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Flywheel Resistance Training for Anterior Cruciate Ligament Rehabilitation

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ABSTRACT

The tearing or rupturing of the anterior cruciate ligament (ACL) has become an increasingly common injury in athletes, particularly in sports that require sharp, pivoting movements and sports that have high deceleration and landing demands. Optimizing each stage of rehabilitation post ACL reconstruction (ACLR) is crucial for successful recovery and the return-to-play of an athlete. Researchers have highlighted the importance of deceleration training and the role of increased eccentric force production and the ability to attenuate rapid braking forces prior to an athletes return-to-sport. There are many training methods that can provide this eccentric overload; however, the focus of this review is on the utility of flywheel resistance training (FRT) during ACL rehabilitation. Due to the limited research of this topic, a narrative review with a systematic approach was conducted. An overview of the literature that has determined the effects of FRT on ACL rehabilitation post ACLR is discussed, including the current loading parameters, and limitations of the research. From the articles included, FRT Bulgarian split squats have been used across studies and have been shown to be effective in eliciting isometric strength gains and improving between-limb strength asymmetries. FRT has also shown to be successful in jump performance, particularly countermovement jump (CMJ) performance. A new perspectives of late-stage ACL rehabilitation with FRT is then proposed, with practical examples provided.

Keywords: Late-stage Rehabilitation, Isoinertial Training, ACL, Eccentric Overload

INTRODUCTION

The partial or full rupturing of the anterior cruciate ligament (ACL) has become an increasingly common injury in athletes, particularly in sports that require sharp, pivoting movements as well as in sports where repeated maneuvers of sudden deceleration, landing and pivoting are necessary (Montalvo et al., 2019). Despite how common ACL tears are and advancements in surgical techniques, return to sport and re-injury rates following ACL reconstruction remain variable.(Manojlovic et al., 2024) Specifically, while approximately 80% of athletes are returning to sport, only 50–65% regain their pre-injury performance levels, and up to 39% are experiencing re-injury (Manojlovic et al., 2024; Wilk et al., 2023). ACL injuries occur both through contact and non-contact mechanisms, with non-contact being the more prevalent cause of injury, skiers, soccer, and football athletes being at higher risk than other athletes (Evans et al., 2024). A non-contact ACL tear takes place when the tibia anteriorly translates while the knee is in a valgus and flexed position, thus applying excessive load and tensile forces on the ACL (Yu & Garrett, 2007). Fleming et al. (Fleming et al., 2001) studied the effects of tibia external load and weight bearing on ACL strain and discovered that anterior force at the proximal tibia significantly increased strain on the ACL as well as increased the internal rotation moment of the knee. Another crucial contributor to the anterior force placed on the ACL are the quadricep muscles, in that these muscles place higher strain on the ACL during knee flexion, caused by increasing peak posterior ground reaction forces during athletic tasks (Yu & Garrett, 2007). Previous researchers have shown individuals with greater peak posterior ground reaction forces during athletic tasks are at a higher risk of a non-contact ACL tear (Yu & Garrett, 2007). Additionally, females appear to be at a greater risk of ACL ruptures with research showing females have a 2-8x increase in injuries, compared to males.(Mancino et al., 2024). This is widely believed to be due to intrinsic risk factors, however it is less clear whether these differences in risk factors are due to sex or a particular threshold measure (Devana et al., 2022). The quadriceps angle is found to be greater in females, as well as the posterior tibial slope, both of which place the tibia at a more anterior position relative to the femur, causing higher stress on the ACL (Devana et al., 2022). Biomechanical factors in landing and abduction movements may also play a role in females being more at risk, however this has not been directly linked to ACL injury rates (Hewett et al., 2005).

Optimizing each stage of rehabilitation after ACL reconstruction (ACLR) is crucial for a successful recovery and the athlete's return to sport. Early rehabilitation lays the groundwork for restoring the athlete's health and performance and can determine how successfully a patient overcomes potential biomechanical dysfunctions following surgery (Waldron et al., 2022). Buckthorpe et al. (Buckthorpe et al., 2024) proposed a set of guidelines and recommendations for ACLR, identifying six key goals for early-stage rehabilitation including; managing pain and swelling, restoring knee joint range of motion (ROM) and strength, normalizing gait patterns, preventing physical deconditioning, and providing psycho-social support to the athlete. As athletes transition from early- to mid-stage rehabilitation, addressing neuromuscular deficits, particularly limb strength imbalances, improving movement quality and motor re-patterning, and re-conditioning fitness, become increasingly vital (Buckthorpe & Della Villa, 2020). Re-learning motor patterns and resolving neuromuscular deficits is essential for optimizing recovery and preventing deconditioning (Buckthorpe, 2021). Strength training both limbs is essential, however training of the uninjured limb in this stage should be aimed to preserve strength and muscle mass rather than enhancing functional strength (Palmieri-Smith & Lepley, 2015). Additionally, restoring closed kinetic chain strength is critical for the athlete's progression to more demanding functional tasks in late-stage rehabilitation (Buckthorpe et al., 2019; Palmieri-Smith & Lepley, 2015). Ensuring sufficient volume of training is reached, continuing to restore strength imbalances, and developing deceleration and landing capabilities are all key goals for late-stage rehabilitation (Buckthorpe, 2019). Buckthorpe et al. (Buckthorpe, 2019) underscored the importance of integrating neuromuscular training into ACLR rehabilitation to improve overall strength, power, and rate of force development (RFD), rather than focusing on isolated training goals during late-stage rehabilitation.

Before an athlete can fully return to their sport, specific criteria must be met to ensure a safe transition and minimize the risk of re-injury (Buckthorpe et al., 2019). In the late-stage rehabilitation phase, emphasis transitions from isolated strength training to functional strength training, serving as the final step before an athlete resumes competitive activity (Buckthorpe & Della Villa, 2020). It is widely accepted that an athlete must achieve full ROM, at least 90% isokinetic strength in the quadriceps and hamstrings, as well as normalized biomechanics in gait, running, and force attenuation, before returning to play (Adams et al., 2012). Current protocols primarily emphasize strength tests and single-leg hop assessments, to enhance multidirectional coordination, maximize explosive strength and power, and develop reactive movement skills (Buckthorpe, 2019; Marques et al., 2020). Implicit in these types of movements are high intensity vertical and horizontal decelerations (Buckthorpe et al., 2024). Rapid decelerations impose significant mechanical loads on the body, often resulting in tissue damage and neuromuscular fatigue, both of which increase the risk of ACL injury (Buckthorpe, 2019; McBurnie et al., 2022). To mitigate the risk of damage accumulation, McBurnie et al. (McBurnie et al., 2022)suggested that training strategies should focus on enhancing an athlete's capacity for load dissipation and developing robust musculoskeletal structures (McBurnie et al., 2022). A key point highlighted in their review is the importance of deceleration training, specifically the role of increased eccentric force production and the ability to attenuate rapid braking forces (McBurnie et al., 2022). There are many training methods and technologies that can provide this eccentric overload; however, the focus of this review is on the efficacy of flywheel resistance training (FRT).

Flywheel resistance training is a relatively new approach that is gaining traction as an important method for training and rehabilitating athletes (Buonsenso et al., 2023). Figure 1 illustrates an individual performing a flywheel squat while wearing a shoulder harness that is attached to a tether, which in turn is attached to a rotating shaft with a flywheel attached. When the individual moves upward (concentric contraction), the tether lengthens spinning the flywheel disc around a rotating shaft/ axis of rotation, thus generating angular momentum (Norrbrand et al., 2010). The angular momentum/ resistance is determined by the concentric movement velocity and the product of the flywheel's mass (m) and radius (r), resulting in rotational inertia ($I = m.r^2$), and is measured as $kg.m^2$ (Norrbrand et al., 2010). The stored angular energy seeks to return to a state of rest as quickly as possible, by rapidly re-wrapping the tether around the rotating shaft, creating an eccentric overload, thereby pulling the individual downwards i.e. eccentric contraction (Vicens-Bordas et al., 2018). The athlete must then decelerate the stored energy from the concentric phase (Buonsenso et al., 2023). As such, FRT is well placed to provide the deceleration control and absorption/dissipation of braking forces, mentioned by McBurnie et al. (McBurnie et al., 2022).

A major advantage of FRT is its capacity to autoregulate resistance based on the athlete's physiological state, adjusting to the user's input. As mentioned previously, the angular momentum stored is directly proportional to the concentric movement velocity. If the individual is injured, ROM, force and/or velocity will be compromised and so the amount of angular momentum created by the individual and stored in the concentric and returned in the eccentric phase will be minimal. As the force-length-velocity capacity of muscle returns, angular momentum increases due to greater concentric input, which in turn produces greater eccentric output. Optimal loading is critical in ACLR recovery, and the capability of the individual to autoregulate their training could help avoid under-prescribing load by providing user defined resistance throughout the full ROM, ensuring continuous load and optimizing muscle stimulation both eccentrically and concentrically (Monajati et al., 2021; Pedrosa et al., 2022).

Given the aforementioned information, the aim of this review is to determine the utility of FRT in the rehabilitation of the ACL. First, the literature is reviewed The information from the existing literature is synthesized to understand the potential strengths and limitations of FRT and a table of loading parameters using FRT for late-stage rehabilitation of ACL is detailed. Thereafter, the gaps in the literature are identified and future research directions articulated. Based on this treatise, a new perspectives approach detailing a periodized approach to FRT is shared.

METHODS

This systematic review was conducted in accordance with the PRISMA guidelines. (Page et al., 2021) The authors search strategy resulted in a total of three research articles from three databases

Figure 1. Athlete performing a squat using the platform flywheel device.

(Google Scholar, PubMed, and Science Direct), therefore a narrative review with a systematic approach is used for this review. The key words used in the search were as follows; "flywheel resistance training" OR "isoinertial training") AND ("ACL rehabilitation" OR "anterior cruciate ligament rehabilitation"). Studies included were peer-reviewed original research articles published in English that investigated flywheel resistance training as part of the rehabilitation of individuals with ACL reconstruction. Studies were excluded if they focused on healthy populations, used only traditional resistance training (TRT) without a flywheel component, were non-English, or were reviews, editorials, abstracts, or animal studies.

OVERVIEW OF CURRENT RESEARCH

In the following section, the researchers that have used FRT for ACL rehabilitation are reviewed. Three research groups with a total of 44 subjects have compared the effects of FRT on ACLR rehabilitation (see Table 1). The use of both males and females in the research is equitable (20 males, 24 females) and subjects were aged between 17 (Stojanović et al., 2023) to 24 years (Henderson et al., 2022; Henderson & Shimokochi, 2024), the average age across studies was 20.4 ± 3.6 years. The subjects were principally team sport athletes such as soccer, volleyball, and handball. Based on the tier system established by McKay et. al. (McKay et al., 2022), subjects used in both Henderson studies (Henderson et al., 2022; Henderson & Shimokochi, 2024) and Stojanović (Stojanović et al., 2023) can be classified as Tier 4, elite, as the athletes included played at an international/NCAA Division I level (McKay et al., 2022). It is important to note that Henderson et al. (Henderson et al., 2022; Henderson & Shimokochi, 2024) utilized the same subjects and experimental conditions; however, the studies were distinct in their experimental focus, as each examined different metrics to address separate research questions and therefore were published as separate papers.

Loading Parameters

A summary of the loading parameters across the three studies can be observed in Table 2. Among the three studies examining the effects of FRT on ACLR rehabilitation, all were conducted during the late stages of the rehabilitation process. The training interventions were 6-8 weeks in duration, with training sessions taking place 2-3 times per week. The most commonly used exercise was the Bulgarian split squat, however Stojanović et al. (Stojanović et al., 2023) also incorporated Romanian deadlifts, half squats and hip thrusts on the flywheel machine. In terms of training volume (load x sets x reps), the methods used across studies were disparate. Henderson et al (Henderson et al., 2022; Henderson & Shimokochi, 2024) performed a single set to exhaustion, while Stojanović et al. (Stojanović et al., 2023) utilized a more periodized approach, in terms of ACLR rehabilitation, with 4-6 sets of 6-10 repetitions for the first three weeks and progressing to 8-10 repetitions for the final three weeks. Additionally, a wide range of loads were employed (0.025-0.075 $kg{\cdot}m^{-2}$) across studies. Given the contrasting approaches used, as well as the limited research, it is hard to make definitive conclusions regarding the optimal loading parameters for ACL rehabilitation. These findings underscore the need for further research exploring the potential benefits of introducing FRT earlier in the rehabilitation process. Such investigations could provide valuable insights into optimizing rehabilitation protocols, improving athlete readiness for return to sport, and creating more efficient recovery pathways.

Results

Researchers comparing FRT and TRT in ACLR patients and athletic populations have reported varying outcomes across muscle function, jump performance, and change of direction testing. Stojanović et al. (Stojanović et al., 2023) found that FRT led to significantly ($p < 0.05$) greater improvements than TRT in multiple assessments: 1) isometric squat strength, FRT resulted in larger gains in both the injured (27.1%, ES = 1.12) and non-injured leg (28.1%, ES = 0.92) compared to TRT (15.2%, ES = 0.85 for both); 2) significant improvements in jump performance were reported in both groups, however the changes in the FRT group were statistically greater e.g. CMJ height, FRT 12.9% (ES = 0.73) whereas TRT 6.7% (ES = 0.34), SL jump height FRT group 23.8% (ES = 1.06) compared to TRT 13.7% (ES = 0.26) and triple hop distance FRT 14.3% (ES = 0.83) and TRT improving by 5.3% (ES = 0.46).

Henderson et al. (Henderson & Shimokochi, 2024) reported significant improvements in SL drop jump height in the injured leg (23.1%, ES = -0.77), compared to the non-injured (0.0%, ES = -0.01), with a large between group effect (ES = -0.90) following eight weeks of Bulgarian split squats on a flywheel device compared to the uninjured leg. In

Table 1. Summary of the three studies on FRT for ACL rehabilitation

Study and Participant Characteristics						Within Group		Between Group
Author	**Groups**	**Subjects (sex, age)**	**Sport (level)**	**Training Intervention Duration Frequency Loading (load x sets x reps)**	**Assessment**	**% Difference**	**ES**	**ES**
Henderson et al. (2022)	Injured leg vs Uninjured leg	N=11 (3 male & 8 female 20.8 ± 2.7)	handball, volleyball, soccer, basketball (collegiate)	8 weeks (completed on injured leg only) 2x/week 1 set to failure First session: 0.025 kg · m^{-2} (female), 0.05 kg · m^{-2} (male) Sessions 2-16: 0.05 kg · m^{-2} (female), 0.075 kg · m^{-2} (male) Bulgarian split squat	Quadricep $RFD_{0\text{-}50ms}$ Quadricep $RFD_{0\text{-}150ms}$ MVIC between leg Quadricep $RFD_{0\text{-}50ms}$ Quadricep $RFD_{0\text{-}150ms}$ MVIC between leg	Injured 23.3% 23.4% NR Uninjured 48.3% NR NR	Injured 0.80* 0.90* 0.40 Uninjured 0.70* 0.30 0.10	0.00-0.01
Henderson et al. (2024)	Injured leg vs Uninjured leg	N=11 (3 male & 8 female 20.8 ± 2.7)	handball, volleyball, soccer, basketball (collegiate)	8 weeks (completed on injured leg only) 2x/ week 1 set to failure First session: 0.025 kg · m^{-2} (female), 0.05 kg · m^{-2} (male) Sessions 2-16: 0.05 kg ·m^{-2} (female), 0.075 kg · m^{-2} (male) Bulgarian split squat	SL DJ height SL DJ height	Injured 23.1% Uninjured 0%	Injured -0.77* Uninjured -0.01	-0.90†
Stojanović et al (2023)	FRT vs TRT in ACLR patients	N=22, (14 male & 8 female 19.9 ± 4.4)	Basketball, soccer, handball (elite)	6 weeks 2x/week Weeks 1-3: 2 sets of 6-10 repetitions; Weeks 4-6 3 sets of 8-10 repetitions 0.075 kg · m-2 Half squat, RDL, SB curl, hip thrust, Bulgarian split squat	Iso strength uninjured Iso strength injured SL jump height CMJ height Limb symmetry SL hop test TL hop test Iso strength uninjured Iso strength injured SL jump height CMJ height Limb symmetry SL hop test TL hop test	FRT 28.1% 27.1 % 23.8% 12.9% 12.3% 23.9% 14.3% TRT 15.2% 18.1% 13.7% 6.7% 18.2% 8.1% 5.3%	FRT 0.92* 1.12* 1.06* 0.73* 0.89* 1.54 0.83* TRT 0.85* 0.74* 0.26* 0.34* 1.09* 0.55 0.46*	2.51† 1.78† 1.48† 2.23† 0.16 1.83 1.78†

*Key: FRT= flywheel resistance training, TRT= traditional resistance training, SL= single leg, DJ= drop jump; * Significant difference between pretest and posttest ($p < 0.05$). † Significant difference between groups ($p < 0.05$). Effect sizes are represented as: Cohen's d= d, small (d = 0.2), medium (d = 0.5), and large (d ≥ 0.8).*

Table 2. Summary of loading parameters for ACL rehabilitation that have currently been used in the literature

Stage of Rehabilitation	Weeks	Frequency	Exercises	Repetitions	Sets	Rest	Load
Late stage	6-8	2-3/week	Bulgarian split squat Half squat Romanian Deadlift	6 to failure	1-3	Not Reported	0.025-0.075 kg · m^{-2}

the injured limb, Henderson et al. (Henderson et al., 2022) found significant ($p < 0.05$) improvements in $RFD_{0\text{-}50ms}$ (23.3%, ES = 0.80), and $RFD_{0\text{-}150ms}$ (23.4%, ES =0.90) following eight weeks of FRT Bulgarian split squats. However, no significant differences were reported between the injured and non-injured limb. While results from these studies are promising, more research is necessary to clarify the role of FRT in improving performance metrics post ACLR, as evidence remains limited.

Summary of Status of the Evidence

In summary, there is a paucity of research quantifying the effects of FRT on ACLR. The methodological quality of the studies included, were evaluated (Brughelli et al., 2008) by two assessors who scored all studies within one point of each other. Stojanović et al. (Stojanović et al., 2023) achieved a score of 17/20, with their primary methodological limitations being the absence of baseline testing and a lack of sport-specific assessments, such as COD or agility tests. Henderson et al. (Henderson et al., 2022; Henderson & Shimokochi, 2024) scored 14/20, the methodological shortcomings noted were; absence of randomization, insufficient clarity regarding baseline testing, the lack of a control group, and the use of assessments that, while somewhat practical, could have been more sport-specific to enhance relevance.

In the limited research conducted thus far, Bulgarian split squats have been consistently utilized across three studies as part of ACL rehabilitation protocols. However, due to inconsistencies in training volume across these studies, it remains unclear what constitutes optimal loading for this exercise in ACLR rehabilitation. Current loading parameters are relatively rudimentary and lack the detailed progression necessary to draw definitive conclusions. Furthermore, as previously stated, the training blocks used in these studies are short, lasting only 6-8 weeks, whereas ACLR recovery may span at least 32 weeks for an athlete to meet the criteria for return to play (Buckthorpe, 2019; Henderson et al., 2022; Stojanović et al., 2023).

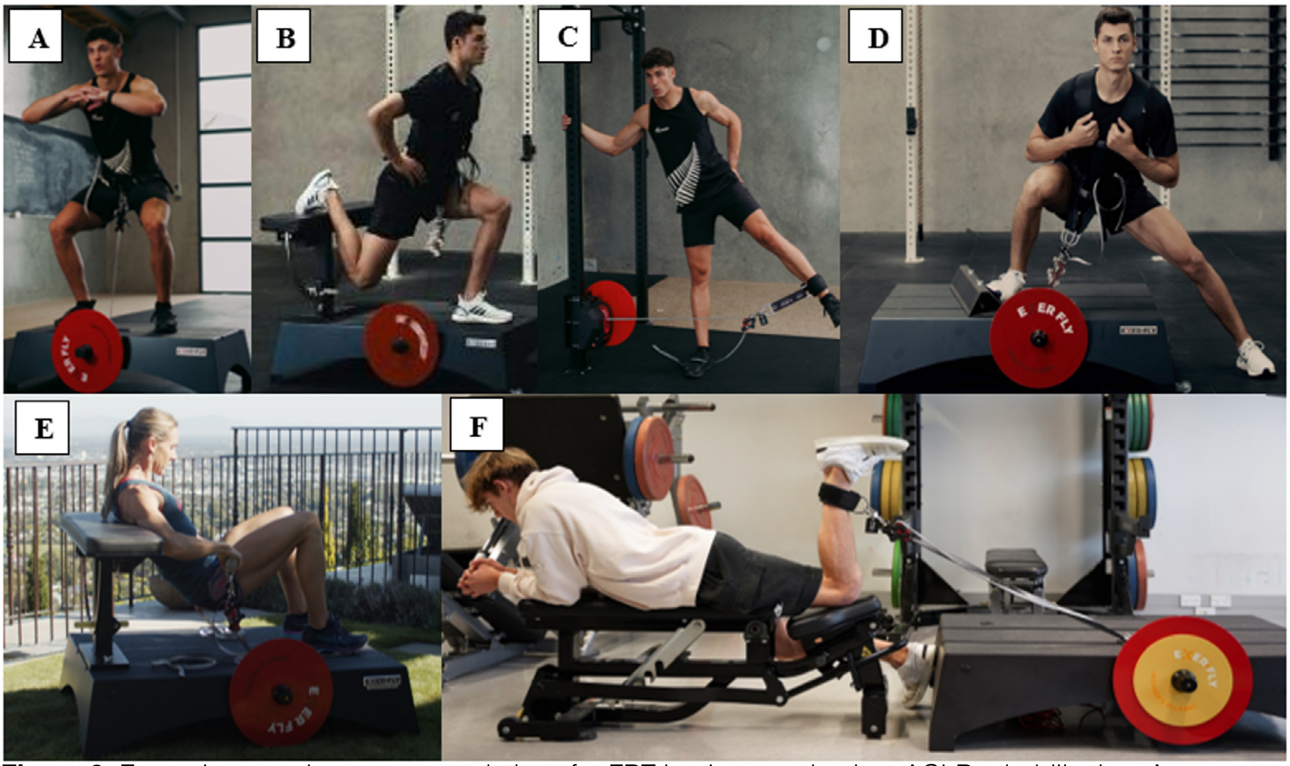

Figure 2. Exemplar exercise recommendations for FRT implementation into ACLR rehabilitation. A= squat; B= Bulgarian split squat; C= standing hip abduction; D= lateral lunge; E= hip thrust; F= prone hamstring curl.

As demonstrated by Stojanović et al. (Stojanović et al., 2023), using 4-6 sets of 8-10 repetitions of Bulgarian split squats was effective in improving strength, power, and limb symmetry, however, as the rehabilitation progresses, it would likely be advantageous to progress loading parameters. For instance, reducing the number of sets and repetitions while progressively increasing the load (rotational inertia) could further enhance maximal strength. This approach aligns with principles of periodization and accommodates the growing capacity of the recovering athlete. With this in mind the next section proposes a framework for the practitioner to use over multiple training blocks.

NEW PERSPECTIVES IN ACL REHAB WITH FRT

The types of flywheel exercises that can be potentially be used during rehabilitation are shown in Figure 2. While thus far, FRT has only been used in what is considered late-stage rehabilitation, there is great potential for it to be introduced earlier in the rehabilitation journey, therefore exemplar programs are detailed across early-, mid-, and late-stage rehabilitation.

Early-stage Rehabilitation

A proposed FRT plan for the early stage of rehabilitation is outlined in Table 3. Early-stage rehabilitation could benefit from low-load, the flywheel providing a safe method to achieve this given the principle of autoregulation discussed previously (Buckthorpe et al., 2024). ROM in the isometric squat is suggested to begin at 60-90° in early-stage and continue to work at 90° in the first half of mid-stage, then progress to full ROM by the end of mid-stage (Buckthorpe et al., 2024; Buckthorpe & Della Villa, 2020). In conjunction with modified training on the flywheel in the injured limb, short term unilateral FRT of the non-injured limb may help aid strength and hypertrophy gains via the cross education effect (Maroto-Izquierdo et al., 2017). Exercises for the injured and non-injured limb should be done in an alternating manner. Due to the neurological and muscular reasonings behind this effect, by incorporating unilateral higher intensity training of the non-injured limb in the early-stage of rehabilitation, it acts as a familiarization period, allowing the athlete to potentially use higher intensities earlier than they would have, had they not been familiarized. The stages of ACLR rehabilitation are subjective to the user, and progression relies on certain milestones being met by the individual (Buckthorpe et al., 2024; Buckthorpe & Della Villa, 2020).

In terms of progression, it is recommended that a combined approach of rate of perceived exertion (RPE) should be used in conjunction with increments in loading of 0.025 kg·m^{-2}. RPE, closely tied to inertial load, has been validated as a successful autoregulation model in rehabilitation and in monitoring exercise load during FRT (Calatayud et al., 2021; Martín-Rivera et al., 2022; Roberts, 2020). As previously stated, initial exercises in early-stage should focus solely on isometric movements, guided by the individual's pain and swelling response. It needs to be noted that isometrics can be easily performed on a flywheel platform by cinching down the tether to the desired angle using a rope clamp. The trained leg can be introduced to FRT for familiarization, with gradual progression.

Mid-Stage Rehabilitation

Gradually increasing the inertial load and movement speed as full ROM is restored and confidence builds. Here, FRT could serve as a useful adjunct

Table 3. Exemplar FRT program for early-stage ACLR

Injured Limb Exercise	Volume (sets x reps)	Load (kg · m^{-2})	Recovery	RPE Scale (1-10)
Knee extension	3x15	0.025	30-60s	4-6
ABD/ADD	2x20	0.025	30-60s	4-6
Quarter squat	3x15	0.025	30-60s	4-6
Isometric squat	5x45s between 60-90°		2 min	4-6
Non-Injured Limb Exercise	**Volume (sets x reps)**	**Load (kg · m^{-2})**	**Recovery**	**RPE Scale (1-10)**
Single leg squat	4x8	0.05	1-2 min	5-7
Single leg RDL	4x8	0.05	1-2 min	5-7
Knee extension	4x8	0.05	1-2 min	5-7
ABD/ADD	4x8	0.05	1-2 min	5-7

to help athletes reacquaint themselves with decelerative forces and braking demands in a controlled manner, perhaps even complementing underwater running or other graded return-to-load activities. (Buckthorpe & Della Villa, 2020). Buckthorpe et al. (Buckthorpe & Della Villa, 2020) suggested the mid-stage of rehabilitation be split into two phases, with the first phase using volume of 12-20 repetitions and the second half using 8-12 repetitions. In addition to its role in reintroducing deceleration, submaximal eccentric training has been shown to significantly enhance strength following ACLR surgery, particularly in the quadriceps (Lorenz & Reiman, 2011; Stojanović et al., 2023). Importantly, submaximal eccentrics are also believed to place less stress on the graft, allowing for safer progression in rehabilitation (Lorenz & Reiman, 2011).

In the first half mid-stage of, FRT should begin at submaximal intensity (RPE 5-7/10) with conservative loading (0.025 kg·m^{-2}). During the mid-stage, the suggested priority is to familiarize the injured leg to FRT without pushing intensity, maintaining conservative submaximal efforts. Familiarization requires multiple sessions, particularly in rehabilitation settings, making it a primary goal of the mid-stage. When moving forward to the second half of mid-stage, training should incorporate higher effort at the same conservative loads. By the end of the mid-stage, the goal would be to reach an RPE of 6-8/10 while achieving full ROM.

Late-stage Rehabilitation

Once an athlete enters late-stage rehabilitation (Table 5), effort should be at or near maximal and loading can now increase Progression should allow for increased movement speed as RPE decreases. Recommended RPE ranges include 5-7 in the mid-stage and 7-9 in the late stage, progressing as symptoms allow. Using FRT to also transition into higher loading, including eccentric overload (see Table 5), could help athletes eventually transition from rehabilitation training to return-to-sport training and may help ensure they are adequately prepared for the demands of the sport (Buckthorpe, 2019, 2021). For example, combining FRT with plyometric elements such as jump variations or focusing on explosive flywheel concentric phases could better prepare the athlete for the dynamic and high-velocity demands of their sport (Buckthorpe, 2021; Henderson & Shimokochi, 2024). These adjustments, paired with appropriate recovery periods, may help bridge the gap between foundational strength training and the high-intensity

Table 4. Exemplar FRT program for mid-stage ACLR

Injured Limb Exercise	Volume (sets x reps)	Load (kg · m^{-2})	Recovery	RPE Scale (1-10)
Hip thrust	3x15	0.05	1-2 min	5-7
Split squat	4x12	0.025	1-2 min	5-7
Single leg calf raise	4x20	0.025	1-2 min	5-7
Squat	4x15	0.025 - 0.05	1-2 min	5-7
Isometric prone hamstring curl	5x45s at 90°		2 min	5-7
Non-Injured Limb Exercise	**Volume (sets x reps)**	**Load (kg · m^{-2})**	**Recovery**	**RPE Scale (1-10)**
Hip thrust	4x8	0.075	2 min	5-8
Split squat	4x8-10	0.05	2 min	5-8
Single leg calf raise	4x10	0.05	2 min	5-8
Squat	4x8	0.075	2 min	5-8
Isometric prone hamstring curl	5x10s		2 min	5-8

Table 5. Exemplar FRT program for late-stage ACLR

Injured & Non-Injured Leg

Exercise	Volume	Baseline Load (kg·m^{-2})	% Boost	Recovery	RPE Scale (1-10)
Squat with triple extension	4x6-8	0.075	5%	2 min	7-9
Bulgarian split squat	4x8	0.05	5%	2 min	7-9
Lateral lunge	4x8	0.05	5%	2 min	7-9

requirements of return-to-play scenarios.

Supramaximal eccentric exercise also plays a crucial role in late-stage ACLR rehabilitation, as it effectively induces hypertrophic adaptations while training the knee to absorb high forces (Lorenz & Reiman, 2011). Some flywheel technologies have motorized eccentric boost technology (Exerfly, Wisconsin, USA) that enables controlled supramaximal training at varying intensities (+1-80% of concentric velocity), making it a potentially valuable tool for transitioning athletes from late-stage rehabilitation to the return-to-sport phase. Overall, a progressive and carefully structured training approach that evolves from general strength to sport-specific power and explosiveness is essential in the later stages of ACL rehabilitation, and FRT may be an effective technique to optimize outcomes and reduce the risk of re-injury (Henderson et al., 2022; Monajati et al., 2021; Stojanović et al., 2023).

These proposed frameworks should be considered as emerging hypotheses based on a blend of current understanding of ACL rehab principles, FRT capabilities, and theoretical reasoning. Future research is needed to validate these concepts and refine their application.

CONCLUSION

Despite advancements in rehabilitation strategies, the number of athletes returning to pre-injury status remain low, and there is no clear consensus as to the most effective rehabilitation strategies (Devana et al., 2022; Waldron et al., 2022). Recognizing that optimal loading is a cornerstone of ACLR rehabilitation, incorporating FRT could offer significant benefits due to its potential adaptability throughout various stages of recovery, and hence be a more effective form of resistance training for ACL patients. Research has demonstrated that FRT effectively enhances muscular strength, RFD, power, and overall force production, which are key for regaining the physical capabilities necessary for high-performance sports (Buckthorpe, 2021; Buckthorpe et al., 2024; Buckthorpe & Della Villa, 2020). Flywheel resistance training (FRT) offers promising potential as an adaptable tool throughout all stages of ACL rehabilitation. Its unique features—including autoregulated resistance, eccentric overload, and versatility for bilateral, unilateral, partial ROM, and isometric exercises—enable individualized loading that matches the athlete's capacity and stage of recovery. These characteristics may simplify load prescription, enhance eccentric control, support cross-education effects, and facilitate safer transitions to sport-specific activities, all of which are critical for restoring strength, stability, and dynamic movement control. (Henderson et al., 2022; Ryan et al., n.d.; Stojanović et al., 2023)

While the theoretical benefits of FRT are compelling, further research is required to fully establish its role across the continuum of ACL rehabilitation. Future studies should document its implementation, effectiveness, and long-term outcomes to determine whether FRT can meaningfully improve recovery timelines, functional performance, and reinjury prevention. Until then, FRT should be considered a promising adjunctive strategy, with its use tailored carefully to individual rehabilitation goals and athlete needs.

CONFLICTS OF INTEREST

The authors wish to declare that Alex Ehlert works for Exerfly.

FUNDING

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ETHICAL APPROVAL

Ethics for this study were approved in line with University's ethics procedure.

AUTHOR CONTRIBUTIONS

Conceptualization, M.M., C.R., A.E., and J.C.; Methodology, M.M., A.E., and C.R.,; Formal Analysis, M.M., and C.R.; Investigation, M.M., A.E., and C.R.,; Data Curation, M.M., and C.R.,.; Writing – Original Draft Preparation, M.M., C.R., and A,E.; Writing – Review & Editing, C.R., and J.C.; Visualization, M.M. and C.R.; Supervision, J.C., C.R., and A.E.; Project Administration, M.M., and C.R.

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REFERENCES

1. Adams, D., Logerstedt, D. S., Hunter-Giordano, A., Axe, M. J., & Snyder-Mackler, L. (2012). Current concepts for anterior cruciate ligament reconstruction: A criterion-based rehabilitation progression. The Journal of Orthopaedic and Sports Physical Therapy, 42(7), 601–614. https://doi.org/10.2519/jospt.2012.3871
2. Beato, M., De Keijzer, K. L., Muñoz-Lopez, A., Raya-González, J., Pozzo, M., Alkner, B. A., Dello Iacono, A., Vicens-Bordas, J., Coratella, G., Maroto-Izquierdo, S., Gonzalo-Skok, O., McErlain-Naylor, S. A., Martin-Rivera, F., Hernandez-Davo, J. L., Arrones, L. S., Sabido, R., De Hoyo, M., Fernandez-Gonzalo, R., & Norrbrand, L. (2024). Current guidelines for the implementation of flywheel resistance training technology in sports: A consensus statement. Sports Medicine, 54(3), 541–556. https://doi.org/10.1007/s40279-023-01979-x
3. Brughelli, M., Cronin, J., Levin, G., & Chaouachi, A. (2008). Understanding change of direction ability in sport: A review of resistance training studies. Sports Medicine, 38(12), 1045–1063. https://doi.org/10.2165/00007256-200838120-00007
4. Buckthorpe, M. (2019). Optimising the late-stage rehabilitation and return-to-sport training and testing process after ACL reconstruction. Sports Medicine, 49(7), 1043–1058. https://doi.org/10.1007/s40279-019-01102-z
5. Buckthorpe, M. (2021). Recommendations for movement re-training after ACL reconstruction. Sports Medicine, 51(8), 1601–1618. https://doi.org/10.1007/s40279-021-01454-5
6. Buckthorpe, M., & Della Villa, F. (2020). Optimising the 'mid-stage' training and testing process after ACL reconstruction. Sports Medicine, 50(4), 657–678. https://doi.org/10.1007/s40279-019-01222-6
7. Buckthorpe, M., Gokeler, A., Herrington, L., Hughes, M., Grassi, A., Wadey, R., Patterson, S., Compagnin, A., La Rosa, G., & Della Villa, F. (2024). Optimising the early-stage rehabilitation process post-ACL reconstruction. Sports Medicine, 54(1), 49–72. https://doi.org/10.1007/s40279-023-01934-w
8. Buckthorpe, M., La Rosa, G., & Villa, F. D. (2019). Restoring knee extensor strength after anterior cruciate ligament reconstruction: A clinical commentary. International Journal of Sports Physical Therapy, 14(1), 159–172.
9. Buonsenso, A., Centorbi, M., Iuliano, E., Di Martino, G., Della Valle, C., Fiorilli, G., Calcagno, G., & Di Cagno, A. (2023). A systematic review of flywheel training effectiveness and application on sport specific performances. Sports, 11(4), 76. https://doi.org/10.3390/sports11040076
10. Calatayud, J., Pérez-Alenda, S., Carrasco, J. J., Cruz-Montecinos, C., Andersen, L. L., Bonanad, S., Querol, F., & Casaña, J. (2021). Feasibility, safety and muscle activity during flywheel vs traditional strength training in adult patients with severe haemophilia. Haemophilia, 27(1). https://doi.org/10.1111/hae.14170
11. Devana, S. K., Solorzano, C., Nwachukwu, B., & Jones, K. J. (2022). Disparities in ACL reconstruction: The influence of gender and race on incidence, treatment, and outcomes. Current Reviews in Musculoskeletal Medicine, 15(1), 1–9. https://doi.org/10.1007/s12178-021-09736-1
12. Evans, J., Mabrouk, A., & Nielson, J. I. (2024). Anterior cruciate ligament knee injury. In StatPearls. StatPearls Publishing. http://www.ncbi.nlm.nih.gov/books/NBK499848/
13. Fleming, B. C., Renstrom, P. A., Beynnon, B. D., Engstrom, B., Peura, G. D., Badger, G. J., & Johnson, R. J. (2001). The effect of weightbearing and external loading on anterior cruciate ligament strain. Journal of Biomechanics, 34(2), 163–170. https://doi.org/10.1016/S0021-9290(00)00154-8
14. Henderson, F. J., Konishi, Y., Shima, N., & Shimokochi, Y. (2022). Effects of 8-week exhausting deep knee flexion flywheel training on persistent quadriceps weakness in well-trained athletes following anterior cruciate ligament reconstruction. International Journal of Environmental Research and Public Health, 19(20), 13209. https://doi.org/10.3390/ijerph192013209
15. Henderson, F. J., & Shimokochi, Y. (2024). Inertial one-leg squat training and drop jump biomechanics in athletes with anterior cruciate ligament reconstruction after return to sport. Journal of Strength and Conditioning Research. https://doi.org/10.1519/JSC.0000000000004983
16. Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S., Colosimo, A. J., McLean, S. G., Van Den Bogert, A. J., Paterno, M. V., & Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. The American Journal of Sports Medicine, 33(4), 492–501. https://doi.org/10.1177/0363546504269591
17. Lorenz, D., & Reiman, M. (2011). The role and implementation of eccentric training in athletic rehabilitation: Tendinopathy, hamstring strains, and ACL reconstruction. International Journal of Sports Physical Therapy, 6(1), 27–44.
18. Mancino, F., Kayani, B., Gabr, A., Fontalis, A., Plastow, R., & Haddad, F. S. (2024). Anterior cruciate ligament injuries in female athletes: Risk factors and strategies for prevention. Bone & Joint Open, 5(2), 94–100. https://doi.org/10.1302/2633-1462.52.BJO-2023-0166
19. Manojlovic, M., Ninkovic, S., Matic, R., Versic, S., Modric, T., Sekulic, D., & Drid, P. (2024). Return to play and performance after anterior cruciate ligament reconstruction in soccer players: A systematic review of recent evidence. Sports Medicine (Auckland, N.Z.), 54(8), 2097–2108. https://doi.org/10.1007/s40279-024-02035-y
20. Maroto-Izquierdo, S., García-López, D., & de Paz, J. A. (2017). Functional and muscle-size effects of flywheel resistance training with eccentric-overload in professional handball players. Journal of Human Kinetics, 60, 133–143. https://doi.org/10.1515/hukin-2017-0096
21. Marques, J. B., Paul, D. J., Graham-Smith, P., & Read, P. J. (2020). Change of direction assessment following anterior cruciate ligament reconstruction: A review of current practice and considerations to enhance practical application. Sports Medicine (Auckland, N.Z.), 50(1), 55–72. https://doi.org/10.1007/s40279-019-01189-4
22. Martín-Rivera, F., Beato, M., Alepuz-Moner, V., & Maroto-Izquierdo, S. (2022). Use of concentric linear velocity to monitor flywheel exercise load. Frontiers in Physiology, 13, 961572. https://doi.org/10.3389/fphys.2022.961572
23. McBurnie, A. J., Harper, D. J., Jones, P. A., & Dos'Santos, T. (2022). Deceleration training in team sports: Another potential 'vaccine' for sports-related injury? Sports Medicine, 52(1), 1–12. https://doi.org/10.1007/s40279-021-01583-x
24. McKay, A. K. A., Stellingwerff, T., Smith, E. S., Martin, D. T., Mujika, I., Goosey-Tolfrey, V. L., Sheppard, J., & Burke, L. M. (2022). Defining training and performance caliber: A participant classification framework. International Journal of Sports Physiology and Performance, 17(2), 317–331.

https://doi.org/10.1123/ijspp.2021-0451

25. Monajati, A., Larumbe-Zabala, E., Goss-Sampson, M., & Naclerio, F. (2021). Injury prevention programs based on flywheel vs. Body weight resistance in recreational athletes. Journal of Strength and Conditioning Research, 35(1), S188–S196. https://doi.org/10.1519/JSC.0000000000002878
26. Montalvo, A. M., Schneider, D. K., Webster, K. E., Yut, L., Galloway, M. T., Heidt, R. S., Kaeding, C. C., Kremcheck, T. E., Magnussen, R. A., Parikh, S. N., Stanfield, D. T., Wall, E. J., & Myer, G. D. (2019). Anterior cruciate ligament injury risk in sport: A systematic review and meta-analysis of injury incidence by sex and sport classification. Journal of Athletic Training, 54(5), 472–482. https://doi.org/10.4085/1062-6050-407-16
27. Norrbrand, L., Pozzo, M., & Tesch, P. A. (2010). Flywheel resistance training calls for greater eccentric muscle activation than weight training. European Journal of Applied Physiology, 110(5), 997–1005. https://doi.org/10.1007/s00421-010-1575-7
28. Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ (Clinical Research Ed.), 372, n71. https://doi.org/10.1136/bmj.n71
29. Palmieri-Smith, R. M., & Lepley, L. K. (2015). Quadriceps strength asymmetry after anterior cruciate ligament reconstruction alters knee joint biomechanics and functional performance at time of return to activity. The American Journal of Sports Medicine, 43(7), 1662–1669. https://doi.org/10.1177/0363546515578252
30. Pedrosa, G. F., Lima, F. V., Schoenfeld, B. J., Lacerda, L. T., Simões, M. G., Pereira, M. R., Diniz, R. C. R., & Chagas, M. H. (2022). Partial range of motion training elicits favorable improvements in muscular adaptations when carried out at long muscle lengths. European Journal of Sport Science, 22(8), 1250–1260. https://doi.org/10.1080/17461391.2021.1927199
31. Roberts, M. (2020). Effect of eccentric flywheel training on musculoskeletal characteristics and physical function in older adults. Coventry University.
32. Ryan, C., Cronin, J., Kulczynski, S., & Ireland, J. (n.d.). New perspectives for the resistance training of runners: Flywheel approach. 2–9.
33. Stojanović, M. D. M., Andrić, N., Mikić, M., Vukosav, N., Vukosav, B., Zolog-Șchiopea, D.-N., Tăbăcar, M., & Melinte, R. M. (2023). Effects of eccentric-oriented strength training on return to sport criteria in late-stage anterior cruciate ligament (ACL)-reconstructed professional team sport players. Medicina, 59(6), 1111. https://doi.org/10.3390/medicina59061111
34. Vicens-Bordas, J., Esteve, E., Fort-Vanmeerhaeghe, A., Bandholm, T., & Thorborg, K. (2018). Is inertial flywheel resistance training superior to gravity-dependent resistance training in improving muscle strength? A systematic review with meta-analyses. Journal of Science and Medicine in Sport, 21(1), 75–83. https://doi.org/10.1016/j.jsams.2017.10.006
35. Waldron, K., Brown, M., & Calderon, A. (2022). Anterior cruciate ligament rehabilitation and return to sport: How fast is too fast? Arthroscopy, Sports Medicine, and Rehabilitation, 4(1), e175–e179. https://doi.org/10.1016/j.asmr.2021.10.027
36. Wilk, K. E., Thomas, Z. M., Arrigo, C. A., & Davies, G. J. (2023). The need to change return to play testing in athletes following ACL injury: A theoretical model. International Journal of Sports Physical Therapy, 18(1). https://doi.org/10.26603/001c.67988
37. Yu, B., & Garrett, W. E. (2007). Mechanisms of non-contact ACL injuries. British Journal of Sports Medicine, 41(suppl 1), i47–i51. https://doi.org/10.1136/bjsm.2007.037192