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Eccentric cycling for ACL-R rehabilitation: A masterclass

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ABSTRACT

Eccentric training is a well-established method for developing strength and its implementation has become increasingly common in anterior cruciate ligament reconstruction (ACL-R) rehabilitation. Although traditionally introduced in later stages of recovery, early progressive eccentric exercise has been investigated from approximately three weeks post-operation in selected patients, with evidence suggesting potential benefits for quadriceps atrophy and strength deficits. Beyond improving strength, eccentric training may also enhance performance in return-to-sport (RTS) assessments. However, its implementation should be gradual and individualized, with consideration of clinical status and loading tolerance, particularly during the early phases of rehabilitation. Eccentric recumbent cycling offers a practical solution, allowing clinicians to monitor power outputs and regulate intensity through rate of perceived exertion (RPE) scales. This article explores the benefits of integrating eccentric cycling into ACL-R rehabilitation and outlines an exemplar eccentric cycling program.

1. Introduction to ACL injury, reconstruction and the loss of muscle size and strength

There are many key aspects to rehabilitation following anterior cruciate ligament reconstruction (ACL-R), with restoring quadriceps strength and power remaining one of the primary areas of focus for clinicians and athletes (Gerber et al., 2007a). Substantial quadriceps atrophy is commonly observed, with reductions in muscle size of 20-30% within the first three months post-surgery, and persistent deficits of 10-20% in size and strength often remaining even after formal rehabilitation has concluded (Gerber et al., 2007a; Lepley & Palmieri-Smith, 2015). These deficits, driven in part by insufficient eccentric strength and control in the reconstructed limb, and by neural changes such as decreased motor unit firing rates, contribute to persistent inter-limb asymmetries and quadriceps activation failure if left unaddressed, compromising functional movement patterns (Lepley et al., 2015). Athletes with greater than 10% quadriceps asymmetry face an elevated risk of re-injury, reflected in poorer RTS assessment performance and disrupted lower-limb biomechanics, and long-term impairments following ACL-R remain common even with more targeted rehabilitation approaches, representing a significant risk to long-term knee health (Gerber et al., 2007b; Harkey et al., 2025; Lepley & Palmieri-Smith, 2015). Restoring quadriceps size and strength therefore remains a central challenge following ACL-R, as lingering asymmetries can delay the recovery of pre-injury mechanics and elevate the risk of secondary injury (Gerber et al., 2006). Consequently, implementing early-phase interventions that preserve muscle morphology and enhance neural activation is essential to optimize rehabilitation outcomes, as resistance training in clinical practice is often applied at insufficient intensity to elicit meaningful structural change following ACL-R (Nichols et al., 2021).

2. The role and benefits of eccentrics in rehabilitation

Eccentric training is one intervention that may be considered during earlier phases of rehabilitation when individual clinical status, surgical considerations, and loading tolerance permit (Douglas et al., 2017; Hedayatpour & Falla, 2015; Lorenz & Reiman, 2011). This mechanical efficiency makes it particularly effective for restoring muscle size, strength, and function following injury. During eccentric contractions, muscle fibers lengthen while producing tension, creating higher mechanical loading and greater muscle remodeling than during concentric

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actions (Gerber et al., 2007a). These stimuli drive enhanced hypertrophic and neural adaptations (Hedayatpour & Falla, 2015; Lorenz & Reiman, 2011), supporting eccentric exercise as a valuable component of evidence-informed rehabilitation. From a neural perspective, eccentric exercise promotes improved motor unit recruitment and firing synchronization, mitigating the neural inhibition frequently observed after ACL-R (Lepley et al., 2017). This enhanced neuromuscular activation facilitates the restoration of coordinated movement patterns (Lepley et al., 2017), and more recent evidence indicates that eccentric training performed at longer muscle lengths may induce greater neuromuscular adaptations (Colard et al., 2025). At the tissue level, the controlled mechanical stress of eccentric loading contributes to increased tendon stiffness and joint stability, both of which support the physical demands placed on the knee during high-load activities (Douglas et al., 2017; Lorenz & Reiman, 2011). Eccentric training is also particularly effective for restoring fast-twitch fibers, which are typically the first affected during muscle atrophy and are highly responsive to eccentric loading, with associated hormonal adaptations (e.g., increased testosterone and muscle cross-sectional area) that may further support hypertrophy (Douglas et al., 2017; Hedayatpour & Falla, 2015). Collectively, these neural, structural, and hormonal adaptations support eccentric exercise as one valuable strategy for addressing the multifactorial deficits that persist after ACL injury.

Return-to-sport (RTS) tests following ACL-R commonly include functional jump assessments, such as single- and triple-hop tests (Sharp et al., 2025). In usual care, these assessments are frequently interpreted using distance-based outcomes or limb symmetry indices, despite inconsistent implementation and limited consideration of movement quality or individual joint contributions (Kotsifaki et al., 2022; Sharp et al., 2025). Although successful jump performance requires the generation and absorption of force during the propulsive and braking phases, satisfactory hop distance does not necessarily indicate restoration of knee joint function (Kotsifaki et al., 2022; Sharp et al., 2025). Athletes may achieve comparable distances by redistributing mechanical demands away from the knee toward the hip and ankle, thereby masking persistent knee-specific deficits (Kotsifaki et al., 2022). Indeed, asymmetries in joint contributions during the propulsive and braking phases of jumping have been reported well into late-stage rehabilitation (Kotsifaki et al., 2022; Sharp et al., 2025), even when RTS criteria are met in usual care. More recent evidence confirms that eccentric-phase deficits are comparable in magnitude to concentric-phase deficits at 6 months post-ACL-R, with limb symmetry indices remaining below the commonly accepted 90% threshold for both phases (Forelli et al., 2025). These findings highlight the importance of considering how performance is achieved, rather than relying solely on distance-based outcomes. Given that deficits may persist during braking and landing tasks following ACL-R, targeted strength training that emphasizes eccentric force production and control may provide a useful strategy for addressing residual impairments and supporting preparation for higher-demand activities.

Although eccentric exercise can induce more muscle damage, specifically at long muscle lengths, than traditional resistance training (Gerber et al., 2007b), when introduced progressively and monitored appropriately, it offers significant benefits to ACL-R rehabilitation (Gerber et al., 2007a). Lepley et al. (2015) reported that eccentric training restored quadriceps strength to pre-injury levels and, in some cases, exceeded them, suggesting that eccentric loading was the primary factor driving recovery (Lepley et al., 2015). It seems that eccentric strength gains not only counteract post-operative weakness but also persist for up to one year after surgery, aligning with previous research as well (Gerber et al., 2007a; Lepley et al., 2015). Similarly, Gerber et al. (2007b) reported that a 12-week progressive eccentric-focused resistance program, initiated as early as three weeks post-operation in appropriately selected participants, was feasible and did not result in adverse knee joint responses within the study context. Participants demonstrated greater improvements in strength, return to pre-injury activity levels, and performance on return-to-sport (RTS) jump assessments compared with the conventional rehabilitation group (Gerber et al., 2007a). These findings suggest that eccentric training may be considered across different stages of ACL-R rehabilitation when progression is individualized according to surgical considerations, clinical presentation, symptom response, ROM, and loading tolerance (Buckthorpe, 2021). Supporting its potential use in later-stage rehabilitation, Stojanović et al. (2023) reported greater improvements in strength and RTS jump performance measures following the integration of eccentric-oriented strength training (Stojanović et al., 2023). Taken together, these findings support eccentric training as a potentially valuable component of ACL-R rehabilitation; however, its timing and progression should be individualized rather than applied according to a universal post-operative time line.

3. Introduction to eccentric cycling

An important consideration when implementing eccentric training in ACL-R rehabilitation is selecting methods that are both safe and effective. Eccentric cycling represents a particularly practical approach, offering a controlled, non-weight-bearing means of introducing eccentric loading early in recovery. In eccentric cycling, the ergometer's motor drives the crank backward, producing a motion that the cyclist must resist as the pedals return toward them. The intensity of resistance can be adjusted by the user within the constraints set by the device, aligning with the principle of auto-regulation and allowing participants to modulate effort according to their perceived capacity. Progressive eccentric exercise initiated from approximately three weeks post-ACL-R surgery has been investigated in a limited number of studies with reported improvements in quadriceps size and strength among selected participants (Gerber et al., 2006; Gerber et al., 2007a). Within these study contexts, eccentric cycling provided a controlled means of introducing progressive eccentric loading during early rehabilitation without reported adverse knee joint responses (Gerber et al., 2007b). However, these findings should not be interpreted as supporting universal initiation at three weeks post-operation, as suitability is likely dependent on individual surgical considerations, ROM, symptom response, and tolerance to loading. Gerber and colleagues outlined practical parameters used within their protocols, including limited knee flexion ranges and gradual progression of resistance and session duration (Gerber et al., 2007b). These parameters may provide useful guidance for clinical application but should be adapted to the individual patient rather than applied as fixed criteria.

Eccentric cycling allows greater torque production at lower oxygen and energy demand compared to concentric cycling (Barreto et al., 2023; Hedayatpour & Falla, 2015; Leong et al., 2013). These characteristics may facilitate relatively high muscular loading while limiting metabolic demand, which may be advantageous during rehabilitation when exercise tolerance and weight-bearing capacity remain constrained (Leong et al., 2013). The ability to adjust range of motion (ROM) and work within partial ROMs may further support the controlled introduction and progression of eccentric exercise. During initial familiarization, the motor-driven pedals may also allow the lower limbs to provide no active resistance. This passive exposure to the cycling motion is distinct from eccentric cycling itself, which begins once the patient actively resists the backward-driven pedals. As active resistance is introduced, eccentric cycling may help re-establish motor control and coordination within a controlled, non-weight-bearing environment before progression to more complex weight-bearing tasks (Gerber et al., 2006). These adaptations may contribute to improvements in strength and movement control that support progression toward advanced, sport-specific tasks later in the rehabilitation process (Gerber et al., 2006).

4. Eccentric cycling: the how

While the theoretical advantages of eccentric cycling are well recognized, successful translation into rehabilitation practice depends on how it is introduced and progressed. The next section explores these practical elements, detailing how to initiate eccentric cycling, guide familiarization, manage range of motion, and progressively adjust resistance throughout the ACL-R continuum.

4.1. Understanding the technology

Eccentric cycling systems are motor-driven ergometers designed to rotate the pedals independently of the user, requiring the rider to apply braking forces to resist the backward motion of the crank. Thus, unlike conventional concentric cycling, where the user generates the pedal motion, eccentric cycling shifts the mechanical demand toward lengthening muscle contractions, allowing for high force production at a relatively low metabolic cost. Key adjustable parameters include pedal cadence, user resistance, and session duration, which can be manipulated to tailor the eccentric stimulus to the individual's stage of rehabilitation. Modern systems also incorporate integrated safety features, such as force or contact sensors within the pedals, emergency stop mechanisms, and programmable limits on cadence, ensuring the modality can support controlled application across different stages of rehabilitation. For safety, the bike will automatically stop if the foot loses contact with the sensor on the pedal (see Fig. 1).

4.2. Set up and range of motion

Implementing eccentric cycling in ACL-R rehabilitation requires careful attention to setup, technique, and load progression to ensure safety and efficacy. When introduced in the early phase of rehabilitation, close monitoring of knee ROM is essential. Contemporary rehabilitation guidance identifies restoration of full extension as an important early rehabilitation priority, with approximately 110–120° of knee flexion (Fig. 2) commonly targeted by four to six weeks post-ACL-R (Buckthorpe et al., 2024). These benchmarks may inform eccentric cycling setup but should not be treated as universal progression criteria, as individual recovery trajectories and surgical considerations vary. ROM should be controlled to maintain knee flexion throughout the pedal cycle, avoiding full extension or "lockout" at the bottom of the stroke.

4.3. Familiarization and safety guidelines

A brief familiarization session is recommended to allow patients to become comfortable with the range of motion, speed, and overall feel of eccentric cycling. Optimal set-up is key for safety and efficacy when using an eccentric bike (see Table 1). Ensuring slight knee bend, as to avoid full extension or "lock out" (Fig. 3) and contact between the mid foot and pedal (Fig. 3) will optimize muscle engagement and reduce any potential discomfort and risk of injury. Once adapted to the unique stimulus, patients can begin learning to actively resist the backward stroke of the pedal. Initially they should be instructed to not offer any resistance and become comfortable with the eccentric cycling motion. Once comfortable they can be instructed to "resist" the pedal as it returns (see Fig. 4), promoting an eccentric contraction as they apply braking forces. Effort should be introduced gradually, as the movement can feel intense if performed maximally. Early sessions should therefore prioritize coordination and controlled resistance over producing maximal effort. This familiarization period minimizes the risk of excessive eccentric muscle damage or delayed onset muscle soreness, both of which could temporarily inhibit progress or alter gait mechanics.

4.4. Autoregulation and resistance considerations

One of the major benefits of eccentric cycling is the ability to autoregulate the eccentric overload. Resistance should be autoregulated based on rate of perceived exertion (RPE) and movement control rather than fixed wattage targets, particularly during early sessions. Early-stage sessions may rely on light resistance to emphasize motor control, with load increased only when the athlete demonstrates consistent smoothness and no adverse knee response (e.g., swelling or pain). Because eccentric cycling can induce high mechanical loading with low metabolic cost, careful monitoring ensures that adaptations occur safely without overloading healing tissues. RPE scales have been widely used in ACL-R rehabilitation and allow for internal load control as well as safe and simple load progression (Germano Maciel et al., 2021, 2022). In addition to resistance, cadence or the number of revolutions per minute

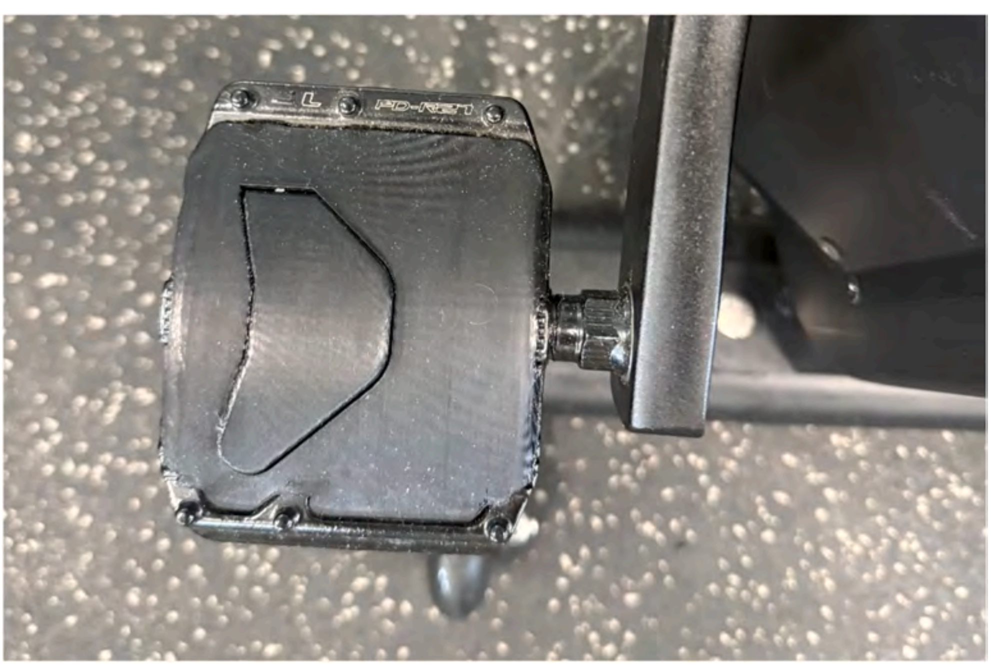

Fig. 1. Pedal sensor on recumbent bike.

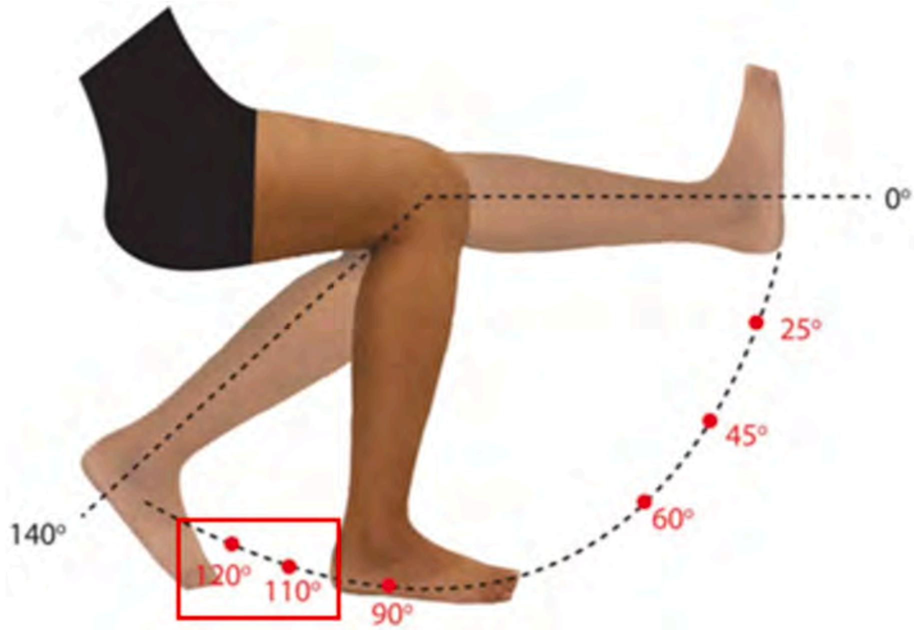

Fig. 2. Seated knee flexion ROM.

Table 1
Safety considerations.

Set Up Considerations	Details and Rationale
Knee flexion	Maintain slight knee flexion; avoid knee lock out. Knee flexion should align with ROM based on rehabilitation timeline. Ensures safe eccentric loading and proper muscle engagement.
Foot position	Contact between the pedal and mid-low foot. Positioning pedal on the ball of foot reduces control and disrupts ability to produce maximal resistance. Bike will stop if contact to the pedal sensor is disrupted.

(RPM), functions as a complementary autoregulatory variable. Moderate cadences (approximately 20–40 RPM) are most commonly recommended and used by researchers and practitioners (Gerber et al., 2007a), whereas the effects of higher cadences (>40 RPM) have not been explored and warrant further investigation. Clinically, cadence may be manipulated to emphasize specific neuromuscular demands or to better approximate functional tasks (e.g., walking or running) without altering external resistance (Gregor et al., 2011).

4.5. Asymmetry monitoring

Monitoring inter-limb asymmetry provides critical information about strength deficits and neuromuscular control during ACL-R recovery. Tracking power output or muscular work (see Fig. 5), if equipment allows, or observing pedal smoothness can help clinicians detect imbalances that may require targeted intervention or load adjustment. These metrics can drive intent, encouraging the athlete to actively engage the injured limb and match performance between sides. As rehabilitation progresses, tracking changes in power and work asymmetry offers an objective means of evaluating readiness and adaptation, particularly given that strength asymmetry remains a persistent issue following ACL-R (Gerber et al., 2006). This feedback loop supports individualized progression and promotes symmetrical lower-limb function as athletes progress through rehabilitation. As an illustrative example, Fig. 5 depicts a representative shift from early, low power outputs and symmetry (A) to later-stage higher work output and symmetry (B), illustrating how tracking these measures can inform rehabilitation and drive balanced recovery. While cycling, attention to the power outputs displayed on the screen, including total power and left/right balance is important. Monitoring asymmetries can help identify if one leg is working harder, allowing real time technique

Fig. 3. Incorrect lockout position (a) vs. correct (b) knee flexion during a cycle.

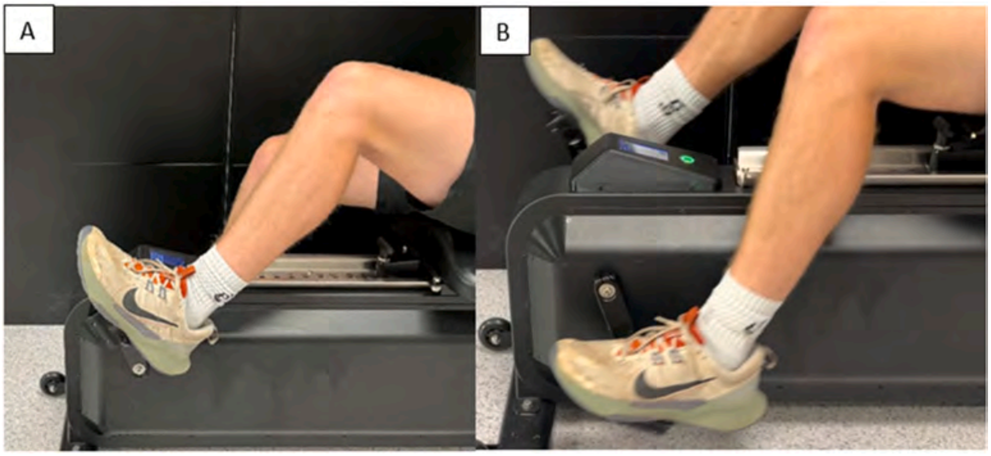

Fig. 4. Depicting a) beginning, b) end of the resistive phase.

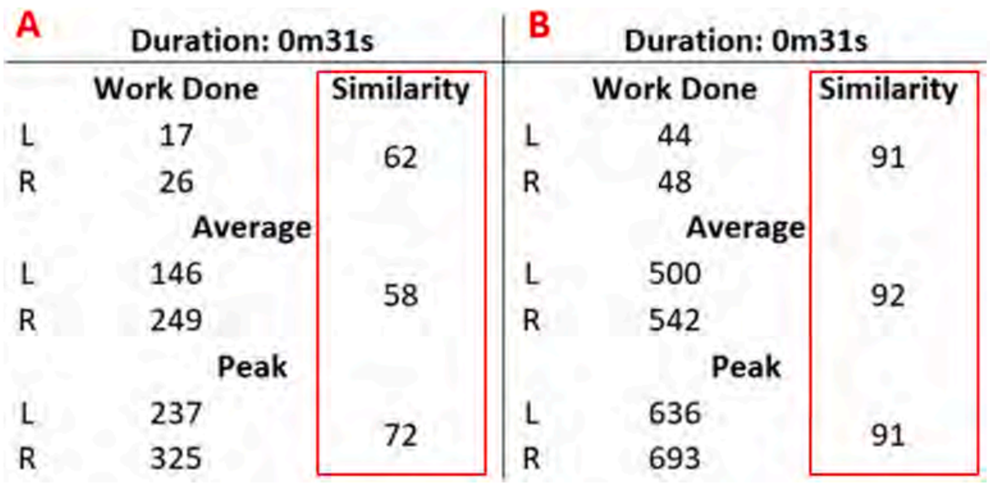

Fig. 5. Representative example of device-generated bilateral power data illustrating how changes in between-limb power asymmetry may be monitored across rehabilitation sessions. Data are presented for illustrative purposes only and do not represent patient outcome data.

adjustments in cadence and exertion. The goal should be to keep left and right power as balanced as possible while focusing on consistent, controlled force throughout the pedalling cycle.

While real-time feedback can encourage symmetrical effort during bilateral cycling, certain stages of rehabilitation may require deliberate limb biasing to address deficits in the reconstructed limb. In these cases, clinicians may implement a 2:1 leg training ratio—structured as two unilateral working sets on the affected limb for every one working set on the unaffected limb— to preferentially increase eccentric loading of the affected limb while maintaining meaningful contribution from the unaffected side. This specific ratio has not been directly validated in the literature and is instead extrapolated from broader principles of asymmetry-focused rehabilitation following ACL-R. It should therefore be regarded as a provisional clinical strategy rather than a standardized recommendation, to be adjusted based on individual patient response. Such an approach allows targeted training of the reconstructed limb without completely unloading or detraining the unaffected limb, which may support continued bilateral coordination and overall training volume. Clinicians can verify that the intended loading is actually occurring by monitoring the same real-time left/right power output display described in the preceding paragraph. This confirms that the affected limb is receiving a proportionally greater share of working load rather than assuming the prescribed ratio is being achieved. When applied alongside ongoing asymmetry monitoring, a 2:1 ratio may help reduce inter-limb disparities while preserving movement quality and avoiding excessive compensatory strategies.

5. Eccentric cycling: the program

Eccentric cycling can be incorporated as a warm-up tool prior to the rehabilitation training session, and as patients progress through rehabilitation stages, the eccentric cycling can also become the main training tool if desired. Athletes can begin with short intervals (e.g., 30 s) for up to three rounds. The first round should be performed at minimal effort to gradually warm the knee through the intended range of motion and allow any necessary postural adjustments. Following this introductory set, working sets can begin.

An exemplar progression, informed by the eccentric ergometry protocols described by Gerber et al. (2007b) and supplemented by the authors' clinical experience, is presented in Table 2 (Gerber et al., 2007a). The proposed parameters are intended to illustrate one approach to manipulating volume and intensity across rehabilitation rather than an established or prescriptive post-operative protocol. Decisions regarding the initiation and progression of eccentric cycling should be individualized and made within the broader rehabilitation plan, considering surgical procedure and concomitant injuries, surgeon-specific restrictions, graft type where relevant, knee ROM, pain and effusion response, wound healing, ability to maintain appropriate lower-limb positioning, and tolerance to previous rehabilitation loading. Accordingly, the post-operative time points provided should be interpreted as

Table 2
Suggested eccentric cycling progression. *Adapted from Gerber* et al.*, 2007*.

Phase	Rehab Weeks	ROM (°)	Warm-up	Volume	Rest	Intensity (RPE)	Cadence (RPM)	Frequency	Session Duration	Goals
1	3-4	110-120°	1 × 30s, minimal effort	2x30s	30-60s	2-3	10-20	3-5x/week	2-3 min	Eccentric loading exposure
Progression criteria: No swelling, pain ≤2/10 during *and* after, stable ROM throughout cycle.										
2	5-8	≥120°	1x30-45s, minimal effort	3-5x30-45s	30-45s	3-4	20-30	2-3x/week	4-8 min	Increase eccentric tolerance, maintain exposure
Progression criteria: Consistent RPE responses, no swelling increase or pain during/after.										
3	7-12	135°	1 × 45s, light effort	3-5x45-75s	45-60s	4-8	20-40	2-4x/week	5-11 min	Develop strength, increase workload
Progression criteria: Stable knee response to increased load and volume.										
4	12+	135°	1x45-60s, light effort	4-6x45-60s	45-60s	7-10	30-40	3-4x/week	6-12 min	Prepare for RTS eccentric demands

Additional notes and considerations
- Increase one variable at a time (e.g. RPE or duration).
- Have athlete's goal to be as symmetrical as possible with power outputs through all training sessions.
- Monitor for pain or discomfort above a 4, swelling, or compensatory patterns (asymmetry in metrics given via bike).
- Eccentric cycling should be used in a manner that is appropriate to the stage of rehabilitation an athlete is in, ensuring intensity is matched with tissue tolerance.

approximate reference points rather than fixed eligibility criteria. Based on the available evidence and the authors' clinical experience, eccentric cycling may be considered from approximately three weeks post-operation in appropriately selected patients who demonstrate adequate ROM, symptom stability, and tolerance to the cycling motion. Patients who do not meet these criteria should begin later, with progression guided by clinical presentation and response rather than time from surgery alone.

The following sections provide more detail to the loading parameters detailed in Table 2.

6. Patient selection and candidacy

The progression outlined in this masterclass is intended for patients following primary, uncomplicated ACL-R who are progressing along a typical post-operative course, with medical clearance to begin knee ROM exercise and weight-bearing activity as appropriate. Patients with concomitant meniscal repair, cartilage/chondral procedures, or other combined surgical procedures often require modified weight-bearing, ROM, or loading restrictions, and should follow surgeon-directed protocol. The timelines presented here may need to be delayed accordingly and are not intended to override surgeon-specific precautions.

Eligibility to begin eccentric cycling should also be judged against current clinical status rather than time since surgery alone. Patients should demonstrate adequate ROM for cycling, defined as sufficient ROM to complete the intended pedal cycle without compensatory movement, alongside minimal or stable effusion and pain that is controlled at rest and during low-load activity. Eccentric cycling should be deferred in the presence of unresolved effusion, uncontrolled pain, wound-healing concerns, suspected graft complications, or any other contraindication identified by the treating surgeon or clinician. Criteria for progressing, holding or discontinuing eccentric cycling once initiated are described in the following section. This protocol is not intended a sa universal or standardized prescription; rather, it represents one clinical framework to be adapted based on individual presentation, graft type, concomitant procedures, and clinician judgement.

7. Progression criteria, stop rules, and adverse-response management

While Table 2 outlines an expected weekly timeline, progression through each phase should ultimately be criterion-based rather than strictly time-based, with pace adjusted according to the patient's individual response. Advancement to the next phase requires: 1) knee ROM meeting the threshold specified for that phase, 2) no increase in joint effusion following the prior session, 3) pain during and after cycling remaining within an acceptable, pre-established limit, and 4) the ability to complete the prescribed volume and intensity at the target RPE without a change in movement quality or symptom presentation.

If effusion increases following a session, intensity and/or volume should be reduced at the next session, and progression should be deferred until effusion returns to baseline. Similarly, if pain exceeds the established threshold, or if RPE at a given workload rises unexpectedly compared to prior sessions, the clinician should hold the patient at the current phase, reduce load, and reassess before advancing further.

Eccentric cycling should be discontinued for that session if the patient reports sharp or sudden pain, if the pedal-contact safety sensor is repeatedly triggered, or if compensatory movement patterns emerge that cannot be corrected with cueing. Sessions should also be modified or deferred in the presence of an acute increase in effusion, wound-healing concerns, or any new post-operative complication, pending clearance from the surgical team. Graft type and concomitant procedures should inform how these criteria are applied. Patients with concomitant meniscal repair, cartilage procedures, or other combined surgeries may require more conservative ROM and loading progressions than those outlined in Table 2, consistent with surgeon-directed restrictions, and clinicians should defer to the surgical protocol whenever it is more conservative than the guidelines presented here. Graft-specific considerations (e.g., anterior knee sensitivity associated with patellar tendon autografts) may likewise warrant individualized adjustments to cadence, resistance, or the pace of ROM progression (Marques et al., 2020).

1. **Phase 1:** Early introduction (3−4 weeks post-op., where clinically appropriate)

Entry into Phase 1 is guided by sufficient knee flexion to complete the intended pedal cycle without symptom provocation or compensatory movement, alongside adequate extension and symptom control. Patients progressing more slowly toward the 110–120° benchmark described by Buckthorpe et al. (2024) may begin Phase 1 correspondingly later, consistent with the 4–6-week timeframe reported in this guidance (Buckthorpe et al., 2024). Once these criteria are met, the primary goal of this phase is to introduce the eccentric cycling stimulus within a constrained and well-tolerated knee ROM. Knee flexion should initially be adapted to the individual's available and symptom-tolerated ROM, rather than restricted to a fixed threshold. Based on clinical rationale, short work intervals and low perceived effort emphasize coordination, confidence, and familiarization with the eccentric braking task rather than strength development. Maintaining symptom stability across and following the pedal cycle is prioritized, as early tolerance to eccentric loading sets the foundation for subsequent volume and intensity progression.

2. **Phase 2:** Foundational eccentric tolerance (5–8 weeks post op. ≥120° knee flexion)

As knee flexion capacity improves beyond 120°, consistent with the criteria as described above (Buckthorpe & Della Villa, 2020) eccentric cycling can be progressed by modest increases in volume and cadence while maintaining submaximal intensity. This phase focuses on building consistent eccentric exposure and improving tissue tolerance without provoking excessive soreness or joint effusion. The gradual expansion of ROM allows greater utilization of the quadriceps length-tension relationship, consistent with evidence that training at longer muscle lengths may enhance hypertrophic adaptation (Solie et al., 2024), while optional asymmetrical loading strategies may be introduced conservatively to begin addressing emerging interlimb differences. Consistency of perceived effort and knee response across sessions is, from a clinical standpoint, a key indicator of readiness for further progression.

3. **Phase 3:** Strength development (7–12 weeks post op., 135° of knee flexion (full ROM))

Once full knee flexion is restored, consistent with the criteria described above (Buckthorpe, 2019), progression shifts away from ROM and toward increases in total eccentric workload and intensity. Based on clinical rationale, longer work intervals and higher RPE targets facilitate meaningful eccentric strength development of the quadriceps, while optional interval-based structures provide a means to manipulate internal load without excessive mechanical strain. At this stage, unilateral loading strategies can be more deliberately applied when asymmetries persist (Gerber et al., 2006), provided the knee demonstrates a stable response to higher loads. Monitoring tolerance to both increased volume and intensity is essential to avoid excessive muscle damage that could interfere with gait or subsequent training (Gerber et al., 2007b).

4. **Phase 4:** Late stage/RTS preparation (12+ weeks post op., 135° of knee flexion (full ROM))

From a clinical perspective, eccentric cycling may be used to support preparation for the high braking forces and rapid force absorption demands characteristic of sport-specific deceleration and change of direction tasks. Higher cadences and intensities increase the eccentric demand on the quadriceps (Green et al., 2018), while maintaining a controlled and low-impact environment. Unilateral loading may be used selectively to address residual asymmetries, though combining maximal effort with asymmetrical loading should be avoided to limit undue joint stress. The overarching objective of this phase is to achieve acceptable interlimb symmetry and robust tolerance to high eccentric loads in preparation for more dynamic on field activities (Buckthorpe, 2019, 2021).

8. Conclusions

Eccentric cycling provides a practical approach for restoring quadriceps strength, motor control, and inter-limb symmetry following ACL-R. When introduced progressively and monitored properly, it can guide rehabilitation with objective feedback, helping athletes engage the injured limb safely and effectively. By integrating these principles into practice, clinicians can support individualized progression, promote balanced recovery, and contribute to the athlete's broader preparation for return to sport.

Human/animal participants statement

This manuscript is a masterclass article that synthesizes existing literature and applied professional insights. No human participants or animals were involved, and no original data were collected. As such, institutional review board approval and informed consent were not required.

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CRediT authorship contribution statement

Margaret M. Michalak: Conceptualization, Data curation, Writing – original draft, Writing – review & editing. **John Cronin:** Conceptualization, Writing – review & editing. **Chloe M. Ryan:** Writing – review & editing. **Michael Rumpf:** Conceptualization, Writing – review & editing. **Daniel O'Brien:** Writing – review & editing. **Christopher Slocum:** Conceptualization.

Declaration of competing interest

The authors declare that they have no conflicts of interest related to this work.

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