Recommendations for hamstring function recovery after ACL reconstruction

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Abstract

It is important to optimise the functional recovery process in order to enhance patient outcomes after major injury such as anterior cruciate ligament reconstruction (ACLR). This requires in part more high-quality original research, but also an approach to translate existing research into practice to overcome the research to implementation barriers. This includes research on ACLR athletes, but also research on other pathologies, which with some modification can be valuable to the ACLR patient. One important consideration after ACLR is the recovery of hamstring muscle function, particularly when using ipsilateral hamstring autograft. Deficits in knee flexor strength after ACLR are associated with increased risk of knee osteoarthritis, altered gait and sport-type movement quality, and elevated risk of re-injury upon return to sport. After ACLR and the early post-operative period, there are often considerable deficits in hamstring function which need to be overcome as part of the functional recovery process. To achieve this requires consideration of many factors including the types of strength to recover (e.g., maximal and explosive, multiplanar not just uniplanar), specific programming principles (e.g., periodised resistance programme) and exercise selection. There is a need to know how to train the hamstrings, but also apply this to the ACLR athlete. In this paper, the authors discuss the deficits in hamstring function after ACLR, the considerations on how to restore these deficits and align this information to the ACLR functional recovery process, providing recommendation on how to recover hamstring function after ACLR.

Key Points

- A knee flexor strength deficit after ACL reconstruction is a strong risk factor for ACL re-injury
- Overcoming deficits in hamstring function after ACL reconstruction is essential for optimal outcomes, satisfactory return to sport and re-injury risk reduction
- Most of the information concerning the hamstrings is devoted to hamstring injury prevention and hamstring muscle injury rehabilitation, with a lack of information on hamstring rehabilitation after ACL reconstruction
- Most training recommendations are focused on un-injured athletes and so needs to be adapted for the injured athlete
- Understanding hamstring training considerations and applying this to the ACL reconstruction patient as part of the ACL functional recovery process is essential

1. Introduction

The outcomes after anterior cruciate ligament reconstruction (ACLR) are less than ideal, with fewer people return-to-sport (RTS) [1] and even less return to performance [2]. A particular concern after ACLR, is the high rate of ACL and knee re-injuries after RTS, particularly amongst young athletes (~30%) [3, 4]. RTS after injury is a complex, multifactorial process and requires a biopsychosocial approach [5]. Current opinion is that if we are to optimise patient outcomes, then we need to optimise our rehabilitation approach. There is however, no consensus on rehabilitation after ACLR, despite considerable effort in recent years to clarify and optimise the process [6-11]. One issue in clinical practice is the large disconnect between research and practice, thought due to ineffective implementation of evidence-based findings [12]. It is also well recognised that if we are to truly impact individual patients, a stronger focus on research implementation is needed to translate efficacious rehabilitative and preventive methods into practice [13-16].

One important piece of the complex puzzle of ACL rehabilitation, is restoring knee flexor muscle function. The hamstring muscles are vitally important for the knee. During forceful dynamic movements, coactivation of the hamstrings is important to provide dynamic knee joint stabilisation and to prevent excessive ACL shear forces [17, 18]. Thus, the hamstring muscles are considered ACL-agonists. ACL injury, the resultant surgery and reduced functionality after surgery significantly impact on hamstring function, with deficits of nearly 50% reported at 4 weeks after ACLR with hamstring tendon autograft (HG) [19]. Restoring hamstring function is a key aspect of the functional recovery process after ACLR [8, 9]. Unfortunately, deficits in knee flexor strength can be high at the time of RTS (0-20%) [20-24] and even for many years after ACLR [25, 26]. Although deficits in knee flexor strength are typically less than that for the knee extensors [27, 28], even small deficits in knee flexor strength can be detrimental to injury risk upon RTS. In particular, within a group of professional football players, Kyritsis et al. [29] reported a 10.6-fold increased risk of ACL re-injury upon RTS, for each additional 10% deficit in knee flexor to extensor ratio. Furthermore, a history of severe knee injury (including ACL injury) increases the risk of a future hamstring strain injury (HSI) [30]. Although there are multiple risk factors for HSIs, likely all inter-relating in a complex manner [31, 32], including previous hamstring history [33-35], age [33-39], hamstring muscle architecture [40-43], lumbo-pelvic hip stability [34, 44-48] and training load [49-54] amongst others, the increased risk of HSI after severe knee injury is likely in part due to the altered hamstring strength function. After HSI, those athletes re-injured upon RTS were ~14% weaker compared to those that remained injury free when assessed prospectively [55]. So, assessing and treating knee flexor strength is a major element of the ACL functional recovery process [8, 9].

The aim of this paper is to translate the research on hamstring function, largely on hamstring strength training for performance, rehabilitation and injury prevention and then demonstrate how this can be applied to the ACLR patient. In doing so, identifying the gaps in literature we currently clearly have with hamstrings rehabilitation in ACLR populations. We discuss important alterations of the hamstring muscles after ACLR, their implications and considerations in programme design to overcome these deficits. Finally, we demonstrate how to apply this information to the ACLR patient, considering the specifics of the pathology and associated surgery. It is hoped this information supports translation of research into practice and supports more optimised hamstring recovery after ACLR, aiding in improving global patient outcomes.

2. Hamstring function changes after ACL rupture and reconstructive surgery – what, why and implications

2.1.Hamstring deficits after ACLR and their implications

Deficits in hamstring function are common after ACLR, irrespective of the surgical procedure [28, 29, 56]. Typical deficits in knee flexor maximal strength are between 0-20% across all contraction modes, at the time of RTS and in the years after RTS [20-24]. In a sample of more than 4000 patients, it was shown that the proportion of patients achieving a knee flexor limb symmetry index (LSI) ≥90% was 47% [28]. More pronounced deficits in knee flexor strength are apparent after ACLR with HG [57, 58]. Cristiani et al. [28] reported that patients after ACLR with bone patella-tendon bone graft (305 patients) had an average knee flexor LSI of 97% 6-months after ACLR. Two-thirds of patients had ≥90%, whilst ACLR patients with HG had an LSI of 89%, with less than half (46%) achieving the 90% LSI cut-off. Recent research assessing knee flexor strength isometrically at 4, 8 and 12 weeks after ACLR with HG reported a LSI of 54, 70 and 76% [19]. Knee flexor deficits after ACLR are also typically more pronounced at shorter muscle lengths/greater knee flexion angles [59], slower velocities [59] and for rate of force development (RFD), than maximal strength [60, 61]. One study has assessed knee flexor RFD after ACLR and reported a lower LSI for RFD during knee flexion (and extension) (average 55%) than maximal force (66%). There was though a higher RFD knee flexor to extensor ratio (average 0.63) compared to the contralateral limb (0.44), due to large deficits in knee extensor RFD [61].

The hamstring muscles are responsible for more than just knee flexion, contributing to hip extension, as well as knee and pelvis stability. In particular, the medial hamstrings are thought to be important for preventing ACL injuries, due to their role in preventing medial condyle lift-off and dynamic knee valgus [62], a known ACL injury risk factor [63, 64]. Of particular relevance after ACLR with HG, is the commonly observed deficits in knee internal rotation strength weakness [65, 66], which would be expected to contribute to the increased external tibial rotation and dynamic knee valgus found in ACLR patients [67].

Muscle architectural changes can also occur independent of muscle size [68] and the BF long head (BF_{LH}) of the ACLR limb has been shown to demonstrate shorter muscle fascicles and greater pennation angles after ACLR with HG [24]. The architectural changes in BF_{LH} are comparable to the changes observed in those with previously HSI of BF_{LH} [69]. Recent evidence suggests that professional soccer players with shorter BF_{LH} fascicles (<10.56 cm) were four times more likely to sustain a future HSI than those with longer fascicles, and that the probability of injury was reduced by around 20% for every 1 cm increase in fascicle length [69]. It has been hypothesized that possessing shorter muscle fascicles, with fewer in-series sarcomeres, may result in an increased susceptibility to eccentrically-induced muscle damage [69, 70], which may predispose the athlete to increased running related HSI.

2.2. Why are there residual deficits after ACLR?

There are multiple reasons why residual deficits in hamstring function may be apparent after ACLR. Understanding these reasons can aid in better design of interventions to address deficits. The deficits will in part depend on the function of the person pre-surgery, rehabilitation factors and the specific surgical technique/graft used.

Firstly, any deficits in hamstring function pre-surgery may be present or magnified post-surgery. Knee flexor weakness is a risk factor for primary ACL rupture [71] as, such predisposing weakness may have played a role in the injury. It is important to consider not only relatively strength deficits (e.g., LSI) but also absolute strength values during then functional recovery process and to support RTS decision making.

Secondly, residual deficits after ACLR, can also be in part due to an insufficient functional recovery process [56], or due to poor compliance after ACLR [72]. A key goal of the functional recovery process is to restore these deficits [9]. Reasons for the on-going deficits have in part been described due to insufficient volume, intensity and frequency of rehabilitation to target the deficits [8, 9, 56].

Finally, more marked deficits in knee flexor function are apparent after ACLR with HG, thought due to issues associated with the donor site. ACLR with HG, essentially results in a grade 4 muscle-tendon lesion. It is well aware after serious muscle lesion, there is often persistent hamstring strength deficits and high risk of HSI re-injury [55, 73, 74], partly explained by chronic neuromuscular inhibition [75]. This may result in a reduced capacity to voluntarily activate the hamstring muscle during eccentric, but not concentric knee flexor efforts [76, 77]. After ACLR with HG, there also appears to be a proximal migration of the semitendinosus (ST) muscle–tendon junction [78, 79]. ST tendon regeneration may take approximately 18 months [80] and may not occur at all in 10–50% of patients [21, 65, 79, 81]. Rehabilitation during this time and for individuals with no tendon regeneration would presumably not load the ST significantly. Muscle size and activation deficits may relate to tendon regeneration, with deficits in ST and gracilis muscle size been greater for tendons that did not regenerate [81]. Typically, there is selective ST muscle atrophy (10- 28%%) with HG [25, 79, 82, 83], commonly accompanied by gracilis muscle atrophy (~30%) [82, 83]. If these deficits are not compensated for with hamstring hypertrophy (e.g. BF and semimembranosus), this will lead to total hamstring volume deficits, which would compromise sagittal plane force capabilities (i.e., knee flexion strength). Additionally, without compensatory semimembranosus (SM) muscle hypertrophy, there would be residual deficits in medial to lateral hamstring muscle volume, which would directly influence transverse plane knee control. Messer et al. [26] reported compensatory hypertrophy of the SM after ACLR with HG, but found a 18% deficit in medial hamstring volume, due to large deficits in ST volume (30%). Other studies have also reported compensatory hypertrophy of BF and not SM [81], which would exacerbate the lateral to medial muscle size (and strength) imbalance.

3. Restoring hamstring function after ACLR – key considerations in program design

The majority of the research on hamstrings is focused on hamstring function for injury prevention and/or rehabilitation of HSI. There is a lack of actual evidence or advice for recovery of hamstring function in ACLR patients. In the absence of specific evidence on ACLR, it is important to consider, learn from and translate the exiting knowledge on hamstring rehabilitation and prevention to the ACLR athlete. Effective hamstring strength recovery is embedded in 1) understanding how to train the hamstrings; 2) understanding the deficits after ACLR and tailoring the hamstring conditioning approach to the required adaptive strategy; 3) understanding the ACLR journey and how to directly apply the approach to the ACLR patient. Section 2 considered the deficits after ACLR and this section will consider how to train the hamstrings after ACLR, considering effective training principles, but also the specifics of an ACLR patient, to understand how these principles need to be adapted. This will cumulate in section 4 where specific recommendations for each stage of the functional recovery process, and specific progression criteria will be presented.

3.1. *Achieve optimal loading*

The cornerstone of effective functional recovery is achieving ‘optimal loading’, (defined as the load applied to structures that maximises physiological adaptation [84]) to bring about specific neural, morphological and mechanical adaptations [84]. A significant challenge for rehabilitation specialists is designing optimal training programmes that facilitate training adaptations, whilst been mindful of biological healing constraints, and tissue capacity [85, 86]. Traditionally, training recommendations are based on evidence in un-injured athletes, such as the American College of Sports Medicine [87]. There is no consensus on specific training programmes recommendations for injured athletes. The optimal loading will depend on the desired mechanical (e.g., maximal strength, RFD, power, muscle strength endurance), neural (intermuscular coordination, motor unit recruitment/ firing frequency) or morphological (e.g., muscle size/volume, architecture, composition, tendon unit properties) adaptations. Various programming principles such as exercise intensity, volume, time under tension and rest between exercise sets are important in terms of achieving the optimal adaptation.

Load refers to the amount of weight assigned to an exercise set and is probably the most important variable in resistance training program design [88, 89]. Strength gains can be observed across many loading intensities, as long as a minimum intensity is achieved, thought to be around 40-60% voluntary activation [90]. Greater gains in strength, likely due to superior neural adaptation’s occur with higher intensities [91], with a dose-response between intensity and strength gains [92-94]. Heavy resistances also appear to be essential for promoting adaptions in RFD and maximal eccentric strength [95-98]. Lighter resistances to fatigue (e.g., sustained efforts/high repetitions, with minimal recovery between sets) are effective for training muscle endurance/work capacity. Intensity is less essential for muscle hypertrophy, likely due to the differing mechanisms available to induce muscle hypertrophy (e.g., mechanical tension, muscle damage and metabolic stimuli)[99].

Training volume appears essential for promotion gains in muscle hypertrophy [100]. It is thought that high volume training may enhance muscle mass gains due to prolonged metabolic stress [101]. High volume training appears less important for promoting maximal strength or eliciting architectural adaptations [102].

To fully restore neuromuscular performance after ACLR incorporation of a periodized neuromuscular training program, respecting tissue healing times and the patients individualised functional recovery, appears important. Periodization can be defined as the planned manipulation of training variables (load, sets and repetition) in order to maximize training adaptations and prevent over-training [85, 103, 104]. Knee flexor strengthening in ACLR patients with HG is normally suggested to be delayed for 6–8 weeks after surgery to allow healing of the harvested graft [105-107]. However, there is no strong evidence for this and lower intensity exercises are advised earlier after surgery, based on anecdotal experience. Those without hamstring graft can be less cautious, respecting the load capacity of the knee as a whole. Initially, lower intensity loading should be used during the earlier stages after ACLR (i.e., end of early stage to mid-stage), when the knee is load compromised and there is likely accompanying swelling and pain, as well as arthrogenic muscle inhibition (AMI), thus contraindicating high loads [9]. This initial lower intensity training will target the recovery of muscle endurance and work capacity as well as hypertrophy through metabolic adaptations [103]. This may be supported by supplementary modalities such as blood flow restriction training [103, 108, 109]. As an athlete gets stronger and overcomes pain, swelling and AMI, higher intensities can and should be used, in a progressive manner. This should initially focus on muscle hypertrophy, with higher volumes at moderate loads (e.g., 6-8 sets of 8-12 RM). This period can then be followed by a greater focus on maximal strength (and improvements in neuromuscular activation), with higher resistance loads and moderate volume. Finally, a transition to explosive strength and power training, in conjunction with very high intensity, low volume resistance training (e.g., < 5RM) is recommended in the final stages prior to RTS. See table 1 for general programming guidelines for each mechanical variable.

[TABLE 1 NEAR HERE]

3.2. Take some lessons from hamstring rehabilitation prevention and incorporate ‘eccentrics’ and longer length strengthening exercises

Contraction type is the most commonly monitored parameter in strength training to prevent HSIs [88]. It is though less frequently discussed when considering hamstring function after ACLR, which typically considers isometric and/or concentric strength via either isometric or isokinetic testing [28, 29, 110, 111]. Adaptations to strength training are mode specific [112-114]. Given that ACL graft failure likely occurs when the hamstring muscle actively lengthens to resist anterior tibial translation [115], and that HSI mainly occur when the hamstrings act eccentrically to brake the knee extension at the end of the running swing phase [116], it would seem relevant to prioritize eccentric strengthening prior to RTS. In the little research published, it appears that eccentric hamstring deficits after ACLR with HG are ~16-20% [22, 23, 25]. In terms of HSI, it appears that higher levels of eccentric but not concentric knee flexor strength have been shown in most [117-120], but not all prospective studies [117, 121] to be associated with a reduced risk of HSI.

Eccentric training overloads the muscle to a greater extent and enhances muscle mass, strength and power more than concentric training [122]. Improvement in knee flexor eccentric strength after 6-10 weeks of knee based eccentric hamstring strengthening are typically 13-19% [112, 123, 124]. Eccentric training in general has also been shown to result in a rightward shift in the torque-joint angle relationship of the knee flexors [125-128], thought due to alterations in muscle fascicle length, which has been shown to increase after eccentric, but not concentrically based resistance training [128]. In particular, a 16-34% increase BF fascicle length following 6-8 weeks of eccentric knee flexor training was reported [119, 128], whilst in one of these studies [119], the authors reported a 6% shortening of BF_{LH} fascicles following concentric only training on the same device. Both low- [129, 130] and high-volume [130-133] programs employing the eccentric-only Nordic hamstring exercise (NHE) observed a 13–24% increase in BF_{LH} fascicle length across a 4- to 10-week training period.

Alterations between isometric and concentric actions versus eccentric actions can occur in part due to altered muscle morphology, but more specifically due to altered neuromuscular activation during eccentric contractions [134]. It is thought after HSI and possibly ACLR with HG, that there is inhibition of the hamstring muscles (specifically the donor/injury site) which results in lower neuromuscular activation during eccentric actions and causes residual deficits in eccentric strength and muscle morphology [26, 75]. As such, although eccentric training may be highly effective, failure to overcome issues associated with hamstring AMI after ACLR, particularly with HG would limit their effectiveness. Thus, eccentric training for the ACLR needs to be considered within the overall functional recovery process.

Evidence suggests that training at longer muscle lengths can achieve similar adaptations in muscle fascicle length to eccentric strengthening. Fascicle length changes for the vastus lateralis were similar after 10 weeks of concentric versus eccentric training at long muscle length [135], whilst 10 weeks of conventional (combined eccentric and concentric contractions) hip extension training at long hamstring lengths resulted in a 13% increase in BF_{LH} fascicle length [132]. Thus, longer length isometrics and concentrics could precede high intensity eccentrics to elicit positive architectural adaptations.

3.3. Balance the use of knee and hip dominant exercises

Although following a knee injury, one may consider hamstring function about the knee, i.e. 'knee flexor strength' to be more important, it is also important to consider hamstring function in conjunction with other muscles (i.e. gluteus maximus, adductor magnus) about the hip, i.e. 'hip extension strength'. Knee flexor weakness is a risk factor for both ACL [29] and future HSI [55, 136]. Interventions aimed at increasing knee flexor strength, particularly eccentric knee flexor strength, have reduced HSI rates, across multiple sports [137-140] and so of course developing knee flexor strength is essential. However, during certain functional tasks, such as the swing phase of sprinting, the moment arm and internal moments at the hip are double that at the knee [141, 142] and the fascicle length of the hamstring muscles (BF mainly) are more sensitive to hip position [143, 144]. Weakness in hip extension strength was identified as a prospective risk factor for HSI in elite level sprinters [145]. Furthermore, weakness of hip extensors may contribute to altered motor patterning in the sagittal plane, leading to increased knee loading motor patterns (Figure 1) [146]. Thus, it is important to consider both knee flexor and hip extensor strength.

[FIGURE 1 NEAR HERE]

As we know, skeletal muscle activation has the potential to influence the functional and structural adaptations to resistance training [132, 147, 148]. There is evidence to suggest that the hamstrings are activated heterogeneously during a range of different exercises [149-154]. Knee dominant exercises (e.g. prone leg curl [151] and NHE [149, 150, 155, 156]) are thought to preferentially activate, as well as result in specific adaptations to chronic exposure to the ST and BF short head. Hip extension exercises (e.g., the stiff-leg deadlift [152] or 45° hip extension exercise [132]) appear to involve to a greater extent and result in more specific adaptations of the semimembranosus and BF_{LH}, as well as at the more proximal regions of the muscle. This reiterates the need for the use of a balanced approach of both knee flexion and hip extension dominant exercises, to target all the hamstring musculature (Figure 2). The specific neuromuscular activation within and between muscles can be modulated during most of these exercises using certain techniques. One example, been changing foot rotation position, which has been shown to selectively upregulate the hamstring muscles, with foot internal rotation increasing activation of the medial hamstrings and foot external rotation increasing the activation of lateral hamstrings [157].

[FIGURE 2 NEAR HERE]

A key consideration after ACLR with HG is whether or not to target the ST. Strong use of knee dominant exercises, indicative of ST specific training, with failed ST tendon regeneration may result in overcompensation of BF_{SH} and altered rotational control about the knee. In this case, targeting the SM with hip dominant exercises to compensate for the ST tendon issues and maintain medial to lateral hamstring muscle balance, may be the superior strategy. However, in the case of ST tendon regeneration, but accompanying AMI, there would appear a need to include specific activation/strengthening exercises for the ST, to provide sufficient stimulus for muscle adaptation. In this case, it is suggested to adopt strong focus on knee dominant exercises using a periodised approach. Actual evidence on this topic is though missing.

3.4. Think about functional and not just isolated strength

Strength is the ability to produce force and is influenced by morphological, biomechanical and neural factors; the contributions of each depend on the strength task [158]. Functional strength is the ability to produce force in situations in which the muscles are commonly used (and injured) [158], whereas isolated strength tasks minimise the degrees of movement freedom and isolate the muscle group of choice, and as such do not mimic the way in which the muscle's function [158]. As described, the hamstring muscles must function during complex tasks to prevent injury, typically eccentrically during acceleration, deceleration and sprinting tasks. These tasks typically require high degrees of fine motor control. There are numerous mechanical and neural differences between isolated force development and force production during these complex sporting tasks. Although isolated strength serves as a 'capacity' to produce force, certain factors may limit the transfer of isolated strength to functional situations. Firstly, Sale [159] likened the expression of strength to a skilled act where agonists must be maximally activated, whilst supported by appropriate synergist and stabiliser activation and opposed by minimal antagonist co-activation. Poor intermuscular coordination, specifically lower than optimal stabiliser muscle recruitment can result in insufficient expression of isolated strength functionally due to agonist and antagonist compensation for dynamic stability, thereby compromising force output [160, 161]. The stabiliser muscle system is becoming recognised as an important contributor to functional strength [161]. There is also evidence that weakness of certain muscles in the lumbo-pelvic-hip or 'core' region may increase the risk of lower limb and/ or ACL [162-168] and hamstring injuries [169-171]. Core stability training has been shown to result in reduced hamstring stiffness, likely due to reduced requirements for the hamstring muscles to compensate as global stabilisers [169]. As well as core 'stability', altered 'pelvic balance' may also contribute to reduced hamstring muscle performance. For example, increased hip flexor tension and reduced hip flexor range of motion (potentially secondary to decreased anterior pelvic stability and compensation) results in both an anterior tilted pelvis and altered intermuscular coordination. Reduced hip flexor range of motion has been associated with reciprocal inhibition of gluteus maximus and synergistic dominance of the hamstrings [172]. Furthermore, an anterior tilted pelvis elicits a stretch on the hamstring muscle resulting in altered length-tension relationship, thereby reducing the ability of the muscle to produce force at longer muscle lengths, typically indicative of injury. This situation would be exacerbated by weakness in hip extension, as well as sacroiliac joint dysfunction [173].

Residual movement impairments are apparent during an array of functional tasks in ACLR patients [174-179]. ACL injury and subsequent reconstruction can lead to altered movement quality of patients bilaterally [176] and has been prospectively linked with elevated secondary ACL injury risk [180, 181]. As such, movement re-training prior to RTS should form an important element of the functional recovery process [8, 9]. Altered movement quality is thought to be due to multiple factors including altered posture (e.g. anterior tilted pelvis, [182, 183]), arthrokinetic dysfunction (e.g. reduced dorsi-flexor range of motion, [184]), muscle imbalances/weakness (e.g. knee extensor weakness, [185]), altered reciprocal muscle inhibition and synergistic dominance [172, 186] and altered proprioception [187, 188]. The hamstring muscles play an important role in supporting optimal lower limb control and alignment [62]. In particular, the medial hamstring are considered important for preventing ACL injury, due to limiting dynamic knee valgus [62], a key movement pattern associated with ACL injury [63, 64].

Alterations in hamstring activation and control have been shown to lead to increased ACL risk. Zebis et al. [189] prospectively linked altered neuromuscular pre-activation of the thigh muscles during a side step cut to ACL injury risk in a cohort of volleyball players during the subsequent 2 years after screening. In particular, a reduced ST to vastus lateralis neuromuscular pre-activation ratio (a 50 ms window prior to ground contact) was associated with elevated ACL injury risk. Muscle pre-activation and feedforward motor strategies are an overlooked but essential aspect of neuromuscular function. ACL ruptures have been shown to occur within 50 ms after ground contact [190]. This is about twice as long as the ACL/ hamstring reflex arc [191]. Thus, the reflex is longer than the injury and therefore, injury prevention in this situation does not rely on feedback processes. Therefore, dynamic stabilisation of joints via muscular pre-activation is essential for joint injury prevention. During movement there is pre-activation of the muscles with recorded surface electromyography (sEMG) values around 125-150 ms before ground contact [189, 192], which allows for the development of tension and thus active stabilisation of joints prior to landing. These sEMG values have been reported to be around 40-60% of maximal sEMG prior to ground contact (10-50 ms time window before foot contact on force platform). A key aspect of hamstring reconditioning for ACL re-injury prevention appears achieving optimal motor patterning during sporting type tasks. The role of dynamic knee valgus in ACL injury mechanisms [193-195] suggests that optimal medial hamstring function, particularly pre-activation is important in preventing ACL injuries [62-64]. Utilising neuromuscular re-training with motor pattern re-learning during sporting type movements to enhance both kinetics (strength/neuromuscular capacity) and kinematics is therefore recommended [8]. Neuromuscular training involving jumping, landing and plyometric type tasks has been shown to both reduce the rate of ACL injuries by half [196] and additionally result in selective upregulated of the medial hamstring muscles [192].

The ability to develop force rapidly, as well as at high muscle speeds are important to produce force during rapid sporting movements. Mechanical stabilisation of the joint to prevent injury, as well as explosive movements such as sprinting involve ground contact times considerably shorter than the time to produce maximal force (50-150 ms vs. 250-300 ms) [197-199]. Additionally, between ~25 and 80 % of the sprint running cycle, the hip is flexing with a peak velocity greater than 700°/s [200], whilst between ~55 and 95 % of the sprinting cycle, the knee is extending with a peak angular velocity greater than 1,000°/s [192]. Deficits in RFD or high-speed strength would be expected to compromise hamstring performance under explosive functional tasks. Thus, it is important to consider the hamstrings ‘explosive’ neuromuscular performance. The ability to generate force rapidly and the associated ability to increase neuromuscular activation from low to high levels [98, 201]. In terms of explosive strength/activation, conventional resistance training such as sustained high force contractions or isoinertial resistance training (even with maximal intention to lift the weight during the concentric phase) has been shown to exert minimal benefits on RFD [97, 98, 160] and no change in early phase neuromuscular activation [98, 160]. This is thought because in response to sustained contractions, the neuromuscular adaptations are specific to the high force aspect of the force-time curve [98, 160, 197]. It appears that for gains in RFD and explosive neuromuscular activation, there is a need for exercises which have rapid increases in force and activation during the task [202]. Most isolated and weight bearing functional tasks involve sustained levels of activation and little explosive element to them. As such, there is a need for some additional tasks to challenge this aspect of neuromuscular function.

We believe a key consideration of effective neuromuscular training is to balance the use of both isolated and functional exercises to enhance muscle strength, address factors influencing movement quality and optimise muscle coordination and motor patterning during foundation and sporting type tasks [9]. Inclusion of corrective lumbo-pelvic-hip training and functional neuromuscular strength exercises, such as foundational tasks (e.g., single leg squat/Romanian deadlift), landing and ballistic drills, plyometrics and agility training is recommended alongside specific isolated hamstring strengthening, as part of a holistic approach to hamstring re-conditioning [158, 203]. It is known that enhanced muscle strength does not directly transfer to enhanced functional performance (kinetics and kinematics) [204-206]. Instead, coordinative changes are required to be able make full use of the enhanced muscle strength [204]. Functional strength exercises require greater coordination and result in task-specific adaptations, due to neural adaptations [160]. They can also support the enhancement of isolated strength, providing sufficient neuromuscular activation and work volumes [161]. Furthermore, tasks such as landing, plyometric tasks and sporting specific movements will challenge inter- and intramuscular coordination, and when performed with appropriate technique and biofeedback aid in optimising coordination and patterning during these tasks [207]. Regaining symmetry in high load sporting tasks may be associated with lower re-injury risk [208].

A weakness of most functional tasks is that they achieve relatively low levels of neuromuscular activation of the hamstring musculature versus other more isolated exercises [149] So, they will not provide the necessary stimulus for the necessary neuromuscular adaptations. Although isolated strength tasks such as the seated leg curls or NHE (knee dominant) or 45º hip extension/bridge exercises (hip dominant) lack specificity and transference to functional exercises/ movement [205], they are considered important for hamstring strengthening. They effectively remove the need for voluntary stabilisation of joints and/or synergistic control of force direction (and thus the need for optimal synergist and/or stabiliser muscle recruitment) and are excellent to target a specific muscle group in isolation. Therefore, they can be highly effective in the presence of specific muscle weakness or inhibition, or when load compromised during the early periods after ACLR. Thus, we recommend a combination both strength and neuromuscular training exercises to optimises neuromuscular function and motor control [209].

4. Summary and recommendations for implementation – Functional recovery of hamstrings over the ACL reconstruction programme

Although there is no consensus on the functional recovery process after ACLR, recent work has been devoted to standardising the ACL rehabilitation journey. Current best practice for ACL rehabilitation appears to involve criterion-based rehabilitation through a series of stages [8, 9, 210]. The functional recovery process can be broadly separated into pre-operative, early, mid and late stage rehabilitation and RTS training (Figure 3) [8, 9]. It is important that the hamstring strengthening approach is placed in context of the overall goals of the program. These include restoring knee function (e.g., pain, swelling, range of motion) as well as neuromuscular function (e.g., maximal isolated and functional strength and explosive neuromuscular performance) of many muscle groups of the lower limbs. Hamstring re-conditioning after ACLR is not as simple as using a series of progressive hamstring exercises, but instead recognising the health status of the athlete, understanding how to train the hamstrings, and knowing how this hamstring conditioning approach needs to be adapted to the ACLR athlete depending on their specific level of functionality.

[FIGURE 3 NEAR HERE]

In general, we recommend a holistic approach to hamstring conditioning [158, 203], after ACLR. This approach should focus on all aspects of function (e.g., neural and morphological and mechanical factors) and respect the unique neuromuscular benefits of different exercises. There are differing levels of functional tasks, including weight-bearing, high load control (landing, jumping/ plyometric) and sport-type/specific (speed, change of direction and agility) tasks (Figure 4) and they can be characterised according to the level of intensity and specificity. In terms of intensity, it is important to consider both the external joint loading (e.g., peak ground reaction forces, rate of force acceptance/production and volume loading), as well as the internal joint torque/ moments and muscle activation. Each task may have unique benefits at a particular time of the recovery process, and so knowing when to use which task and in which way is a key aspect of the ‘art’ of rehabilitation/ re-conditioning. Table 2 contains our recommendations on hamstring conditioning after ACLR, using a criterion-based approach, with specific stage goals and hamstring goals after ACLR. There is a progressive transition from low to high load, static to fast dynamic, isolated to functional, and isometric to eccentric. Below we provide suggestions for hamstring functional recovery after ACLR with HG across the progressive stages, tailored for ACLR with HG.

[FIGURE 4 NEAR HERE]

[TABLE 2 NEAR HERE]

Early stage: Early stage rehabilitation 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 [9, 211] Deficits in knee flexor isometric force of nearly 50% have been reported at 4 weeks after ACLR [19], which generally coincides with a transition from early to mid-stage rehabilitation [9]. Minimising knee flexor strength deficits during the early stage would make strength recovery much easier during the subsequent mid-stage stage of rehabilitation. Current recommendations are to delay specific strengthening of the hamstrings after ACLR with HG for 6–8 weeks [105-107] to facilitate appropriate donor site recovery. However, we advise use of isometric/concentric exercises of low intensity at short-medium muscle lengths. It is important during this stage though to avoid strenuous activities which may potentially result in damage to the graft.

Mid stage: The mid-stage has been described as having three primary goals, 1) resolution of large muscle strength asymmetries; 2) restoration of movement quality during foundation motor tasks (weight-bearing functional tasks and jogging on treadmill) and physical fitness reconditioning [9]. In terms of hamstring rehabilitation, the mid-stage aims to adopt a relatively simple programme to overcome large (typically 50%) [19], knee flexor deficits on a load compromised knee. A key goal in mid-stage, is to restore knee flexor maximal strength to within at least 20% of the contralateral limb [8, 9]. This is typically done alongside some basic motor patterning restoration (e.g., functional exercises such as squat and running gait) [9], which will facilitate appropriate motor patterning on which to utilise a stronger functional strengthening approach during the late-stage. Recently, we discussed how to optimise the mid-stage after ACLR in general [9] and suggested separating mid-stage into a first and second half. The first half in regards to hamstring conditioning would use low-to moderate loads, potentially conjunction with supplementary modalities, such as blood flow restriction training to restore muscle volume and work capacity [9]. A balance of both knee and hip dominant exercises is recommended, with a focus on isometric or concentric actions. Progression to the second half is based on clinical experience as opposed to specific criteria [9], but involves a transition to both isolated and functional exercises at moderate loads (6-12 RM), in order to maximise muscle volume and reduce muscle strength deficits. Emphasising optimal technique is essential during functional exercises to ensure positive motor control adaptations [9, 207].

Late-stage and RTS training: The late-stage rehabilitation and RTS programme involves a stronger emphasis on hamstring functional recovery. Recent work by Buckthorpe [8] provides a framework for late-stage rehabilitation and RTS training involving 5 progressive stages. In general, 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 [8, 10]. In particular, the program using a balanced approach of high load isolated strengthening, functional strength exercises, motor patterning re-training and on-field reconditioning [9]. It aims to optimally prepare an athlete safely for RTS at low risk of re-injury and in terms of hamstring function, aims for i) full normalisation of 'isolated knee flexor and hip extensor muscle strength'; ii) optimisation of hamstring control during sporting-type tasks; iii) full restoration of eccentric strength at long muscle lengths and iv) restoration of maximal and explosive strength across all velocities.

Restoring explosive muscle performance is a key aspect of late-stage rehabilitation and RTS training. One training modality which has received little attention in functional recovery after ACLR but has done so more recent for HSI rehabilitation/prevention, is used of high speed running [158, 203, 212, 213]. Running (high speed and sprinting) has both high specificity and intensity, both in terms of the resultant ground reaction forces and hamstring specific muscle work and neuromuscular activation and may support optimisation of hamstring neuromuscular function (e.g., strength, RFD, power) and motor patterning. The evidence on the use of high speed/sprint running indicates similar gains in eccentric maximal muscle strength versus the NHE [214]. Sprint running has been shown to result in the highest neuromuscular activation of the hamstring musculature, with other exercises such as NHE amongst others shown to only achieve 18 to 75% of the EMG activation during sprinting [215]. High speed/ sprint running demands high internal forces of the hamstrings (up to 9 $Nm.kg^{-1}$), which is dependent on the running speed [216]. The amount of kinetic energy absorbed in the limb is proportional to the running speed squared, such that the negative work done (energy absorbed) by the hamstrings increases substantially with running speed [217]. Furthermore, the hamstring work was shown to double from 7 $m.s^{-1}$ to 9 $m.s^{-1}$ [216]. High speed/sprint running is considered problematic for hamstring muscles (i.e., mechanism for injury) [218, 219] but if used appropriately considered essential for HSI prevention [203]. We suggest it forms a major element of the hamstring re-conditioning during RTS, which may support a reduction in HSI reoccurrence upon RTS [220] and improve athletic/sprint performance [214].

RTS testing: We recommend screening hamstring function after ACLR. As described, hamstring strength deficits have been prospectively shown to possess the highest risk factor for ACL re-injury after ACLR [29]. However, assessing knee flexor function does not form part of the standard ACL RTS testing, which typically involves i) time; ii) knee function; iii) hop testing and sometimes iv) isometric or isokinetic knee extensor testing [29, 111, 221]. Buckthorpe [8] proposed more stringent criteria for RTS after ACLR to improve the sensitivity and specificity [8]. Although, more comprehensive investigations could be made, ensuring restoration of 90% LSI knee flexor strength and 60% knee extensor/flexor ratio is recommended for all patients after ACLR. Furthermore, considering the absolute strength is recommended, with a 1.5 $Nm.kg^{-1}$ knee flexor peak torque advised prior to RTS (assessed isokinetically at 90º s-1) (e.g., 60% of 2.5 Nm kg^{-1} for knee extensors) [8, 9]. Further assessing the knee flexor strength either isokinetically (eccentric flexor to concentric extensor peak torque > 1 and/or eccentric peak torque >2.5 Nm kg^{-1}) or using the NordBord (LSI >90% and peak torque >350 N) [203, 222] is recommended where possible. Assessment of knee flexor absolute and relative (to body mass and knee extensors) RFD may be useful, but clinically challenging [8, 202]. Achieving peak running speeds during on-field rehabilitation (and quantifying with GPS technology and/or speed gates where possible) is also recommended. It is important though that there is a greater appreciation of the importance of hamstring function in ACL re-injury prevention and that sufficient time and quality of work is devoted to the recovery of hamstring function prior to RTS.

5. Conclusion

The hamstrings are important for the ACL and knee as a whole. After ACLR and more so when using the hamstrings as the choice of graft, their recovery during the functional recovery process is important. Failure to recover strength of the hamstring muscles may compromise knee health and elevate re-injury risk upon RTS. This is likely due to inability to compress and stabilise the knee and prevent alterations in frontal and traverse plane knee control, known to stress the ACL. It is suggested to emphasise greater importance on the recovery of hamstring strength after ACLR, and here is presented some important considerations. It is recommended to utilise a holistic approach to target the recovery of both knee flexor and hip extensor strength as well as multiplanar function. This should involve a periodised resistance training program aligned to the ACL functional recovery approach. A progressive approach from isolated low intensity to functional and high intensity training aligned to the overall knee status is recommended with screening of hamstring function as part criterion based functional recovery and RTS.

Compliance with Ethical Standards

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The authors declare they have no conflicts of interest relevant to the content of this review.

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Figure legends

Figure 1. An example of a knee/quadriceps dominant movement strategy with upright trunk, resulting in greater knee load. This is most commonly associated with the knee excessively positioned anterior to toes (A). An optimal movement strategy balancing hip and knee contributions, with the knee slightly but not excessively over the toe and similar hip and knee flexions (B).

Figure 2. Examples of knee dominant hamstring exercises, A) Nordic hamstring exercise, B) swiss ball single leg roll outs and C) isokinetic knee flexion as well as hip dominant hamstring exercises D) single leg stiff leg loaded deadlift, E) single leg bridge on box (<90° knee flexion) and F) rear foot loaded elevated split squat (as an example of weight bearing functional exercises, not specifically hamstring dominant exercises).

Figure 3. The functional recovery processes after ACL reconstruction. Modified from Buckthorpe and Della Villa [9].

Figure 4. The four exercise categories to support exercise selection after ACL reconstruction including neuromuscular re-activation exercises, high load isolated strength exercises, foundation and high load (jumping/ landing) motor re-patterning and speed and agility exercises. Each exercise will have differing loading properties and stimuli for neuromuscular adaptation.