11 Return to Running After Anterior Cruciate Ligament Reconstruction

Alessandro Compagnin, Marco Gastaldo, and Francesco Della Villa

11.1 Introduction

Anterior cruciate ligament (ACL) injury is one of the most common and devastating knee injuries in pivoting and contact sports [1]. With an annual incidence of 68.6 injuries per 100,000 person-years, more than 200,000 ACL tears occur in the United States annually (incidence rates of ACL injuries vary between populations being studied) [1, 2]. ACL surgery is often performed as a first-line treatment after the injury. Anterior cruciate ligament reconstruction (ACLR) is the predominant method of surgery in current practice and hundreds of thousands of these surgeries are performed every year [3]. Despite being one of the most studied and discussed topic in the Sport Medicine literature, no consensus has been reached about many aspects of this recovery process and it is well established that outcomes after ACLR are far from being perfect [4].

Because of the nature of the majority part of the sports that are practised nowadays (e.g., football, basketball, etc.), running is considered a foundational task for every athlete involved in those activities (most sports require the player to be able to run) [5]. Return to running after ACLR is considered by the athlete and the rehabilitation team a milestone in the recovery process but, although the importance of running is well established in the rehabilitation community, there is not a consensus on the pathway that has to be followed to allow a patient to return to run successfully. A correct and thorough running implementation can represent a useful training stimulus for the athlete but on the other hand, if introduced too early or with the wrong progression, it can pose a threat for the athlete's recovery process. To bridge the gap between research and practice, and to optimize the outcomes after ACLR, there is the need to provide clinicians who work with ACL injured patients a clear criteria-based progression for running implementation. To guide the patient in the return to running process, a deep understanding of the running demands (biomechanics, forces to be absorbed, different running types, etc.) and the patient's injury and current condition (injured body area, biological healing time, athlete's physical profile, etc.) is paramount.

Therefore, the aim of this chapter is to provide a clear understanding of the running biomechanics, analysing the features of the ACL injury and

A. Compagnin
Isokinetic Medical Group, FIFA Medical Centre of Excellence, London, UK
e-mail: a.compagnin@isokinetic.com

M. Gastaldo
Isokinetic Medical Group, FIFA Medical Centre of Excellence, Turin, Italy
e-mail: m.gastaldo@isokinetic.com

F. Della Villa (✉)
Education and Research Department, Isokinetic Medical Group, FIFA Medical Centre of Excellence, Bologna, Italy
e-mail: f.dellavilla@isokinetic.com

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consequential reconstruction, to present an easily implementable checklist to utilize before allowing a patient to resume running and to provide a clear rehabilitation progression to help the clinician achieving those goals with ACL reconstructed patients.

11.2 The Demands of Running

The decision of introducing a new task during the rehabilitation process of an athlete should be based on the analysis of that task demands and the athlete's envelope of function as described by Dye in 1996 [6]. The envelope of function can be defined as the range of load that can be applied across an individual joint in a given period without reaching a supraphysiologic overload or structural failure [6]. In other words, this envelope indicates the load tolerance of a specific joint determined by multifactorial elements (anatomical, kinematic, physiological, etc.). Indicators that an imposed task demand is superior to the athlete's joint envelope of function can include pain, discomfort, functional instability, effusion, warmth and tenderness [6]. Failure to match the task demands and the athlete's load tolerance may result in exposing the athlete to tasks which they are not prepared for. In order to prevent this to happen, it is important to fully understand and quantify the demands of the task in terms of level of loading that may be placed on the body, and estimate the load tolerance of the athlete. Starting from the analysis of the task, the level of loading of a specific activity can be considered as:

– Peak loading (e.g., peak ground reaction forces) [5];
– Volume load (e.g., load times repetition) [5];
– Rate of loading (e.g., time over which it is delivered/experienced) [5].

Biomechanical studies reported that for every step taken during running, the weight acceptance of the athlete is estimated to be around 2–3 times the athlete's body mass [7]. It is important to stress that the ground reaction forces are variables depending on many modifiable and non-modifiable factors such as running biomechanics (modifiable) [8, 9], footwear and orthotics (modifiable) [8, 9], environment and running surface (modifiable) [8], athlete strength (modifiable), running speed (modifiable), athlete biological characteristics like age, height, etc. (non-modifiable). A variation on the previously mentioned parameters could potentially change both the force-time and centre of pressure patterns, influencing in this way the task total load.

11.3 Criteria to Return to Running After ACLR

Once the task demands are clear, it is time to better understand the load tolerance of the athlete to implement the right activity at the right moment. An accurate assessment of many aspects of the athlete is paramount to create the "athlete profile" and understand if the patient is ready or not to resume running. There is not a consensus in the current literature about which criteria should be achieved before allowing a patient to return to running. This lack of support by the current evidence on the topic leaves the clinicians without safety guidelines to follow in order to implement a safe and effective return to run process.

In a recent scoping review, Rambaud et al. (2018) reported that in deciding when a patient is ready to return to running, time-based criteria after ACLR was the most cited criterion [10]. The median time from which return to run was permitted was 12 postoperative weeks [10]. There are many consequences of different nature that can arise from this choice:

1. *Risk of harming the athlete*: the ability to perform specific tasks like running is not only related to the time that has passed since the surgery, but more specifically to the patient's function [4], strength, mobility, movement quality, etc. If a patient's load tolerance is not trained enough to accept the force generated by the running, the athlete will be exposed to overload and risk of injury;
2. *Athlete's psychological failure*: when a specific time frame has been communicated to

the athlete, that date becomes a fixed point for the patient. Depending on multifactorial elements (e.g., surgery characteristics, rehabilitation process, level of the athlete, etc.), every patient has a different rate of progression and will achieve different training targets at different times. If the criteria to allow a patient to return to run post ACLR is only based on time, and the patient is not able to run at that specific moment in time, the athlete will likely think that they are "failing" since running is still not possible [5].

Time-based criteria are selected arbitrary and do not reflect the athlete's function and readiness to run. Fewer than 1/5 studies reported clinical, strength or performance-based criteria for return to running, even though the best evidence recommends performance-based criteria combined with time-based criteria to commence running activities following ACLR [7]. A shift from time-based to criteria-based rehabilitation approach is necessary during the ACL rehabilitation process. Different papers presented multiple objective criteria that should be achieved before allowing a patient to return to run. The criteria presented in those articles can be divided into five different categories (see Table 11.1 for more information about the Return to Running criteria after ACLR) that are suggested to be achieved before allowing a patient to return to run:

11.3.1 Joint Homeostasis

Goals: Absent or minimal pain on a numerical rating scale (NRS, ≤3) during walking [11, 12], zero or trace effusion [4].

The "quiet knee" is a knee that does not show (or shows in minimal part) typical signs of inflammation (pain, redness, heat, swelling and loss of function). Pain and swelling can result in arthrogenic muscle inhibition (AMI), a complex and multifactorial neurophysiological phenomenon that hinders optimal recruitment of the knee spanning muscles (especially knee extensors), limiting the ability of the athlete to produce force. Before starting to run it is suggested to minimize pain and reach a minimal activity related effusion status (≤1 cm change at the supra patella circumferential measurement in response to activity) [18].

11.3.2 Knee Mobility

Goals: Full knee extension (straight knee, equal to the other side) and ≥120°/130° of knee flexion [4, 5, 11, 12].

Restoring joint range of motion (flexion and extension) is paramount during the rehabilitation process. Even small knee extension deficits as little as 3° appear to adversely affect post-surgical subjective and objective outcomes after ACL reconstruction [19, 20]. Depending on the running speed and technique, knee flexion angles can reach values as high as 120° of knee flexion. Restoring knee joint mobility is critical for the recovery of optimal gait and running biomechanics.

11.3.3 Gait Biomechanics

Goals: Walk on a treadmill for at least 10 min without pain or swelling [12] and with an optimal biomechanics.

Abnormal gait patterns have been associated with muscle weakness, decreased functional performance, low patient satisfaction outcomes after surgery and with post-operative complications including osteoarthritis [5]. Abnormal gait patterns often become further exacerbated when the patient returns to running. Re-establishing normal gait early and safely after surgery is a key priority [5].

11.3.4 Strength

Open kinetic chain strength goals: Limb Symmetry Index (LSI) for Quadriceps and Hamstrings Strength ≥70% assessed by isometric or isokinetic knee extension and flexion [4, 5, 10].

Closed kinetic chain strength goals: Single leg closed kinetic chain peak strength of at least 1.25 times body mass on leg press [4, 5].

Table 11.1 Recommended criteria for running implementation after anterior cruciate ligament reconstruction. Each outcome measure, specific test and published reference are included, as well as the goal to achieve in order to allow the patient to start to run

Category	Outcome measure	Test	Goal
Joint homeostasis	Pain	Numeric Rating Scale (NRS)	Absent or minimal pain on a numerical rating scale (NRS) (NRS <3) during walking [11, 12]
	Effusion	Stroke test	Zero or trace effusion [4]
		Knee circumference measurements [13]	Minimal activity related effusion (<1 cm change patella)
Knee mobility	Extension	Prone hang test [14]	Straight knee (0°). The heel height difference is measured (approximately 1 cm = 1°)
			Equal to the other side
		Supine with a long-arm goniometer	Straight knee (0°). Bony landmarks: greater trochanter, lateral femoral condyle, and lateral malleolus.
	Flexion	Supine/prone with long arm goniometer	Knee flexion ≥120°/130° [4, 5, 11, 12]
Gait biomechanics	Walk assessment	Visual or 2D assessment of walking gait	Walk on a treadmill for at least 10 min without pain or swelling [12] and with an optimal biomechanics
	Thigh muscles, open kinetic chain (OKC) strength	Isokinetic strength assessment of quadriceps and hamstrings muscles [4]	Limb Symmetry Index (LSI) for Hamstrings and Quadriceps strength ≥70% [1, 4, 5]
		Isometric strength assessment of quadriceps and hamstrings muscles [4]	Limb Symmetry Index (LSI) for Hamstrings and Quadriceps strength ≥70% [1, 4, 5]
	Closed kinetic chain (CKC) muscle strength	Leg Press Test [4]: 90° knee flexion and seat at 45°, maximal weight achieved for 8 RM test	Single limb closed kinetic chain peak strength of at least 1.25 times body mass on single limb leg press [4, 5] or 1.5 × BM predicted 1 RM [4]
Strength	Calf capacity	Single leg heel raises [15]: The athlete stands on one foot on the edge of a step and performs a heel raise through full ROM. Heel raises are performed at 1 repetition every 2 s [4]. The test is concluded when the subject is unable to move through the full range or slows below the cadence [4]	Greater than 20 reps and within 5 repetitions versus the other side [4]
	Gluteal muscle capacity	Single leg bridge test (variation [16]): The athlete is supine with 90° knee flexion angle, one foot on the floor and arms crossed on the chest. The subject lifts the hips from the floor to neutral hip position and then returns down to the ground [4]. The test is concluded when the subject cannot reach the height or gives up [4]	Greater than 20 reps and within 5 repetitions versus the other side [4]
Functional outcomes	Movement quality assessment	Single Leg Squat [4, 17]: Squat to at least 60° of knee flexion, minimal trunk motion, minimal pelvic motion and no hip adduction nor internal rotation [4]	Good movement quality (no zeros and score greater than 6) [4]

Accessory muscles strength: Optimal work capacity of glutes and calf muscles [11, 12] (single leg calf raises [15] and glutes bridges [16] capacity test greater than 20 reps and within 5 repetitions versus the other side [4]).

Lower limb weakness (in particular of the knee extensor compartment) alters biomechanics, reduce functional performance, and may be linked to poorer return to sport outcomes [4]. Extensive research indicates that most patients are unable to sufficiently restore quadriceps strength after ACLR at the moment of return to running and sport.

Restoring isolated or analytic strength of knee flexors and extensors muscles is only one of the many components of the strength recovery process after ACLR. Running and most of functional activities are performed in a closed kinetic chain fashion and for this reason, assessing and recovering closed kinetic chain strength is necessary to allow a gradual progression to more demanding activities. The ability to perform functional tasks involves the neuromuscular system in the production, transmission and dissipation of the ground reaction forces via the neuromuscular system. Inability to absorb those forces through the neuromuscular system (e.g. insufficient functional eccentric muscle strength of the lower limb) would result in movement compensations and/or overreliance/acceptance of the passive restraints such as ligament, joint complexes, and fascial system, potentially resulting in overload and/or acute injuries. Developing and testing the athlete's lower limbs ability to produce and accept force can provide the necessary foundation and understanding on when the athlete may be ready to return to run ACLR.

Optimization of the gluteal musculature is needed to be able to control movement patterns, especially during single-leg activities [21]. The tri-planar function of the gluteus maximus and gluteus medius (abduction, extension, external rotation) serves to control femoral adduction and internal rotation and to produce hip extension, thereby protecting the knee from high-risk positions that increase ACL strain [21]. Deficits in hip muscle strength after ACLR have been reported in the literature [22]. 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 [4]. A lack of appropriate neuromuscular control and strength of the gluteal muscles has been related to high-risk landing strategies during single-leg activities [21]. 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 is recommended [4].

Calf muscle strength is important for load acceptance and propulsion. Biomechanical studies found that the soleus muscle contributes the most muscle force production during running at speeds up to 7 m s^{-1} [23] and that the ankle eccentrically accepts up to 50% of the impact forces from landing [24]. During single-leg drop landing task, the muscles that generated the greatest posterior shear force have been reported to be the soleus, medial hamstrings, and biceps femoris [25]. Since ACL injury occurs promptly after initial contact, the soleus may be particularly important for reducing the likelihood of ACL injury, as it makes a more substantial contribution to the posterior shear joint reaction force during the first 25% of the landing phase [25]. Reduced ankle plantarflexion strength is likely to affect both load absorption and propulsion significantly during running gait [18] and potentially lead to compensatory strategies in functional activities such as running.

11.3.5 Functional Outcomes

Goal: "Good" movement quality on Single Leg Squat testing [4, 17].

Squatting movement can be defined as the foundational exercise for the majority part of the most practised sport nowadays. The Single Leg Squat (SLS) variation involves a triple extension-flexion movement performed on one leg. To optimally execute a single leg squat, the athlete must have sufficient lower limb strength (the movement involves supporting and moving the whole bodyweight up and down), balance (in order to stay on one leg), and neuromuscular control to execute the movement with a proper technique (motor strategy and lower limb/pelvis/trunk alignment). Poor single leg squat performance is associated with poor biomechanics in more complex tasks as this forms the motor pattern foundation for many tasks involving single leg stance and triple flexion and extension [4].

11.4 Return to Running Progression

Return to running after anterior cruciate ligament reconstruction (ACLR) is a long and intricate process that has to be carefully pre-planned and tailored on the patient in order to optimize the outcomes of ACLR rehabilitation. As previously stated in the preceding section, the patient must achieve many different goals to be allowed to resume running in a safe and effective way. To achieve those goals with the patient, the medical team has to identify the rehabilitation priorities (in accordance with the current rehabilitation stage) and address them keeping in mind the upcoming new priorities. In this section, the authors will present a series of rehabilitation strategies (Table 11.2) that can be implemented to achieve the previously mentioned goals and bring the patient back to running.

11.4.1 Pain (Knee Homeostasis): Absent or Minimal Pain on a Numerical Rating Scale (NRS)

The sources of pain after ACLR can be many and dealing with pain is one of the priorities of the early-stage rehabilitation [27, 38]. When a specific load imposed to a joint is greater than the joint's loading ability to handle that load, pain is one of the body signals that indicate this overload. Pain can be used to determine task and exercise progression, as these factors will relate to the loading stress experienced by the knee [39]. Dealing with pain is necessary during the ACLR rehabilitation process and, in order to do so, clinicians can utilize different strategies (Fig. 11.1): (a) temporary decrease the load imposed to the joint; (b) increase the load tolerance of the joint; (c) temporary decrease the pain by the use of cryotherapy [40] or transcutaneous electrical nerve stimulation (TENS) [29, 41]. Progression to a more demanding task or exercise is allowed only when increase of pain is not reported by the patient (numeric rating scale) as response to previous tasks [5].

11.4.2 Effusion (Knee Homeostasis): Zero or Trace Effusion [4] with Minimal Activity Related Effusion (<1 cm Change Patella)

Swelling and subsequent changes in knee circumferences after a task are signs of joint overload. Managing swelling is necessary during the ACLR rehabilitation process and these are some suggested strategies by the authors that can be implemented by the clinicians to do so (Fig. 11.2): (a) use of cryotherapy (there is a debate in the literature regarding the effects of ice on joint swelling and more evidence is needed); (b) joint elevation; (c) stimulate the "muscle pump action" with movement and exercise therapy; (d) knee load management and monitoring [5]; (e) lymphatic massage; (f) hydrotherapy [26].

11.4.3 Knee Extension and Flexion (Mobility): Straight Knee (0°) or Equal to the Other Side and Knee Flexion ≥120°/130°

Regaining full knee extension is a priority in the early-stage of rehabilitation as it can reduce pain, stimulate joint homeostasis, help to prevent the formation of scar tissue and capsular retractions that may limit joint mobility [40] and allow the patient to regain a normal gait pattern. Even small knee extension deficits as little as 3°

Table 11.2 Suggested rehabilitation strategies in order to achieve the desired goal and allow the patient to return to run. Each outcome measure, specific goal, and published reference for supporting the suggested rehabilitation strategies are listed in the following table

Outcome measure	Goals	Rehabilitation strategies
Pain	Absent or minimal pain on a numerical rating scale (NRS) (NRS <3) during walking [11, 12]	Temporary decrease the load imposed to the joint
		Increase the load tolerance of the joint
		Temporary decrease the pain using cryotherapy
Effusion	Zero or trace effusion [4]	Use of cryotherapy (there is a debate in the literature regarding the effects of ice on joint swelling and more evidence is needed)
		Joint elevation
	Minimal activity related effusion (<1 cm change patella)	Stimulate the "muscle pump action" with movement and exercise therapy
		Knee load management and monitoring
		Lymphatic massage Hydrotherapy [26]
Knee extension and flexion	Full knee extension (straight knee, equal to the other side) [5]	Low-load—long-duration mobility exercises performed multiple times per day [27] Manual therapy (patella mobility and terminal knee extension or flexion)
	Knee flexion >120°/130°	Active exercise at the end of the range of motion
Walking biomechanics	Walk on a treadmill for at least 10 min without pain or swelling [12] and with optimal biomechanics	Full knee extension [5, 11, 28]
		Good quadriceps muscle activation (no quadriceps lag on active straight leg raise [5])
		Minimal and non-reactive swelling to activities [5, 11, 28]
		Good neuromuscular control of the gait movement [5, 11, 28]
		Gradual increase of the knee walking volume
Quadriceps muscle strength	Limb Symmetry Index (LSI) >70% on Isokinetic/Isometric Test [4, 5]	Quadriceps analytic exercises (OKC and safe implementation) [28, 29]
		Use of modalities (neuromuscular electrical stimulation (NMES [4] and blood flow restriction training (BFR) [4, 29–31]
		Implementation of a periodized approach to strength training [29]
		Cross-education phenomenon [32–35]
		Gradual implementation of CKC exercises targeting the thigh musculature
Hamstrings muscle strength	Limb Symmetry Index (LSI) >70% on Isokinetic/Isometric Test [4, 5]	Low-intensity hamstring exercises initiated in the early-stage of rehabilitation followed by progressive overload [36]
		Use of modalities (NMES and BFR) [36]
		Medial to lateral hamstrings balance [36] training all hamstrings functions (hip extension, knee flexion and knee rotations)
		Full ROM strengthening exercises (especially deep knee flexion angles where the strength deficit is more accentuated)
		Progressive eccentric strength training [36]
Calf strength and capacity	Greater than 20 reps and within 5 repetitions versus the other side [4]	Calf muscle strengthening (Gastrocnemius and Soleus)
		Anti-pronation muscles strengthening

(continued)

Table 11.2 (continued)

Outcome measure	Goals	Rehabilitation strategies
Glutes strength and capacity	Greater than 20 reps and within 5 repetitions versus the other side [4]	Restore optimal lumbo-pelvic stability and balance [37]
		Strengthen the gluteus muscles [55] training all the most important gluteal functions (hip extension, abduction, and external rotation);
		Re-integrate the gluteal muscle into the motor pattern [37]
Closed kinetic chain muscle strength	Single leg closed kinetic chain peak strength of at least 1.25 times body mass on single limb leg press [4, 5]	Closed kinetic chain strength training
		Strengthening of all the lower limb muscles contributing to CKC force production
Movement quality	Good Single Leg Squat Movement Assessment [4, 17]	See Fig. 11.10 for an example of task intensity progression suggested to gradually reach the demands of the single leg squat

Fig. 11.1 Examples of suggested rehabilitation strategies to implement to decrease pain. *TENS* Transcutaneous electrical nerve stimulation

Fig. 11.2 Examples of suggested rehabilitation strategies to implement to manage the swelling

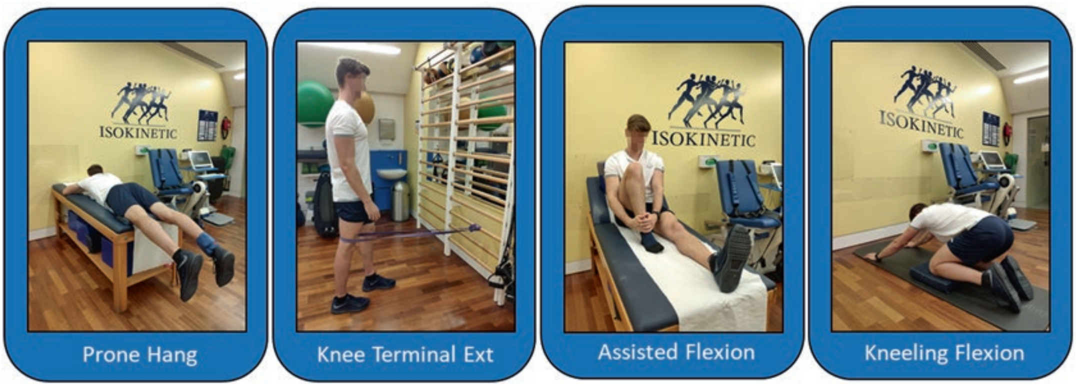

Fig. 11.3 Examples of suggested rehabilitation strategies to implement to recover the knee full mobility. The first couple of exercises can be used to recover the passive and active knee extension. The second couple of exercises can be used to improve the passive knee flexion. *Ext* Extension

appear to adversely affect post-surgical subjective and objective outcomes after ACL reconstruction [19, 20]. Although the initial primary focus of the early-stage rehabilitation is on obtaining full knee extension, the recovery of knee flexion is still key in order to maximize the outcomes after ACLR, but it is achieved in a much more gradual manner [27]. To recover full knee mobility after ACLR the following strategies can be implemented (Fig. 11.3): (a) low-load—long-duration mobility exercises performed multiple times per day [27]; (b) manual therapy (patella mobility and terminal knee extension or flexion); (c) active exercise at the end of the range of motion.

11.4.4 Walking Biomechanics: Walking on a Treadmill for At Least 10 min Without Pain or Swelling [12] and With Optimal Biomechanics

Untreated abnormal gait patterns can hinder the return to run process and the global outcomes of ACLR rehabilitation. Walking is a functional activity that can be optimally restored only if full knee extension is achieved [5, 11, 28], good quadriceps muscle activation is reached (no quadriceps lag on active straight leg raise [5]), swelling is minimal and non-reactive to activities [5, 11, 28] and good neuromuscular control of the gait movement is showed [5, 11, 28]. To restore walking, the previously stated criteria should be met. Allowing a patient to start to walk with sub-optimal biomechanics can lead to increase in running compensatory strategies at the time of return to running. Once these goals have been achieved, walking tolerance can be developed gradually increasing the walking volume (Fig. 11.4).

11.4.5 Quadriceps Muscle Strength: Limb Symmetry Index (LSI) >70% on Isokinetic/Isometric Test for Quadriceps Strength [4, 5]

After ACLR, strength recovery is one of the main obstacles that patients encounter during the rehabilitation process. The traumatic effects of injury and subsequent surgery result in large deficits in the thigh muscle (especially knee extensors muscles) volume, neural activation and strength. Failure to achieve less than a 20% difference versus the contralateral limb is common at 6-month post-ACLR [42]. 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 (conventional LSI) [43].

Fig. 11.4 Examples of suggested rehabilitation strategies to implement to improve walking mechanics and tolerance

To improve the outcomes of ACLR rehabilitation process, full strength recovery has to be achieved. Limiting the strength loss between injury and surgery with the implementation of pre-operative treatment is showing promising results in the literature [28, 29, 44]. Following a structured rehabilitation plan after ACLR is necessary to completely restore the strength-velocity curve after the surgery. Strategies that can be implemented after ACLR in order to recover the strength are the following (Fig. 11.5): (a) quadriceps analytic exercises (OKC and safe implementation) [28, 29]; (b) use of modalities (neuromuscular electrical stimulation (NMES) [4, 28, 29, 45] and blood flow restriction training (BFR) [4, 29–31]; (c) implementation of a periodized approach to strength training [29]; (d) cross-education phenomenon [32–35]; (e) gradual implementation of CKC exercises targeting the thigh musculature.

11.4.6 Hamstrings Muscle Strength: Limb Symmetry Index (LSI) >70% on Isokinetic/Isometric Test for Hamstrings Strength [4, 5]

The hamstrings muscle complex is vitally important for the knee since this muscle group can be defined as ACL agonists (their contraction decreases ACL strain). The hamstrings muscles have many functions but of particular interest after ACLR (especially with hamstrings graft) is the function of the medial hamstrings in preventing medial condyle lift-off and dynamic knee valgus, a known ACL injury risk factor [36, 46]. Strategy to restore hamstrings strength before allowing a patient to return to run include (Fig. 11.6): (a) low-intensity hamstring exercises initiated in the early-stage of rehabilitation followed by progressive overload [36]; (b) use of modalities (NMES and BFR) [36]; (c) medial to lateral hamstrings balance [36] without neglecting any of the hamstrings functions (hip extension, knee flexion and knee rotations); (d) full ROM strengthening exercises (especially deep knee flexion angles where the strength deficit is more accentuated); (e) progressive eccentric strength training [36].

11.4.7 Calf Strength and Capacity: Greater than 20 Reps and Within 5 Repetitions Versus the Other Side [4]

Plantarflexion strength and work capacity importance has been extensively discussed in the previous section and enhancing the strength of the calf

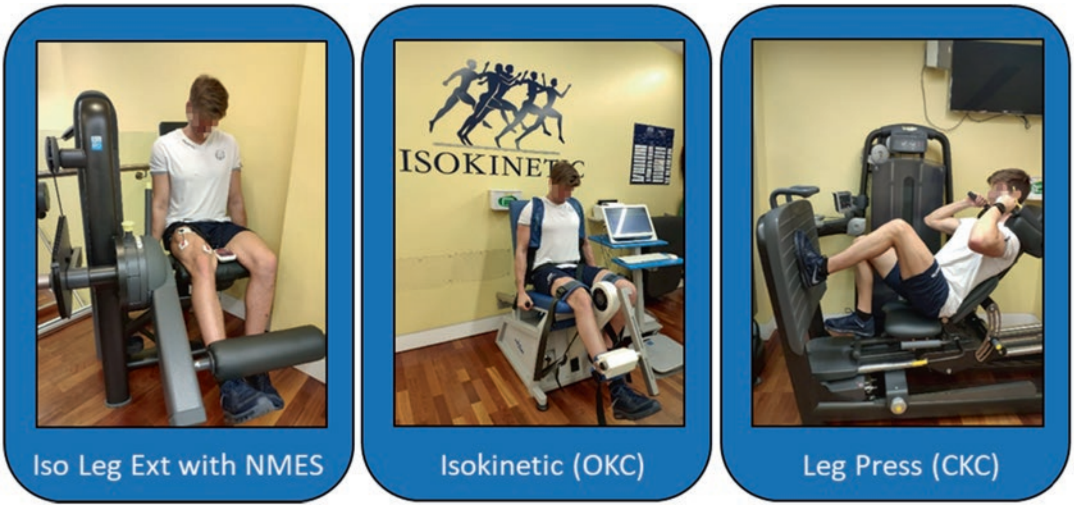

Fig. 11.5 Examples of suggested rehabilitation strategies to implement to improve quadriceps strength. *Iso* isometric, *Ext* extension, *NMES* neuromuscular electrical stimulation, *OKC* open kinetic chain, *CKC* closed kinetic chain

Fig. 11.6 Examples of suggested rehabilitation strategies to implement to improve hamstrings strength. *Hs* hamstrings, *RDL* Romanian Deadlift

muscles has positive effects on the return to running process. The authors suggest not to limit the assessment and treatment intervention to calf muscle (gastrocnemius and soleus) only, but to extend it to the whole ankle complex, especially to the muscles that control the pronation of the foot (intrinsic foot muscles, tibialis posterior and flexor hallucis longus). Here there are some examples of suggested intervention to maximize the function of the ankle complex before allowing a patient to return to run (Fig. 11.7).

11.4.8 Glutes Strength and Capacity: Greater than 20 Reps and Within 5 Repetitions Versus the Other Side [4]

The glutes complex is of vital importance for the lower limb health, and especially for the knee. In a healthy individual, the gluteus maximus is considered the biggest (volume) and strongest muscle of the body. The gluteus maximus is prone to inhibition after injury and weakness of the glu-

Fig. 11.7 Examples of suggested rehabilitation strategies to implement to improve the ankle complex strength and stability. The first couple of exercises can be used to improve calf strength while the second couple are suggested with the goal of increasing the foot stability and prevent excessive pronation during functional exercises. *Gastro* Gastrocnemius, *Iso* Isometric, *FHL* Flexor Hallucis Longus

Fig. 11.8 Examples of suggested rehabilitation strategies to implement to improve gluteal strength. The suggested exercises follow a specific progression to maximize the gluteal strength: (1) restore optimal lumbo-pelvic stability and balance; (2) analytic gluteus strengthening; (3) re-integrate the gluteal muscles into the motor pattern

teal muscles can contribute to altered movement patterns which increase knee and ACL loading and are thought to be important risk factors for ACL injury [4]. Restoring the strength of the gluteal complex is of fundamental importance to optimize the return to run process after ACLR. In order to do so, the authors suggest the following indications (Fig. 11.8): (a) restore optimal lumbo-pelvic stability and balance [37]; (b) strengthen the gluteus muscles [37] training all the most important gluteal functions (hip extension, abduction and external rotation); (c) re-integrate the gluteal muscle into the motor pattern [37].

11.4.9 Movement Quality: Good Single Leg Squat Movement Assessment

Functional exercises and performance can be considered as the expression of one's ability of utilizing their neuromuscular system to complete

Fig. 11.9 Suggested exercise progression to safely achieve an optimal movement quality on Single Leg Squat. This exercise progression gradually increases the task demand exercise after exercise, allowing the patient to gradually adapt to the increased load of the new task. Do not proceed with this exercise sequence if the patient reports an adverse reaction (pain, increase of swelling, instability, etc.) to the previous task implementation

a specific task. Reasons for sub-optimal movement quality that differs from the "good quality" execution have to be found assessing the neuromuscular system and all its sub-components (intramuscular coordination, intermuscular coordination, balance, mobility, etc.). Once the reason for the dysfunctional movement has been found, it can be addressed through neuromuscular training strategies by the clinician. From the task demand intensity stand of view, a possible exercise progression for a correct Single Leg Squat implementation is illustrated in Fig. 11.9.

11.4.10 Lumbo-Pelvic, Trunk and Core Stability

Even if core stability is not included in the criteria checklist for the return to run process, it does not mean that it is not important. Core stability and lumbo-pelvic control are important in the rehabilitation process after ACLR especially during functional movements. An ipsilateral trunk lean may increase ACL loading as a result of a lateral shift in centre mass, achieving a resultant vector line lateral to the knee joint and causing a knee abduction moment [47]. During the rehabilitation of an ACL reconstructed patient, the approach to core training will evolve from "simple" to "complex". The focus will shift from "local stabilizers" (analytic core work) to "global stabilizers" (functional core work), to conclude with "load transfer" tasks (higher power functional exercises with trunk control) (Fig. 11.10). All the core functions should be trained during the recovery process (e.g. anti-extension, anti-lateral flexion, rotational exercises, etc.).

Once the patient has achieved all the previously stated criteria for return to running, a gradual running implementation is suggested. Depending on the patient readiness, many parameters can be modified to increase or decrease the task demands for the athlete (running surface, speed, volume, frequency, shoes, etc.).

Inefficient running biomechanics play an important role in the development and incidence of running injuries [48]. After anterior cruciate ligament (ACL) reconstruction (ACLR), athletes demonstrate significant alterations in surgical limb running biomechanics as compared with the non-surgical limb and healthy controls [49]. These running alterations include decreased peak knee flexion angles [49], decreased knee flexion excursion [49], decreased peak knee extensor moment [49] and increased initial impact forces [50]. If a runner has poor kinematics patterns and running form, it will affect the body's ability to absorb external forces and put them at risk of developing overuse injuries [48].

Patients should be exposed to gradual load to allow the clinician to assess the running biomechanics and improve it based on his or her needs. Assessment of running biomechanics with 2D or 3D video on a treadmill has shown to be an accurate way of analysing running style [51]. Assessing the athlete's running gait from the first run gives the opportunity to the clinician to provide feedbacks to the patients to optimize the running technique and decrease joint overload.

Fig. 11.10 Suggested categories of exercise progression to optimize the core function. Progress from working on the local stabilizers to the global stabilizers, and finally introduce load transfer exercises

Table 11.3 Example of application of the progressive overload principle to running. Especially when a new task is introduced, it is suggested to gradually increase the global task demands to allow the body to adapt to the new stimulus

Level	Session	Frequency	Total run (min)
1	5 × (30″ run–30″ walk)	2	5
2	5 × (1′ run–30″ walk)	2	10
3	5 × (1′ run–30″ walk)	3	15
4	4 × (2′ run–1′ walk)	3	24
5	3 × (4′ run–1′ walk)	3	36
6	2 × (8′ run–2′ walk)	3	48
7	2 × (10′ run–2′ walk)	3	60
8	1 × 20′ run	3	60

Patients should resume running from a low load condition (changes of running surface, water running, AlterG treadmill, etc.) (Fig. 11.10) and they should follow the progressive overload principle applied to running (Table 11.3), starting from a foundational level (e.g. walk-run interval training) (Fig. 11.11).

When the patient starts to run for the first time after ACLR it is important to keep in mind that it will not be perfect. The patient might report that he or she feels the injured side different from the other side, that the run is not fluid or that running is "odd", but this has to be considered normal, and part of the rehabilitation process. The first run will set a baseline for the athlete and for the clinician that will assess the running gait of the patient and consequentially adjust the rehabilitation plan (in terms of running feedbacks, treatment goals, exercise selection, etc.) to assist the athlete in re-establishing an optimal running technique.

11.5 Conclusions

Return to running after anterior cruciate ligament reconstruction (ACLR) is not an easy task and lack of guidelines leaves clinicians and patients without a clear route to follow. This chapter guides you through the authors' clinical reasoning utilized before implementing a new task with an athlete after ACLR. From an accurate analysis of the task demands, it is possible to understand the needs that an athlete has to satisfy before resuming that specific task. Assessing the patient's envelope of function gives the clinician information about the patient's readiness in terms of the ability of the athlete to cope with a return

Fig. 11.11 Example of different running surfaces that can be used to modulate the load of the running task. Start from low impact running task demand and depending on the patient response to the task, increase or decrease the task demands

to the running programme. Based on the return to running criteria, the authors suggest practical rehabilitation strategies that can be implemented to expand the patients' envelope of function and assists them on achieving those criteria. Once the athlete achieves all the criteria and is considered ready to resume running by the medical team, the clinicians should implement a gradual return to the running programme. This program should start from low impact running (managing volume, intensity, running surface, etc.) and, applying the principle of overload to running, it should gradually increase the task demands with the goal of achieving the patient's running goals.

References

1. Dragoo JL, Braun HJ, Durham JL, Chen MR, Harris AHS. Incidence and risk factors for injuries to the anterior cruciate ligament in National Collegiate Athletic Association football data from the 2004-2005 through 2008-2009 National Collegiate Athletic Association Injury Surveillance System. Am J Sports Med. 2012;40(5):990–5.
2. Sanders TL, Kremers HM, Bryan AJ, Larson DR, Dahm DL, Levy BA, Stuart MJ, Krych AJ. Incidence of anterior cruciate ligament tears and reconstruction: a 21-year population-based study. Am J Sports Med. 2016;44(6):1502–7.
3. Monk PA, Davies LJ, Hopewell S, Harris K, Beard DJ, Price AJ. Surgical versus conservative interventions for treating anterior cruciate ligament injuries. Cochrane Database Syst Rev. 2016;4(4):CD011166.
4. Buckthorpe M, Della Villa F. Optimising the 'mid-stage' training and testing process after ACL reconstruction. Sports Med. 2019;50(4):657–78.
5. Buckthorpe M, Tamisari A, Della Villa F. A ten task-based progression in rehabilitation after acl reconstruction: from post-surgery to return to play—a clinical commentary. Int J Sports Phys Ther. 2020;15(4):611–23.
6. Dye SF. The knee as a biologic transmission with an envelope of function. Clin Orthop Relat Res. 1996;325:10–8.
7. Cavanagh PR, Lafortune MA. Ground reaction forces in distance running. J Biomech. 1980;13(5):397–406.
8. Moore IS. Is there an economical running technique? A review of modifiable biomechanical factors affecting running economy. Sports Med. 2016;46(6):793–807.
9. Sun X, Lam W-K, Zhang X, Wang J, Fu W. Systematic review of the role of footwear constructions in running biomechanics: implications for running-related injury and performance. J Sports Sci Med. 2020;19(1):20–37.
10. Rambaud AJM, Ardern CL, Thoreux P, Regnaux J-P, Edouard P. Criteria for return to running after anterior cruciate ligament reconstruction: a scoping review. Br J Sports Med. 2018;52(22):1437–44.
11. Della Villa F, Ricci M, Perdisa F, Filardo G, Gamberini J, Caminati D, Della Villa S. Anterior cruciate ligament reconstruction and rehabilitation: predictors of functional outcome. Joints. 2015;3(4):179–85.
12. Della Villa S, Della Villa F, Ricci M, Doral MN, Gasbarro G, Musahl V. ACL risk of reinjury: when is it safe to return (time or criteria). In: Injuries and health problems in football; 2017. pp. 581–592.
13. Jakobsen TL, Christensen M, Christensen SS, Olsen M, Bandholm T. Reliability of knee joint range of motion and circumference measurements after total knee arthroplasty: does tester experience matter? Physiother Res Int. 2009;15:126–34.

14. Sachs RA, Daniel DM, Stone ML, Garfein RF. Patellofemoral problems after anterior cruciate ligament reconstruction. Am J Sports Med. 1989;17(6):760–5.
15. Hébert-Losier K, Wessman C, Alricsson M, Svantesson U. Updated reliability and normative values for the standing heel rise test in healthy adults. Physiotherapy. 2017;103(4):446–52.
16. Freckleton G, Cook J, Pizzari T. The predictive validity of a single leg bridge test for hamstring injuries in Australian rules football players. Br J Sports Med. 2014;48(8):713–7.
17. Crossley KM, Zhang W-J, Schache AG, Bryant A, Cowan SM. Performance on the single-leg squat task indicates hip abductor muscle function. Am J Sports Med. 2011;39(4):866–73.
18. Herrington L, Myer G, Horsley I. Task based rehabilitation protocol for elite athletes following anterior cruciate ligament reconstruction: a clinical commentary. Phys Ther Sport. 2013;14(4):188–98.
19. Shelbourne DK, Wilckens JH, Mollabashy A, DeCarlo M. Arthrofibrosis in acute anterior cruciate ligament reconstruction. The effect of timing of reconstruction and rehabilitation. Am J Sports Med. 1991;19(4):332–6.
20. Logerstedt D, Scalzitti D, Risberg MA, Engebretsen L, Webster KE, Feller J, Snyder-Mackler L, Axe MJ, McDonough CM, Altman RD, Beattie P, DeWitt J, Elliott JM, Ferland A, Fitzgerald GK, Kaplan S, Killoran D, Kvist J, Marx R, Torburn L, Zachazewski J. Knee stability and movement coordination impairments: knee ligament sprain revision 2017. J Orthop Sports Phys Ther. 2017;47(11):A1–A47.
21. Dix J, Marsh S, Dingenen B, Malliaras P. The relationship between hip muscle strength and dynamic knee valgus in asymptomatic females: a systematic review. Phys Ther Sport. 2019;37:197–209.
22. Petersen W, Taheri P, Forkel P, Zantop T. Return to play following ACL reconstruction: a systematic review about strength deficits. Arch Orthop Trauma Surg. 2014;134(10):1417–28.
23. Dorn TW, Schache AG, Pandy MG. Muscular strategy shift in human running: dependence of running speed on hip and ankle muscle performance. J Exp Biol. 2012;215(11):1944–56.
24. Fong C-M, Blackburn JT, Norcross MF, McGrath M, Padua DA. Ankle-dorsiflexion range of motion and landing biomechanics. J Athl Train. 2011;46(1):5–10.
25. Maniar N, Schache AG, Pizzolato C, Opar D. Muscle contributions to tibiofemoral shear forces and valgus and rotational joint moments during single leg drop landing. Scand J Med Sci Sports. 2020;30(9):1664–74.
26. Buckthorpe M, Pirotti E, Della Villa F. Benefits and use of aquatic therapy during rehabilitation after acl reconstruction—a clinical commentary. Int J Sports Phys Ther. 2019;14(6):978–93.
27. Wilk KE, Arrigo CA. Rehabilitation principles of the anterior cruciate ligament reconstructed knee: twelve steps for successful progression and return to play. Clin Sports Med. 2017;36(1):189–232.
28. van Melick N, van Cingel REH, Brooijmans F, Neeter C, van Tienen T, Hullegie W, Nijhuis-van der Sanden MWG. Evidence-based clinical practice update: practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus. Br J Sports Med. 2016;50(21):1506–15.
29. Buckthorpe M, La Rosa G, Della Villa F. Restoring knee extensor strength after anterior cruciate ligament reconstruction: a clinical commentary. Int J Sports Phys Ther. 2019;14(1):159–72.
30. Patterson SD, Hughes L, Warmington S, Burr J, Scott BR, Owens J, Abe T, Nielsen JL, Libardi CA, Laurentino G, Rodrigues Neto G, Brandner C, Martin-Hernandez J, Loenneke J. Blood flow restriction: exercise considerations of methodology, application, and safety. Front Physiol. 2019;10:533.
31. Hughes L, Rosenblatt B, Haddad F, Gissane C, McCarthy D, Clarke T, Ferris G, Dawes J, Paton B, Patterson SD. Comparing the effectiveness of blood flow restriction and traditional heavy load resistance training in the post-surgery rehabilitation of anterior cruciate ligament reconstruction patients: a UK National Health Service Randomised Controlled Trial. Sports Med. 2019;49(11):1787–805.
32. Lepley LK, Grooms DR, Burland JP, Davi SM, Mosher JL, Cormier ML, Lepley AS. Eccentric cross-exercise after anterior cruciate ligament reconstruction: novel case series to enhance neuroplasticity. Phys Ther Sport. 2018;34:55–65.
33. Papandreou M, Billis E, Papathanasiou G, Spyropoulos P, Papaioannou N. Cross-exercise on quadriceps deficit after ACL reconstruction. J Knee Surg. 2013;26(1):51–8.
34. Harput G, Ulusoy B, Yildiz TI, Demirci S, Eraslan L, Turhan E, Tunay VB. Cross-education improves quadriceps strength recovery after ACL reconstruction: a randomized controlled trial. Knee Surg Sports Traumatol Arthrosc. 2018;27(1):68–75.
35. Lepley LK, Palmieri-Smith RM. Cross-education strength and activation after eccentric exercise. J Athl Train. 2014;49(5):582–9.
36. Buckthorpe M, Danelon F, La Rosa G, Nanni G, Stride M, Della Villa F. Recommendations for hamstring function recovery after ACL reconstruction. Sports Med. 2020;51(4):607–24.
37. Buckthorpe M, Stride M, Della Villa F. Assessing and treating gluteus maximus weakness—a clinical commentary. Int J Sports Phys Ther. 2019;14(4):655–69.
38. Gokeler A, Dingenen B, Mouton C, Seil R. Clinical course and recommendations for patients after anterior cruciate ligament injury and subsequent reconstruction: a narrative review. EFORT Open Rev. 2017;2(10):410–20.
39. Myer GD, Brent JL, Ford KR, Hewett TE. A pilot study to determine the effect of trunk and hip focused neuromuscular training on hip and knee isokinetic strength. Br J Sports Med. 2008;42(7):614–9.
40. Andrade R, Pereira R, van Cingel R, Staal JB, Espregueira-Mendes J. How should clinicians

rehabilitate patients after ACL reconstruction a systematic review of clinical practice guidelines (CPGs) with a focus on quality appraisal (AGREE II). Br J Sports Med. 2020;54(9):512–9.
41. Hopkins J, Ingersoll CD, Edwards J, Klootwyk TE. Cryotherapy and transcutaneous electric neuromuscular stimulation decrease arthrogenic muscle inhibition of the vastus medialis after knee joint effusion. J Athl Train. 2002;37(1):25–31.
42. Palmieri-Smith RM, Thomas AC, Wojtys EM. Maximizing quadriceps strength after ACL reconstruction. Clin Sports Med. 2008;27(3):405–24.
43. Wellsandt E, Failla MJ, Snyder-Mackler L. Limb symmetry indexes can overestimate knee function after ACL injury. J Orthop Sports Phys Ther. 2017;47(5):334–8.
44. Eitzen I, Holm I, Risberg MA. Preoperative quadriceps strength is a significant predictor of knee function two years after anterior cruciate ligament reconstruction. Br J Sports Med. 2009;43(5):371–6.
45. Kim K-M, Croy T, Hertel J, Saliba S. Effects of neuromuscular electrical stimulation after anterior cruciate ligament reconstruction on quadriceps strength, function, and patient-oriented outcomes: a systematic review. J Orthop Sports Phys Ther. 2010;40(7):383–91.
46. Hewett TE, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes a prospective study. Am J Sports Med. 2005;33(4):492–501.
47. Della Villa F, Buckthorpe M, Grassi A, Nabiuzzi A, Tosarelli F, Zaffagnini S, Della Villa S. Systematic video analysis of ACL injuries in professional male football (soccer): injury mechanisms, situational patterns and biomechanics study on 134 consecutive cases. Br J Sports Med. 2020;54(23):1423–32.
48. Hulme A, Oestergaard Nielsen R, Timpka T, Verhagen E, Finch C. Risk and protective factors for middle- and long-distance running-related injury. Sport Med. 2017;47(5):869–86.
49. Pairot-de-Fontenay B, Willy RW, Elias ARC, Mizner RL, Dubé M. Running biomechanics in individuals with anterior cruciate ligament reconstruction: a systematic review. Sports Med. 2019;49(9):1411–24.
50. Noehren B, Wilson H, Miller C, Lattermann C. Long-term gait deviations in anterior cruciate ligament–reconstructed females. Med Sci Sports Exerc. 2013;45(7):1340–7.
51. Souza RB. An evidence-based videotaped running biomechanics analysis. Phys Med Rehabil Clin N Am. 2015;27(1):217–36.