18–39 year olds)	Poor balance/muscle coordination will alter neuromuscular control and may limit the expression of muscle strength [60, 61]. Multi angle static balance forms the pre-requisite to any dynamic activity [20]; without good static balance performance during dynamic tasks is likely to be significantly compromised. Having sufficient balance with eyes open and closed is important to progress but also ensure sufficient visual-motor retraining and joint position sense
Movement quality	*Single leg squat test* [182] Squat to at least 60° knee flexion Minimal trunk motion Minimal pelvic motion No hip adduction or internal rotation	Good movement quality (no zeros and score greater than 6)	The squat forms the foundation exercise for many sporting type tasks. Poor squat is associated with poor biomechanics in more complex tasks as it forms the motor pattern foundation for many tasks involving single leg exercise and triple flexion and extension
Running gait	*Assessment of running gait at 8–10 km h^{-1}* [140, 176] Qualitative and/or quantitative assessment of running mechanics including where possible good control of frontal plane alignment (minimal dynamic knee valgus, lateral trunk lean, pelvic drop) and sagittal plane loading (optimal triple flexion angles, e.g. no knee avoidance)	Sufficiently normalised running gait and ability to run for > 10 min at 8 km h^{-1}	Running represents a functional task which all people should do and a milestone mark for the ACLR patient. Assessing running gait on a treadmill may allow the clinician to provide feedback (visual or immediate or delayed feedback with video recording) cues to support the improvement of the athlete's running technique [161]. Poor running gait at low speeds will be exaggerated at high speeds and restoring running mechanics prior to progressing to multi-directional movement retraining is important

ROM range of motion, *AMI* arthrogenic muscle inhibition, *F/E* flexor: extensor ratio, *RTS* return-to-sport, *RM* repetition maximum, *reps* repetitions, *BM* body mass

Compliance with Ethical Standards

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