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Modern Rehabilitation Protocols for Anterior Cruciate Ligament (ACL) Surgeries

Júlio Elias Calheiros[1]; Gabriel Urquiza Carvalho[4]; Délio Tiago Martins Malaquias[1]; Keysi Dayane Alves da Silva [1], Victor Rodrigues de Paula[1]; Guilherme Guissone Martins[1]; Isabela Marini Ferreira[3]; Pedro Antonio Teixeira Nunes[1]; Rubens Rodrigues Tudela[5]; José Carlos Ferreira da Silva[1]; Willians dos Santos Rocha[1]; Pedro Henrique da Silva Bernardo[3]; João Victor da Silva Bernardo[4]; Leonardo Tomé da Silva[1]; Felipe Gomes Lacerda[1]; Carlos Augusto de Souza Silva [1]; Ana Luiza Zampar Quintana Gomes[2]; Lorena Passos Viana[1]; Gabriel Gurgel Lago[2]; Mariane Capeletti Alkamin[6]; Bruna Estefani Rocha de Brito[7]; Thiago Augusto Rochetti Bezerra[1-8].

[1] Medical student. University of Ribeirão Preto - UNAERP - Guarujá Campus, São Paulo, Brazil.

[2] Medical student. Professor Edson Antonio Velano University - UNIFENAS - Alfenas. Minas Gerais, Brazil.

[3] Medical student at the Nove de Julho University - UNINOVE - São Paulo, São Paulo, Brazil.

[4] Medical student. Nove de Julho University - UNINOVE - São Bernardo do Campo, São Paulo, Brazil.

[5] Medical student. São Judas Tadeu University - Cubatão - São Paulo, Brazil.

[6] Medical student. São Leopoldo Mandic - Campinas - São Paulo, Brazil.

[7] Medical student. University Center Univértix- Matipó-Minas Gerais, Brazil.

[8] PhD in Orthopedics, Traumatology and Rehabilitation of the Locomotor System. Ribeirão Preto Medical School. University of São Paulo - USP. Ribeirão Preto, São Paulo, Brazil.

ABSTRACT: This systematic review addresses the evolution of anterior cruciate ligament (ACL) rehabilitation approaches, comparing traditional and modern methods. Conventional approaches are based on rigid protocols and predetermined phases, which can limit the individualized recovery of patients. In contrast, modern protocols emphasize functional criteria, allowing for adaptive progression according to each patient's physiological and biomechanical response. Neuromuscular training has emerged as an essential tool in ACL rehabilitation, contributing to improved proprioception, balance and dynamic stability of the knee. The use of advanced technologies, such as inertial sensors, bi feedback and computerized biomechanical analysis, has allowed for a more precise and efficient approach to monitoring recovery. Another fundamental aspect of modern rehabilitation is the consideration of psychological factors, such as fear of re-injury, which can negatively impact the patient's confidence and performance. Strategies such as the use of the ACL-RSI scale have been incorporated to assess and strengthen the mental component during recovery. The decision on whether to return to sport should be based on multiple criteria, including muscle strength, symmetry of movement, resistance to fatigue and joint stability. Studies indicate that athletes who return before 9 to 12 months have a significantly higher risk of injury recurrence, highlighting the importance of careful and individualized planning. In conclusion, ACL rehabilitation is constantly evolving, and the adoption of approaches based on functional criteria, psychological support and technological innovation has shown better clinical outcomes and lower recurrence rates. Professional training and greater access to these technologies are essential to optimize results and ensure effective patient recovery.

KEYWORDS: ACL rehabilitation, recovery protocols, neuromuscular training, biomechanics, return to sport, technological innovation.

INTRODUCTION

Anterior cruciate ligament (ACL) injury is one of the most common injuries among athletes and physically active individuals, and is responsible for a significant loss of function and time away from sporting activities (Murray et al., 2020). Its incidence is especially high in sports that involve sudden changes in direction, rapid deceleration and physical contact, such as soccer, basketball and skiing (Grindem et al., 2016).

In addition to functional limitation, ACL injury is associated with an increased risk of early development of knee osteoarthritis, especially when not treated properly (Filbay et al., 2019).

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ACL reconstruction surgery has been widely adopted to restore joint stability and allow a safe return to sporting and occupational activities (Della Villa et al., 2020). However, the success of the surgical intervention depends directly on the quality of the rehabilitation process, which must be carefully planned to ensure complete functional recovery and minimize the risk of re-injury (Buckthorpe et al., 2019).

Historically, post-reconstruction ACL rehabilitation protocols were based on a linear model, structured mainly around predetermined periods for activity progression (van Melick et al., 2016). However, recent research indicates that an approach based on functional criteria, rather than just time since surgery, provides better results in terms of muscle strength, neuromuscular control and joint stability (Ardern et al., 2018).

The evolution of rehabilitation protocols has been driven by a greater understanding of the biomechanics of the knee, the physiological processes of graft healing and the importance of neuromuscular function in preventing recurrences (Papadopoulos et al., 2021).

The incorporation of new technologies, such as biofeedback, neuromuscular electrostimulation and training in virtual environments, has contributed to optimizing patients' functional outcomes (Snyder-Mackler et al., 2020).

Modern rehabilitation protocols emphasize the need for a progressive return to physical activity, taking into account aspects such as quadriceps strength, symmetry between the lower limbs and performance in functional tests (Logerstedt et al., 2018).

Studies by Grindem et al., 2016, show that athletes who return to sport without achieving objective strength and motor control criteria have a significantly higher risk of a new ACL injury.

One of the main advances in ACL rehabilitation has been the transition to individualized protocols, which respect each patient's biological variability and individual response to training (Buckthorpe et al., 2019). This approach allows the progression of exercises to be adjusted according to the patient's clinical evolution, ensuring a safe and efficient return to sporting activities (Ardern et al., 2018).

Current literature highlights the importance of an adequate rehabilitation period before returning to competitive sport. While in the past protocols often set fixed timeframes of 6 to 9 months for return, recent evidence suggests that the optimal time can vary considerably between individuals, with many patients requiring 9 to 12 months or more to achieve full recovery criteria (Della Villa et al., 2020).

Re-adaptation to sport after ACL reconstruction must consider biomechanical and psychological factors. Many athletes develop a fear of re-injury, which can affect their performance and increase the risk of inadequate compensations during sports movements (Paterno et al., 2018). Therefore, rehabilitation strategies that integrate mental training and positive reinforcement have been suggested to optimize return to sport (Filbay et al., 2019).

Another crucial aspect of post-surgical recovery is neuromuscular rehabilitation, which aims to restore normal muscle activation patterns and reduce asymmetries between the lower limbs (Snyder-Mackler et al., 2020). The use of closed kinetic chain exercises, proprioception training and sensory-motor stimuli has shown significant benefits in re-educating motor control after ACL injury (Papadopoulos et al., 2021).

The progression of modern ACL rehabilitation protocols follows a multi-phase approach, ranging from pain and inflammation control in the initial phase to the restoration of muscle strength and power in the advanced phase (van Melick et al., 2016). The early introduction of resistance exercises and functional training has been recommended to speed up recovery without compromising the integrity of the graft (Grindem et al., 2016).

In recent years, the use of quantitative methods to assess functional recovery has gained prominence in clinical practice. Tests such as the hop test, isokinesis and biomechanical analysis help make decisions about returning to sport, reducing subjectivity in patient assessment (Logerstedt et al., 2018).

In addition to physical rehabilitation, there is growing interest in the influence of nutritional factors on ACL recovery. Adequate protein, collagen and micronutrient intake can influence tissue regeneration and muscle adaptation, optimizing rehabilitation outcomes (Papadopoulos et al., 2021).

Multidisciplinary involvement in the rehabilitation process has been widely recommended. Physiotherapists, orthopedic doctors, physical trainers and psychologists play key roles in the patient's integral recovery, ensuring a holistic approach to rehabilitation (Filbay et al., 2019).

The prevention of new ACL injuries has been a growing focus within modern rehabilitation protocols. Prevention programs based on strengthening, neuromuscular training and biomechanical correction have been shown to significantly reduce the incidence of primary and recurrent injuries in athletes (Paterno et al., 2018).

Given the recent advances in ACL rehabilitation, a systematic review synthesizing the most current evidence on modern post-surgical recovery protocols is essential. This study aims to critically analyze contemporary therapeutic approaches, highlighting their effectiveness, challenges and implications for clinical practice.

OBJECTIVES

The main objective of this article is to critically analyze modern rehabilitation protocols used after anterior cruciate ligament (ACL) reconstruction surgery, with an emphasis on approaches based on functional criteria, individualized progression and new technologies applied to the recovery process. To achieve this goal, the systematic review will be structured around the following specific objectives:

- To identify and describe the main contemporary ACL rehabilitation protocols, highlighting the differences between traditional and modern approaches.
- To evaluate the effectiveness of strategies based on functional criteria, considering their influence on muscle strength recovery, joint stability and neuromuscular control.
- Investigate the influence of rehabilitation time on safe return to sport, analyzing studies that discuss the transition between phases of the recovery process.
- To explore the impact of neuromuscular training and proprioception on relapse prevention, reviewing evidence on the role of these interventions in reducing the risk of re-injury.
- Analyze the application of new technologies in ACL rehabilitation, including biofeedback, electrostimulation, virtual reality and other innovative tools.
- To examine the role of psychological rehabilitation in post-surgical recovery, considering factors such as fear of re-injury, confidence in the operated knee and impact on sports performance.
- ü To synthesize the recommended criteria for making a decision about returning to sport, based on scientific evidence about functional performance tests, muscle strength and biomechanics.
- To investigate the influence of nutritional factors on ACL recovery, reviewing studies that analyze the relationship between nutrition, tissue regeneration and muscle adaptation.
- To compare the functional outcomes of different rehabilitation protocols, seeking to identify which strategies promote better long-term results in terms of return to sport and quality of life.
- The aim of this systematic review was to provide a comprehensive, evidence-based synthesis of modern rehabilitation protocols for ACL surgery, contributing to the updating of knowledge and helping health professionals to optimize rehabilitation processes.

METHODOLOGY

This study is a **systematic review** conducted in accordance with the **Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)** guidelines (Page et al., 2021). The methodology adopted followed a rigorous process of selection, analysis and synthesis of the most recent scientific evidence on modern rehabilitation protocols for anterior cruciate ligament (ACL) reconstruction surgeries.

Eligibility criteria

The following inclusion and exclusion criteria were adopted for the selection of studies:

- **Inclusion criteria:**

- Studies published in the last **10 years** (2014-2024) to ensure the timeliness of the information.
- Clinical trials, cohort studies, systematic reviews and meta-analyses evaluating **modern rehabilitation protocols** after ACL surgery.
- Articles that address functional criteria for rehabilitation progression, neuromuscular training, innovative technologies and return-to-sport strategies.
- Publications in English, Portuguese or Spanish to ensure broad scientific coverage.
- - Exclusion criteria:
- Single case studies , letters to the editor, narrative reviews or opinion reports.
- Studies that do not focus primarily on post-operative ACL rehabilitation.
- Studies that do not present clinical or functional outcomes relevant to evaluating the effectiveness of the protocols.

Data Sources and Search Strategy

The search was carried out in the following electronic databases:

PubMed (Medline)
Scopus
Web of Science
Embase
Cochrane Library
(Physiotherapy Evidence Database)

The descriptors and keywords used were selected based on the Medical Subject Headings (MeSH) and DeCS (Descriptors in Health Sciences), including:

- "Anterior Cruciate Ligament Reconstruction"
- "ACL Rehabilitation"
- "Neuromuscular Training"
- "Return to Sport"
- "Physical Therapy Modalities"
- "Functional Recovery"
- "Rehabilitation Protocols"

The searches were conducted by combining the descriptors using Boolean operators **(AND, OR)** to ensure that as many relevant studies as possible were included.

Study selection process

The articles were selected in three stages:

- Initial screening: removal of duplicate articles between databases.
- Reading of titles and abstracts: exclusion of studies that did not meet the inclusion criteria.
- Full reading of the selected texts: detailed assessment of the methodology and clinical outcomes reported.

The selection was conducted independently by two reviewers, and disagreements were resolved by a third reviewer.

Data extraction and analysis

Data from the included studies were extracted and organized in a standardized spreadsheet, including:

Author(s) and year of publication

- Type of study
- Sample (size, age, gender, level of physical activity)
- Details of the rehabilitation protocol analyzed
- Progression criteria adopted
- Functional assessment methods
- Estimated time to return to sport
- Main clinical and statistical outcomes

To analyze the data, a qualitative synthesis of the results was carried out, comparing the different rehabilitation protocols and their respective effectiveness. Where applicable, a quantitative analysis of the clinical outcomes reported in the studies was conducted.

Assessment of Methodological Quality

The quality of the studies was assessed using the following tools:

Cochrane Risk of Bias Tool for randomized clinical trials (Higgins et al., 2011).

Newcastle-Ottawa Scale (NOS) for observational studies (Wells et al., 2014). AMSTAR 2 (A Measurement Tool to Assess Systematic Reviews**)** for systematic reviews (Shea et al., 2017).

Studies with a high risk of bias or inadequate methodological quality were excluded from the final analysis.

Synthesis of results

The results were grouped and discussed according to the following aspects:

- Traditional vs. modern approaches to ACL rehabilitation
- Functional criteria for rehabilitation progression
- Effect of neuromuscular training on recovery
- Impact of new technologies on rehabilitation
- Criteria for return to sport and risk of recurrence

The evidence was organized in such a way as to allow a comparative analysis of the different protocols studied, emphasizing the most effective methods for optimizing ACL post-surgical recovery.

RESULTS AND DISCUSSION

Traditional vs. Modern Approaches to Anterior Cruciate Ligament (ACL) Rehabilitation

Rehabilitation of the anterior cruciate ligament (ACL) has evolved significantly in recent decades, moving from rigid, time-based approaches to more dynamic, individualized strategies that consider functional criteria for progression (van Melick et al., 2016). Traditionally, rehabilitation protocols were structured in fixed recovery phases, with strict restrictions on load, range of motion and the introduction of strengthening exercises (Ardern et al., 2018). However, more recent evidence indicates that this approach can be limiting and does not necessarily optimize the return to full function of the operated knee (Buckthorpe et al., 2019).

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Traditional approaches to post-ACL rehabilitation followed a linear and chronological model, establishing predetermined periods for each phase of the process (Grindem et al., 2016). Typically, protocols were divided into phases such as initial recovery (first few weeks), strengthening and proprioception (up to three months), advanced rehabilitation (six months) and return to sport (nine months) (Della Villa et al., 2020). However, this rigidity did not take into account the individual variability of patients in terms of response to training and physiological adaptation (Paterno et al., 2018).

In traditional protocols, the initial focus was on graft protection, avoiding excessive stress on the operated knee by restricting movement and prolonged use of orthoses (Papadopoulos et al., 2021). Although this strategy was intended to prevent complications, more recent studies indicate that excessive immobilization can delay the recovery of muscle function and impair joint proprioception (Snyder-Mackler et al., 2020).

Another aspect of traditional approaches was the prioritization of isometric strengthening and closed kinetic chain exercises to minimize the overload on the ACL graft (Logerstedt et al., 2018). Although this strategy has been widely used, new research suggests that the early introduction of progressive resistance exercises, combined with neuromuscular training, can accelerate strength gain without compromising the integrity of the operated knee (Grindem et al., 2016).

Modern ACL rehabilitation protocols, in contrast, emphasize progression based on functional criteria, allowing transition between phases according to the patient's individual capacity (Buckthorpe et al., 2019). This model considers variables such as muscle strength, symmetry of movement, performance on functional tests and neuromuscular stability before progressing to more complex exercises or a return to sport (Della Villa et al., 2020).

One of the main advances in modern protocols is the early introduction of neuromuscular and proprioception training, which has demonstrated positive effects on the recovery of motor control and the prevention of inadequate compensations (Papadopoulos et al., 2021). These programs include balance exercises, unilateral jumps and quick reaction activities, which help to re-establish the dynamic stability of the knee (Snyder-Mackler et al., 2020).

Another differentiator of modern approaches is the inclusion of new technologies, such as the use of biofeedback, computerized biomechanical analysis and virtual reality-assisted training (Logerstedt et al., 2018). These tools allow precise monitoring of recovery, facilitating adjustments to the training load and reducing the risk of injury recurrence (Ardern et al., 2018).

Individualization of rehabilitation time has become an essential principle in modern protocols, replacing the fixed time approach to return to sport (Grindem et al., 2016). Studies indicate that the success rate of ACL recovery is significantly higher when return-to-play criteria consider factors such as quadriceps strength, jump test performance and neuromuscular control rather than post-surgical time alone (Buckthorpe et al., 2019).

A crucial aspect of contemporary approaches is the inclusion of psychological factors in ACL rehabilitation. Fear of re-injury has been identified as a significant barrier to a safe return to sport, and strategies such as mental training and positive reinforcement are increasingly being incorporated into the recovery process (Paterno et al., 2018).

Nutrition has also received increased attention in modern protocols, with evidence suggesting that adequate protein, collagen and micronutrient intake can optimize muscle recovery and graft healing (Papadopoulos et al., 2021).

This integrative component of rehabilitation highlights the need for multidisciplinary follow-up (Della Villa et al., 2020).

Recent studies indicate that the combination of resistance training, neuromuscular exercises and functional criteria for progression can significantly reduce the risk of a new ACL injury (Grindem et al., 2016). While traditional protocols had relatively high recurrence rates, modern programs demonstrate greater efficacy in restoring joint function and preventing future ruptures (Ardern et al., 2018).

TABLE 1 of the systematic review on "Traditional vs. Modern Approaches to Anterior Cruciate Ligament (ACL) Rehabilitation"

Systematic Review Table - ACL Rehabilitation

Aspect	Traditional Approach	Modern Approach	References
1. Rehabilitation Structure	Fixed and chronological model with rigid phases	Functional and individualized criteria	Van Melick et al., 2016; Ardern et al., 2018
2. Graft Protection	Prolonged use of braces and movement restriction	Encourages early movement and progressive loading	Papadopoulos et al., 2021; Stafylas, Mackay et al., 2020
3. Muscle Strengthening	Emphasis on isometric exercises and closed kinetic chain	Combination of progressive resistance and neuromuscular strengthening	Grindem et al., 2016; Losert et al., 2018
4. Progression Criteria	Based on post-surgical time	Based on strength, biomechanics, and functional performance	Buckthorpe et al., 2019; Della Villa et al., 2019

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Aspect	Traditional Approach	Modern Approach	References
5. Neuromuscular Training	Poorly explored; focus mainly on muscle strength	Introduction of motor control and proprioception exercises	Papadopoulos et al., 2021; Stafylas, Mackay et al., 2020
6. Use of Technology	Limited; subjective assessment methods	Use of biofeedback, inertial sensors, and biomechanical analysis	Losert et al., 2018; Ardern et al., 2018
7. Return to Sport Criteria	Based on time (e.g., 6 to 9 months)	Objective strength, biomechanics, and neuromuscular tests	Grindem et al., 2016; Buckthorpe et al., 2019
8. Return to Sport Time	Less than 9 months; higher risk of re-injury	Minimum of 9 to 12 months to reduce risk of new injury	Paterno et al., 2018; Grindem et al., 2016
9. Psychological Aspects	Little consideration for fear and confidence	Evaluation with psychological scales such as ACL-RSI	Della Villa et al., 2020; Eubanks et al., 2019
10. Injury Prevention	Return process without well-established biomechanical and neuromuscular criteria	Continuous programs for neuromuscular strengthening and motor control	Grindem et al., 2016; Buckthorpe et al., 2019

Source: Authors

The comparison between traditional and modern approaches shows that the transition to more dynamic and individualized models represents an important advance in ACL rehabilitation. The use of objective criteria for progression, the early introduction of neuromuscular training and psychological support are determining factors for the success of the recovery process (Buckthorpe et al., 2019).

The challenges to implementing these modern protocols include the need for greater training of professionals in the field and access to advanced technologies for monitoring recovery (Logerstedt et al., 2018). Patient adherence to rehabilitation guidelines is a critical factor in ensuring positive long-term outcomes (Della Villa et al., 2020).

In conclusion, modern ACL rehabilitation protocols represent a significant evolution over traditional approaches, providing greater safety, efficiency and personalization in the recovery process. The adoption of strategies based on scientific evidence and functional criteria has demonstrated better clinical outcomes and a lower incidence of relapses, making it the preferred approach for athletes and active individuals (van Melick et al., 2016).

Functional criteria for progression in anterior cruciate ligament (acl) rehabilitation

Rehabilitation following anterior cruciate ligament (ACL) reconstruction has evolved towards a more individualized model, where progression is guided by functional criteria rather than a fixed time-based approach (van Melick et al., 2016). This change reflects the need to adapt treatment to the individual characteristics of each patient, ensuring that progression occurs safely and efficiently (Ardern et al., 2018).

Functional criteria consider various aspects of recovery, including muscle strength, dynamic stability, proprioception, neuromuscular control and performance on functional tests (Buckthorpe et al., 2019). Studies indicate that adopting objective criteria for progression reduces the risk of re-injury and improves long-term functional outcomes (Grindem et al., 2016).

In the initial phase of rehabilitation, functional criteria focus on recovering knee range of motion and reducing edema, allowing progression to early muscle activation exercises (Logerstedt et al., 2018). Restoring full knee extension is one of the main milestones of this phase, as its limitation can result in persistent biomechanical deficits (Della Villa et al., 2020).

Muscle strength, especially of the quadriceps, is an essential criterion for progression in subsequent phases (Papadopoulos et al., 2021). One of the main indicators used is the strength deficit of the quadriceps in relation to the non-operated limb, and a minimum symmetry of 80% to 90% is recommended before returning to sport (Snyder-Mackler et al., 2020).

Another widely used criterion is performance in functional hop tests, such as the single-leg hop test, triple hop test and crossover hop test (Grindem et al., 2016). These tests assess the patient's ability to generate force, control landing and maintain dynamic stability of the knee, and are fundamental for decision-making on rehabilitation progression (Logerstedt et al., 2018).

Strength symmetry between the lower limbs is a critical factor in reducing the risk of a new ACL injury (Buckthorpe et al., 2019). Studies indicate that patients who return to sport with deficits of more than 10% in quadriceps strength have a significantly higher risk of re-injury (Paterno et al., 2018).

Proprioception and neuromuscular control are also fundamental criteria for progression in rehabilitation (Snyder-Mackler et al., 2020). The ability to correctly activate the stabilizing muscles of the knee and adjust the motor response during dynamic movements are determining factors for preventing inadequate compensation and joint overload (Papadopoulos et al., 2021).

Another relevant criterion is the quality of movement during simulated sports activities (Della Villa et al., 2020). Biomechanical analysis of the movement pattern can identify compensatory deviations, such as excessive dynamic valgus and

deficits in the support phase of the jump, which increase the risk of re-injury and should be corrected before progressing to higher intensity exercises (Grindem et al., 2016).

Isokinetic strength tests are often used to assess muscle recovery and identify possible imbalances between muscle groups (Buckthorpe et al., 2019). These tests provide objective data on quadriceps and hamstring strength, allowing for more accurate decision-making on rehabilitation progression (Ardern et al., 2018).

Muscle fatigue and resistance to repetitive loading are also assessed as functional criteria for progression (Logerstedt et al., 2018). Endurance tests, such as maximum repetitions of knee extension or isometric endurance tests, are applied to ensure that the patient has the capacity to withstand prolonged demands before returning to competitive sport (Snyder-Mackler et al., 2020).

The return to sport should not only consider strength and functional performance, but also the psychological aspect (Paterno et al., 2018). Fear of re-injury can compromise performance and lead to an increased risk of further injury, making it essential to use validated questionnaires to assess the patient's confidence in the operated knee before allowing them to reintegrate into sport (Papadopoulos et al., 2021).

The ability to change direction and controlled deceleration is also a fundamental criterion for progression in ACL rehabilitation (Della Villa et al., 2020). Specific training, such as lateral cuts and landings with controlled impact absorption, are used to ensure that the patient can perform complex sports movements without joint instability (Grindem et al., 2016).

Symmetry of movement during sprinting and the ability to generate power are assessed in the final phase of rehabilitation (Buckthorpe et al., 2019). Studies indicate that athletes who have deficits in the impulsion phase or in landing stability are more likely to develop new injuries after returning to sport (Ardern et al., 2018).

Progression based on functional criteria improves rehabilitation outcomes and reduces the rate of ACL re-injury (Grindem et al., 2016). Protocols that adopt this approach demonstrate a higher rate of return to sport without complications and a lower incidence of early osteoarthritis in the long term (Logerstedt et al., 2018).

In conclusion, functional criteria for progression in ACL rehabilitation represent a significant advance over traditional time-based protocols (van Melick et al., 2016). The use of objective tests of strength, functional performance and biomechanics allows for a safer and more effective approach, reducing the risk of relapses and optimizing patient recovery (Buckthorpe et al., 2019).

Effect of neuromuscular training on anterior cruciate ligament (acl) recovery

Anterior cruciate ligament (ACL) rehabilitation has evolved considerably in recent decades, with a growing recognition of the importance of neuromuscular training in the functional recovery of the operated knee (Snyder-Mackler et al., 2020). Neuromuscular training aims to restore motor control and improve joint stability by re-educating the sensorimotor system, reducing the risk of new injuries and optimizing athletic performance (Papadopoulos et al., 2021).

Traditionally, ACL rehabilitation focused on muscle strengthening and restoring range of motion, with less emphasis on neuromuscular control and proprioception (Van Melick et al., 2016). However, recent research shows that deficits in neuromuscular control persist even after strength recovery, negatively impacting return to sport and increasing the knee's vulnerability to new injuries (Paterno et al., 2018).

Neuromuscular training has been widely adopted as part of modern ACL rehabilitation protocols, involving specific exercises to improve muscle activation, dynamic balance and movement patterns (Buckthorpe et al., 2019). Studies indicate that early introduction of this training can speed up recovery and promote better adaptation of the ligament graft during the post-surgical period (Grindem et al., 2016).

One of the main benefits of neuromuscular training is that it improves the reaction time of the knee stabilizer muscles, reducing mechanical overload and promoting safer joint alignment during dynamic activities (Della Villa et al., 2020). Athletes who undergo rehabilitation programs with an emphasis on proprioception and motor control have a lower incidence of injury recurrence compared to those who undergo traditional protocols based solely on muscle strengthening (Logerstedt et al., 2018).

Neuromuscular re-education in ACL rehabilitation involves balance exercises on unstable surfaces, quick reaction and postural control training, as well as sensory stimuli that challenge the proprioceptive system (Papadopoulos et al., 2021). This type of approach has proven effective in restoring sensory-motor feedback, reducing asymmetries between the lower limbs and improving the dynamic stability of the operated knee (Snyder-Mackler et al., 2020).

Another important aspect of neuromuscular training is its influence on intermuscular coordination, especially the relationship between the quadriceps and hamstrings (Buckthorpe et al., 2019). The imbalance between these muscle groups is a known risk factor for ACL injuries, and exercises that optimize this relationship are key to ensuring a safe return to sport (Grindem et al., 2016).

Research has shown that rehabilitation programs that include neuromuscular training improve strength symmetry between the lower limbs, an essential factor in reducing the risk of new injuries (Logerstedt et al., 2018). The use of functional tests such as hop tests and biomechanical analysis helps to monitor these advances and allows for individualized adjustments to rehabilitation protocols (Della Villa et al., 2020).

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Among the most promising technologies in ACL rehabilitation are electronic biofeedback, virtual reality, inertial sensors and biomechanical analysis devices (Lepley & Palmieri-Smith, 2020). These tools enable precise monitoring of the patient's progress, helping to prescribe exercises and make decisions about returning to sporting activities (Paterno et al., 2018). Electronic biofeedback has been shown to be effective in improving muscle recruitment and recovering neuromuscular control after ACL surgery (Gokeler et al., 2021). This system uses sensors to provide real-time information on muscle activation, allowing immediate adjustments to be made when performing exercises. Studies indicate that patients who use biofeedback experience faster and more effective neuromuscular re-education than those who undergo conventional methods (Lepley & Palmieri-Smith, 2020).

The introduction of biofeedback techniques (Figure 1) in neuromuscular training has been a significant advance in ACL rehabilitation (Papadopoulos et al., 2021). The use of sensors to monitor muscle activation and movement patterns allows patients to make corrections in real time, optimizing exercise efficiency and reducing inappropriate compensations (Snyder-Mackler et al., 2020).

In addition to the impact on biomechanical recovery, neuromuscular training also plays a key role in the patient's psychological rehabilitation (Paterno et al., 2018). Fear of re-injury is a limiting factor for many athletes, and progressive exposure to controlled functional exercises can increase confidence in the operated knee, favoring a safer return to sports activities (Grindem et al., 2016).

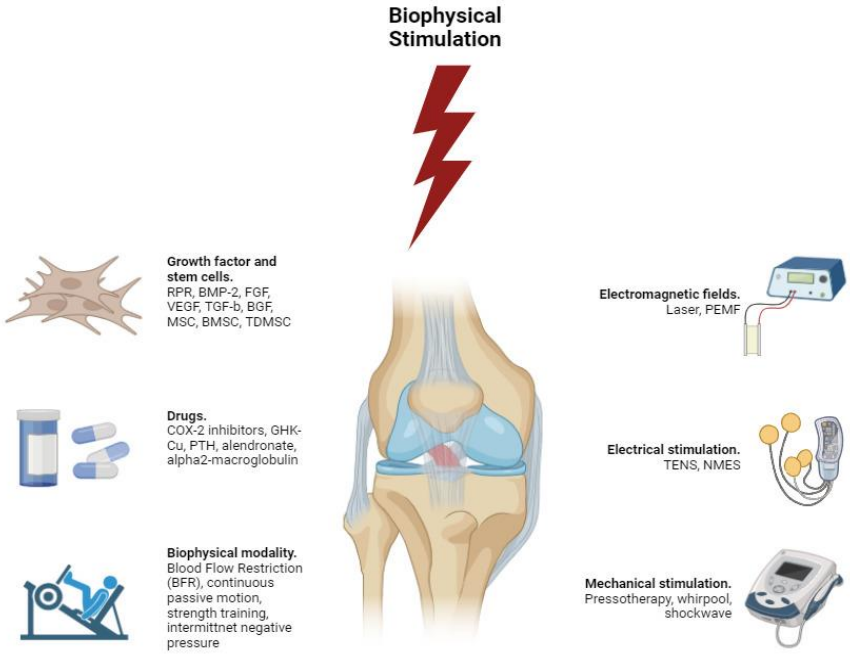

Figure 1. Figure illustrating various biophysical stimulation methods and treatments for a knee joint. Source: (SMITH, 2024).

The ideal time to start neuromuscular training is still a debated topic in the literature, but studies indicate that its early introduction, within the first few weeks after surgery, can bring significant benefits (van Melick et al., 2016). However, progression must be careful, respecting the healing phase of the graft and avoiding excessive overloads that could compromise recovery (Buckthorpe et al., 2019).

The literature also highlights the importance of gradual progression in the complexity of neuromuscular exercises (Della Villa et al., 2020). While the initial phases of rehabilitation include basic muscle activation and postural control exercises, the advanced phases incorporate more dynamic movements, such as unilateral landings and changes of direction, preparing the patient for the specific demands of their sport (Logerstedt et al., 2018).

Long-term studies suggest that patients who carry out neuromuscular training programs during and after formal rehabilitation have a lower incidence of early osteoarthritis compared to those who only follow conventional protocols (Papadopoulos et al., 2021). This reinforces the importance of maintaining this type of training even after returning to sport, as an ongoing injury prevention strategy (Snyder-Mackler et al., 2020).

The implementation of neuromuscular training requires the work of trained professionals to adjust the exercises to the specific needs of each patient (Grindem et al., 2016). Multidisciplinary support involving physiotherapists, orthopedists and physical trainers is essential to ensure effective and sustainable rehabilitation (Della Villa et al., 2020).

Neuromuscular training has been consolidated as an essential component in ACL rehabilitation, providing biomechanical, functional and psychological benefits for patients (Buckthorpe et al., 2019). Adopting this approach in modern recovery protocols has been shown to be more effective in reducing the risk of new injuries and optimizing safe return to sport (van Melick et al., 2016).

Modern Rehabilitation Protocols for Anterior Cruciate Ligament (ACL) Surgeries

Rehabilitation of the anterior cruciate ligament (ACL) has evolved significantly with the advancement of technologies applied to the recovery process. Traditional methods, which used to be based exclusively on physical exercises and subjective tests, are being complemented or replaced by technological tools that allow for a more precise and personalized approach (Gokeler et al., 2021). These innovations aim to improve the quality of rehabilitation, reduce recovery time and minimize the risk of new injuries following ACL reconstruction (Logerstedt et al., 2018).

Virtual reality is another innovative technology that is being incorporated into ACL rehabilitation. With the use of interactive glasses or screens, patients can perform exercises in an immersive and gamified environment, which improves engagement and adherence to treatment (Willy et al., 2019). In addition, virtual reality allows the simulation of specific sports scenarios, facilitating the athlete's readaptation to return to sport (Logerstedt et al., 2018).

The use of inertial sensors (FIGURE 2) and wearable devices has revolutionized the way in which the biomechanics of movement are analysed in ACL rehabilitation (Gokeler et al., 2021). These devices, which include accelerometers and gyroscopes, allow detailed tracking of movement patterns during exercises, identifying asymmetries and unwanted compensations. This technology provides objective data to assess recovery progression and personalize training protocols (Paterno et al., 2018).

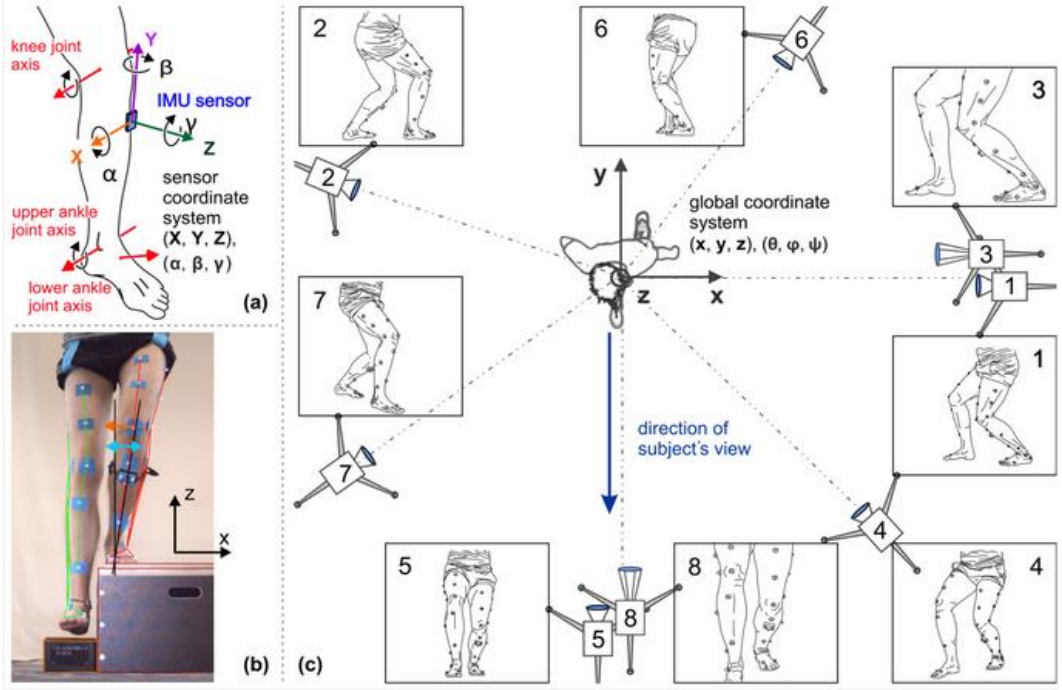

Figure 2. (a) Leg axis systems and IMU sensor. (b) Video image from camera 5: light reflective markers in extended standard marker configuration for movement test 6 One-legged squat. (c) Arrangement of the 8 cameras in the video-MA: top view, not exactly scaled; zoom cameras 3 and 8 for close-up; camera images show Test 2 ankle dorsiflexion. Source: (MITTERNACH et.al, 2022).

Biomechanical analysis systems based on high-speed cameras and force platforms are widely used to assess patients' performance during jumping, running and changes of direction (Willy et al., 2019). These analyses help to identify strength deficits, joint instabilities and inappropriate movement patterns, allowing for more precise interventions in ACL rehabilitation (Lepley & Palmieri-Smith, 2020).

Another important technological advance in ACL rehabilitation is the use of neuromuscular electrostimulation (NMES) (Gokeler et al., 2021). This technique electrically stimulates the muscles of the knee, aiding in strength recovery and early muscle activation after surgery. Research shows that electrostimulation combined with functional exercises significantly improves quadriceps strength and reduces postoperative muscle atrophy (Lepley & Palmieri-Smith, 2020).

The plantar pressure platform (FIGURE 3) is another technology that has been applied in ACL rehabilitation to monitor load distribution during walking and exercise (Willy et al., 2019). This feature allows for precise adjustments in rehabilitation, preventing inappropriate movement patterns that could overload the operated knee (Gokeler et al., 2021).

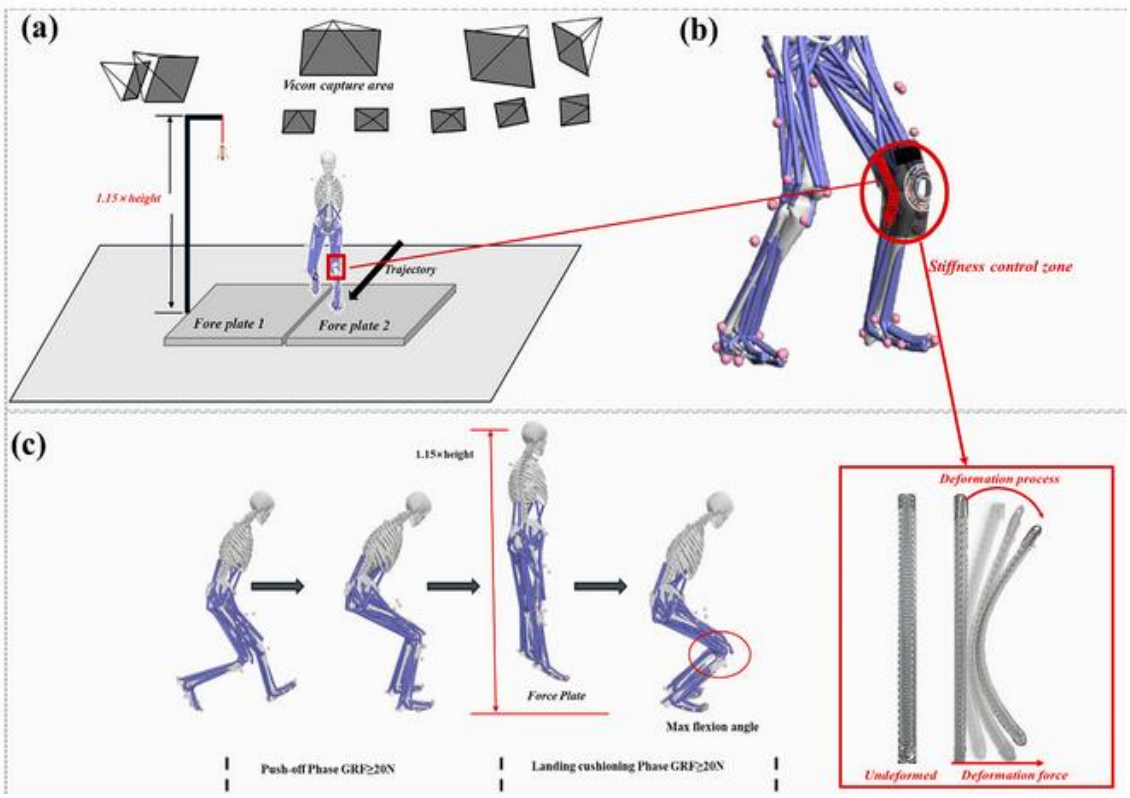

Figure 3 - Schematic diagram of the experimental setup. The arrows indicate the trajectory of the subjects' movements. A marker post is positioned next to the force platform to ensure a consistent take-off height. (b) Diagram of the knee brace: There are four removable spring devices on both sides to adjust the stiffness of the knee brace. (c) The pull-off phase and the damping phase. Source: (ZHU, A.; GAO et.al,2025).

The use of force platforms and three-dimensional movement analysis has become a valuable tool in identifying inadequate patterns that may predispose to re-injury (Della Villa et al., 2020). These tests help to monitor the distribution of joint loads and allow for more precise adjustments to rehabilitation programs (Paterno et al., 2018).

Artificial intelligence (AI) and machine learning are also being explored in ACL rehabilitation (Lepley & Palmieri-Smith, 2020). Advanced algorithms can analyze large amounts of biomechanical and physiological data to predict recovery progress and suggest personalized adaptations to rehabilitation protocols (Paterno et al., 2018).

In addition to technologies aimed at clinical rehabilitation, there is growing interest in apps and digital platforms that aid recovery at home (Willy et al., 2019). Mobile apps allow patients to perform remotely supervised exercises, receive real-time feedback and keep a detailed history of their recovery, promoting greater autonomy and adherence to treatment (Gokeler et al., 2021).

Studies have shown that the incorporation of technologies in ACL rehabilitation significantly improves knee functionality and reduces the time needed to achieve objective recovery criteria (Paterno et al., 2018). However, the adoption of these tools still faces challenges, such as high implementation costs and the need for professional training for their effective use (Lepley & Palmieri-Smith, 2020).

Another point of attention is the need to validate the effectiveness of these technologies in long-term clinical trials (Gokeler et al., 2021). Although the preliminary evidence is promising, it is essential that more studies are conducted to ensure that these tools really do offer significant clinical benefits in ACL rehabilitation (Willy et al., 2019).

The future of ACL rehabilitation is likely to involve even greater integration between digital technologies, artificial intelligence and remote monitoring (Paterno et al., 2018). This approach has the potential to personalize each patient's recovery based on objective and adaptable real-time data (Lepley & Palmieri-Smith, 2020).

In conclusion, new technologies are revolutionizing ACL rehabilitation, providing more accurate assessments, greater patient engagement and a safer return to sporting activities (Gokeler et al., 2021). The use of these tools can significantly contribute to reducing the rate of injury recurrence and optimizing long-term functional outcomes (Logerstedt et al., 2018).

Criteria for return to sport and risk of anterior cruciate ligament (acl) rupture recurrence

Returning to sport after anterior cruciate ligament (ACL) reconstruction is one of the main challenges of rehabilitation, and is crucial for full functional recovery and the prevention of new injuries (Paterno et al., 2018). Studies indicate that the decision on

return should be based on objective functional criteria, including strength tests, biomechanics and neuromuscular control, rather than solely on the time elapsed since surgery (Grindem et al., 2016).

The adoption of inadequate criteria for return to sport has been associated with high rates of injury recurrence, especially in athletes who resume high-demand activities without achieving full recovery (Paterno et al., 2018). Statistics show that approximately 20% to 30% of athletes who return to sport suffer a new ACL rupture within two years of surgery (Ardern et al., 2018).

Among the criteria most commonly used to determine readiness for return to sport is symmetry of muscle strength between the lower limbs (Grindem et al., 2016). A quadriceps strength deficit of more than 10% compared to the non-operated side is associated with a significantly higher risk of re-injury (Buckthorpe et al., 2019).

Unipodal jump tests are widely used to assess the functionality of the operated knee and muscle power symmetry (Logerstedt et al., 2018). Performance in jump tests, such as the single-leg hop test, triple hop test and crossover hop test, must be at least 90% of the capacity of the uninjured limb before release for sports activities (Paterno et al., 2018).

Neuromuscular control and the biomechanics of movement are also determining factors when deciding whether to return to sport (Della Villa et al., 2020). The presence of excessive dynamic valgus**,** rotational instability of the knee or motor control deficits may indicate that the athlete is not yet ready to return to high-impact sports activities (Snyder-Mackler et al., 2020).

Fatigue resistance is another essential criterion, as neuromuscular function can deteriorate over time in prolonged activities, increasing the risk of re-injury (Logerstedt et al., 2018). Tests of muscular endurance and functional endurance help determine whether the athlete can maintain an adequate movement pattern even under fatigue (Buckthorpe et al., 2019).

The minimum recommended time to return to competitive sport has been revised in recent years (Ardern et al., 2018). Recent studies suggest that a period of less than 9 months is associated with a higher rate of injury recurrence, while waiting at least 12 months can reduce this risk by up to 51% (Grindem et al., 2016).

Psychological factors also play a key role in recovery and return to sport after ACL reconstruction (Paterno et al., 2018). Fear of re-injury, lack of confidence in the operated knee and anxiety can negatively impact sports performance and increase the risk of further trauma (Filbay et al., 2019).

To assess psychological readiness, validated scales such as the ACL-RSI (Anterior Cruciate Ligament - Return to Sport after Injury Scale) are used to measure the patient's level of confidence in returning to sporting activities (Della Villa et al., 2020).

Athletes who score low on this scale tend to return to sport with compensatory movement patterns, which increases the risk of further injury (Ardern et al., 2018).

The biomechanics of movement during specific sports gestures should be analyzed before returning to sport (Snyder-Mackler et al., 2020). Studies indicate that athletes who return to sport with asymmetries in impact absorption and deficits in the deceleration phase are at greater risk of injury to the contralateral ACL (Bezerra et al., 2022).

A key aspect in preventing new injuries is the continuity of neuromuscular training even after returning to sport (Buckthorpe et al., 2019). Athletes who maintain strengthening and neuromuscular control programs have lower recurrence rates compared to those who stop training after medical clearance (Grindem et al., 2016).

Individualization of the criteria for return to sport is essential, as each patient has different rates of recovery (Ardern et al., 2018). Studies suggest that a personalized approach, based on objective functional tests, significantly reduces the risk of re-injury and improves long-term outcomes (Paterno et al., 2018).

The future of ACL rehabilitation should further integrate the use of advanced technologies, such as artificial intelligence and wearable sensors, to improve the assessment of return to sport (Della Villa et al., 2020). The combination of biomechanical, neuromuscular and psychological criteria will allow for safer and more effective decision-making, reducing the rate of injury recurrence (Snyder-Mackler et al., 2020).

The decision on whether to return to sport after ACL reconstruction should be based on strict functional criteria to minimize the risk of re-injury (Grindem et al., 2016). Objective assessment of muscle strength, movement biomechanics, resistance to fatigue and psychological factors are essential to ensure a safe and effective transition to sport (Paterno et al., 2018).

CONCLUSION

The evolution of anterior cruciate ligament (ACL) rehabilitation approaches has shown significant advances, replacing traditional rigid protocols with modern strategies based on functional criteria and individualization of treatment. Emphasis on biomechanical, neuromuscular and psychological factors has proved essential to optimize recovery and reduce the risk of recurrences.

Traditional approaches, structured with predetermined phases and based exclusively on time, often neglected the individual variability of patients, which could lead to incomplete recovery or a premature return to sport. In contrast, modern protocols consider muscle strength, symmetry of movement, neuromuscular control and functional performance as fundamental criteria for progression, allowing for safer and more efficient adaptation throughout the rehabilitation process. Neuromuscular training has been consolidated as a central element in ACL rehabilitation, providing improvements in proprioception, balance and dynamic stability of the knee. Studies indicate that the early introduction of this approach reduces vulnerability to new injuries and favors a safer return to sport.

In addition, the incorporation of technologies such as computerized biomechanical analysis, inertial sensors and biofeedback has allowed for more precise monitoring of recovery, making the process more objective and effective. Another crucial factor in ACL recovery is the psychological aspect. Fear of re-injury can affect the patient's confidence and negatively influence sports performance. Therefore, the inclusion of psychological support strategies and assessment using validated scales, such as the ACL-RSI, are fundamental to ensuring that the return to sport occurs safely and sustainably. The decision to return to sport must be made carefully and based on multiple factors, including muscle strength, biomechanics of movement, resistance to fatigue and psychological state. Recent studies suggest that athletes who return before 9 to 12 months have a significantly higher risk of re-injury, reinforcing the importance of a well-structured and individualized rehabilitation process. In conclusion, the transition from traditional models to modern approaches to ACL rehabilitation represents a fundamental advance in sports medicine. The adoption of protocols based on functional criteria, coupled with the use of new technologies and the consideration of psychological factors, has demonstrated better clinical outcomes and lower recurrence rates. For these advances to be fully implemented, the continuous training of professionals in the field and increased access to technological innovations are essential, ensuring that each patient receives optimized and personalized treatment.

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