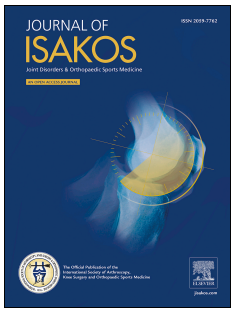

Rehabilitation And Advances In Surgical Reconstruction For Anterior Cruciate Ligament Insufficiency: What Has Changed Since The 1960s? - State Of The Art

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PII: S2059-7754(22)00094-3

DOI: https://doi.org/10.1016/j.jisako.2022.10.001

Reference: JISAKO 59

To appear in: *Journal of ISAKOS*

Received Date: 27 November 2021

Revised Date: 29 March 2022

Accepted Date: 10 October 2022

Please cite this article as: Piedade SR, Leite Arruda BP, Antunes de Vasconcelos R, Parker DA, Maffulli N, Rehabilitation And Advances In Surgical Reconstruction For Anterior Cruciate Ligament Insufficiency: What Has Changed Since The 1960s? - State Of The Art, *Journal of ISAKOS*, https://doi.org/10.1016/j.jisako.2022.10.001.

REHABILITATION AND ADVANCES IN SURGICAL RECONSTRUCTION FOR ANTERIOR CRUCIATE LIGAMENT INSUFFICIENCY: WHAT HAS CHANGED SINCE THE 1960S? - STATE OF THE ART

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All the authors declare no Conflicts of Interest and Source of Funding

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REHABILITATION FOLLOWING SURGICAL RECONSTRUCTION FOR ANTERIOR CRUCIATE LIGAMENT INSUFFICIENCY: WHAT HAS CHANGED SINCE THE 1960S? - STATE OF THE ART

Abstract

Anterior cruciate ligament (ACL) insufficiency can be disabling, given the physical and sports activity constraints that negatively impact the quality of life. Consequently, surgery is the main approach for most active patients. Nonetheless, ACL reconstruction cannot be successful without adequate pre- and postoperative rehabilitation. Since the 1960s, post-ACL reconstruction rehabilitation has evolved, mainly from advances in surgery, coupled with a better understanding of the biological concepts of graft revascularization, maturation and integration, which have impacted ACL postoperative rehabilitation protocols. However, new technologies do involve a definite learning curve which could affect rehabilitation programs and produce inconsistent results. The development of rehabilitation protocols cannot be defined without an accurate diagnosis of ACL injury and considering the patient's main physical demands and expectations. This article discusses how postoperative rehabilitation following ACL reconstruction has changed from the 1960s to now, focussing on surgical technique (type of tendon graft, fixation devices, and graft tensioning), biological concepts (graft maturation and integration), rehabilitation protocols (prevention of ACL injuries, preoperative rehabilitation, postoperative rehabilitation), criteria to return to sports, patient's reported outcomes (PROM), and outcome. Although rehabilitation plays an essential role in managing ACL injuries, it cannot be fully standardized pre- or postoperatively. Pre- and postoperative rehabilitation should be based on an accurate clinical diagnosis, patients' understanding of their injury, graft tissue biology and biomechanics, surgical technique, the patient's physical demands and expectations, geographical differences in ACL rehabilitation, and future perspectives.

Keywords: Anterior Cruciate Ligament Injuries; Rehabilitation; Anterior Cruciate Ligament Reconstruction; Physical Functional Performance; Return to Play; Patient Report Outcome Measures

Introduction

Anterior cruciate ligament (ACL) insufficiency can be disabling, given the physical and sports activity constraints which it imposes and impact negatively on quality of life [**1**]. The importance of the anterior cruciate ligament (ACL) on knee stability was first reported in the period 460-370 BC, but only in the mid-19th century was the clinical description of ACL deficiency actually recorded.[**2, 3**] **The clinical tests for the diagnosis of ACL injury started to be developed in the 1960s [4], when surgical treatment for ACL insufficiency focused on extra-articular techniques** [**5, 6, 7**]

The pivot shift and Lachman tests, more accurate and specific clinical tests, were gradually introduced to evaluate the anatomical functional integrity of the ACL [**8, 9**].
The initial satisfactory results of extra-articular reconstruction techniques were found to gradually deteriorated, and intra-articular techniques started to be employed. [**5**] With the continuous development of new devices for graft fixation, a better understanding of different tendon graft biomechanical behavior, ACL anatomy and biomechanics, surgical reconstruction of the ACL has become a much more predictable procedure [**10, 11**].
Nevertheless, surgery cannot be successful without adequate postoperative rehabilitation. The advances in surgery, coupled with better understanding of the biological concepts of graft revascularization, maturation and integration, have impacted on ACL postoperative rehabilitation protocols [**12, 13**]

This article discusses how postoperative rehabilitation following ACL reconstruction has changed from the 1960s to the present day, focussing on **surgical technique** (type of tendon graft, fixation devices, and graft tensioning), **biological concepts** (graft maturation and integration), **rehabilitation protocols (**prevention of ACL injuries, preoperative rehabilitation, postoperative rehabilitation**), criteria to return to sports**, **patient's reported outcomes** (PROM), and **outcome**.

ACL reconstruction surgical techniques

Several authors proposed extra-articular reconstructions, including anterolateral tenodesis, using the fascia lata combined with a posteromedial imbrication[**14, 15**]. The procedure was followed by immobilization of the knee in a cast for 6 to 8 weeks, an obvious obstacle to early postoperative rehabilitation [**4, 16**]. As peripheral reconstructions did not afford long term knee stability, the focus of surgery shifted to intra-articular reconstructions [**17**]

In the early 1960s, Jones described a technique of intra-articular reconstruction of the ACL using an ipsilateral patellar-tendon bone graft, keeping the distal end of the patellar tendon attached to the tibial tubercle [**17**]. This technique resulted in a graft shorter than desired, and the position of the femoral tunnel was therefore forcedly non-anatomical. These potential problems stimulated new surgical approaches and grafts, such as the over-the-top technique using fascia lata [**18, 19]** A free patellar-tendon bone graft allowed to harvest a graft of adequate length, thus allowing to drill appropriate tibial and femoral tunnels, and gained worldwide popularity **[20, 21, 22**].

Later, novel surgical procedures were proposed, including double-bundle reconstruction, ACL reconstruction associated with anterolateral ligament reconstruction, and the use of different grafts, with no surgical techniques manifestly superior to the others [**23, 24**]. **FIGURE 1 summarizes the process of ACL rehabilitation since the 1960's.**

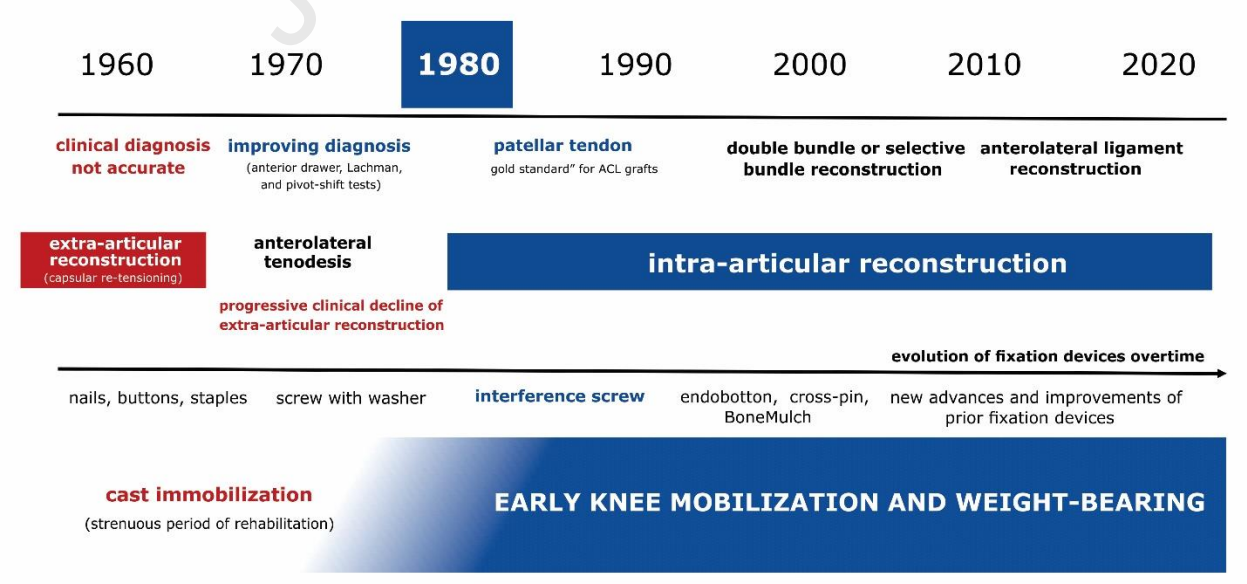

Figure 1 - Summary of ACL postoperative rehabilitation evolution during the advances of clinical diagnosis, graft fixation devices, and surgical techniques.

Graft fixation

A critical variable for the success of ACL reconstruction is the method of fixation of the graft. Originally, tendon grafts were sutured to the surrounding periosteum. This remained the main option until the early 1940s, when nails, buttons, staples, and the concept of press-fit fixation of the bone-end of the bone-patellar tendon-bone graft were introduced.[**15, 17,25, 26**] In the 1980's, with the advent of arthroscopy, screw with washer fixation became widely used. Around that time, Lambert described intra-tunnel fixation with a cortical screw [**27, 28**].

In the mid-1980's, Kurosaka et al. developed the interference screw.[**29**] This system allowed rigid fixation, rapid graft integration into the bone tunnels, and positively sped up rehabilitation following ACL reconstruction [**30**]. Interference screws were initially conceived to fix the bone portion of the graft in the femoral and tibial tunnels. In the late 1980s, Pinczewski [**31**] reported good ACL postoperative outcomes using interference screw fixation with soft tissue grafts.

Cortical screws and washers evolved, and serrated washers were developed to prevent graft slipping into the bone tunnel. In the 1990's, the interference screws became rounded and less sharp, minimizing their potential damage to the hamstring tendon during tunnel fixation. Other new devices were the endobotton, cross-pin ("rider" fixation), and BoneMulch (transverse screw). All these devices are now available in metallic and bioabsorbable materials [**32, 33, 34**].

The use of biologics

Being an intra-articular ligament with a thin synovial membrane, the ACL has a low potential for spontaneous healing [**35**]. **The management of partial and incomplete tears of the ACL remains controversial [36].** To avoid surgical reconstruction in patients with

partial ruptures, biologicals, such PRP, MSCs, GFs, have been used to favour healing of partial ACL tears, and biologicals have been employed to accelerate tendon graft integration to the bone tunnel following surgical reconstruction [**37, 38**].

Some authors reported an increase in ACL cell density and neovascularization with better collagen fibers maturation and biomechanical properties following the use of orthobiologicals. Although these findings seem impressive, the use of biologicals did not result in clinically relevant improvement compared to the patients who underwent ACL surgery without them [**39, 40**].

Graft tensioning

Graft tensioning plays a critical role in surgical outcomes, as it affects the mechanical behaviour of the tendon graft. Postoperatively, the ACL tendon graft may elongate because of its viscoelastic characteristics [**41**]. This biomechanical phenomenon, stress relaxation, may be a critical factor for graft failure and post-reconstruction outcomes [**42, 43]** Graft tensioning before implantation prevents excessive graft elongation postoperatively. Most graft tensioning protocols apply tension to the graft in a cyclic or static mode [**44, 45**]. However, in clinical practice, the forces applied to the graft may vary from each surgeon, and the various protocols do not take into account the graft used, and whether two different tendons are coupled together. Also, the type of fixation and the surgeon's experience are not taken into account [**41**].

Strategies of ACL injury rehabilitation

Nearly three decades ago, Shelbourne reported that the patients who ignored a restrictive rehabilitation program and challenged themselves early actually did better following ACL reconstruction [**30, 46**]. Nevertheless, supervised rehabilitation remains an integral part of management of patients with anterior cruciate ligament injuries.[**47, 48**]

An ACL injury impacts on several fields, causing motor dysfunction, deficits of neuromotor interaction compromising muscle balance, and psychological distress. All

these points reinforce the importance of a comprehensive rehabilitation program approach, both pre-and postoperatively. [**49, 50, 51**]

Preoperative Rehabilitation

Preoperative rehabilitation following ACL reconstruction aims to achieve better quadriceps motor control and range of motion (ROM), establishing favourable clinical conditions to prevent anterior knee pain and quadriceps inhibition in the early postoperative phase. [**30, 52**] In addition, preoperative rehabilitation may also contribute to reduce the occurrence of new injuries and decrease the risk of knee osteoarthritis. **Moreover, patients should be informed on the pro and cons of conservative and operative management of ACL injury before deciding on the best treatment**.[**53]** This preoperative intervention may increase the patient's awareness and better understanding of their injury and the importance of rehabilitation, improving the functional and psychological recovery, and positively reflecting on postoperative outcomes. **Table 1 presents the main goals of the preoperative strategy of ACL reconstruction.**

In 1996, Shelbourne et al. [**47**] demonstrated, in retrospective studies, that intensive rehabilitation protocols initiated before surgery may have a beneficial impact on functional outcome after surgery. After more than 25 years, systematic reviews have validated these programs and their positive effects on postoperative functional outcomes [**52**].

Preoperative rehabilitation of ACL injury focuses on regaining knee range of motion, quadriceps and hamstring strengthening and muscle balance, knee proprioception, plyometrics, and specific functional rehabilitation.[**54**] However, when analyzing the effectiveness of this preoperative rehabilitation process on postoperative physical and psychological outcomes, a recent review identified a lack of consensus on the optimal preoperative program regarding the content, frequency, and length. Therefore, even though preoperative rehabilitation of patients with ACL insufficiency is recommended as a valuable tool for postoperative outcomes, more research should be performed. [**55**]

Table 1 shows the main goals of preoperative Rehabilitation of ACL injury.

TABLE 1 – **MAIN GOALS OF PREOPERATIVE REHABILITATION OF ACL INJURY** (3-24 weeks)

MAIN GOALS OF PREOPERATIVE REHABILITATION OF ACL INJURY (3-24 weeks)	
control and diminish pain, swelling and inflammation	
restore normal knee range of motion, especially extension	
identify and approach psychological hurdles involved in return sports practice	fear or lack of trust in the knee discussing pros and cons of treatment options
muscles strengthening and stretching exercises	quadriceps and hamstring hip strength and stability closed kinetic chain exercises open kinetic chain exercises balance and coordination training
Balance and proprioception	Single leg standing, BAPS board and BOSU ball exercises
neuromuscular training	core strengthening and balance, plyometrics, resistance and speed training (drop and jump exercises)
improve quality of life	

Postoperative Rehabilitation

ACL postoperative rehabilitation aims to minimize knee pain, swelling, and inflammation following surgical trauma, reestablish full knee range of motion and neuromuscular control, enhance recovery, and return to pre-injury physical or sports activities level. The better understanding of graft biomechanics, biology, advances in surgical technique, and improvements in graft fixation devices have guided the development of postoperative rehabilitation protocols.

At the beginning of the 1980s, the graft was protected during the first several postoperative weeks. At that time, the rehabilitation protocol following a modified Jones patellar tendon-bone graft involved knee immobilization and no weight-bearing for 6 to 8 weeks [**30**]. Rehabilitation transitioned from rigid knee immobilization to immediate, continuous passive motion in 1983. [**56, 57**].

At that time, Shelbourne and Nitz [**30**] collected subjective and objective data from two populations that differed in terms of whether they had followed the recommended cautious approach or had voluntarily strayed away from it and accelerated their weight-bearing mobilization and physical activities. Surprisingly, non-compliant patients experienced better outcomes than compliant ones, returning to their normal function sooner, with no adverse effects.

The development of new reliable fixation devices such as the interference screw (Kurosaka's screw) contributed to change the early rehabilitation protocol, allowing early knee mobilization and weight-bearing [**29, 30, 58**]. **Figure 1 shows the changes in ACL postoperative rehabilitation with the advances in clinical diagnosis, graft fixation devices, and surgical techniques.**

Postoperative rehabilitation protocols

The rehabilitation protocols have evolved, in line with new knowledge on how tendon grafts behave under mechanical stresses in the early postoperative stages [59, 60]. A suitable rehabilitation protocol should maintain the integrity of the graft during the various

phases of maturation to avoid breakdowns and functional instability. The most recent international clinical consensus [**58**] agrees that the ideal physiotherapy protocol should include early mobilization, cryotherapy, functional quadriceps electrical stimulation and weight unloading during the first three weeks postoperatively, in addition to incorporating both closed and open kinetic chain exercises and neuromuscular control. Functional braces and continuous passive motion are not recommended, and rehabilitation can be undertaken under supervision by a rehabilitation specialist or, in selected patients, at home. Both closed and open kinetic chain exercises can be introduced before the third postoperative months, restricting only the angle of execution of the quadriceps strengthening in open-kinetic chain mode between 45 and 90 degrees [**58]**. Furthermore, there is currently no evidence of superiority of closed over open kinetic chain exercises in terms of return to sport, ligament laxity, functional questionnaires, or reported physical function, regardless of the graft or **surgical techniques [**59**].**

Current evidence-based postoperative ACL rehabilitation

Continued advances in ACL reconstruction techniques and a better understanding of the biological healing time frames of ACL grafts support the adoption of more aggressive rehabilitation involving early mobilization, and strength and endurance conditioning. However, some linear or non-linear periodic model of changes and adjustments on variable intensity, volume, and frequency are performed to avoid muscle and neuromuscular overloading and consequently fatigue. In this context, periodization of ACL rehabilitation seems to be an attractive strategy to optimize adaptation of the neuromuscular system and increase muscle performance. In clinical practice, periodization programs of ACL rehabilitation may change according to the number and exercise order, rest periods, training frequency, among others. **[61]**

Most of the recent ACL postoperative rehabilitation protocols include initial (phases 1 and 2) and late phases (phase 3 and 4). [62, 62, 63, 64] The first phase of the initial rehabilitation program spans between 2 and 5 weeks, and phase 2 covers 2 to 12 weeks. In phase 1, isometric exercises of the quadriceps and hamstrings muscle complexes, active and passive mobilization to gain knee ROM, and cryotherapy are the most commonly reported components of the program. Transcutaneous (TENS) and neuromuscular (NMES)

electrical nerve stimulation, hip abduction and adduction exercises, knee and patella mobilization, gait training and ankle exercises are commonly adopted. In phase 2, rehabilitation concentrates on neuromuscular training and proprioception exercises, aiming to regain full active and passive ROM of the knee. Progressive resistance training, including leg press, calf and step-ups, and exercise bike, stepping on the stepping machine or a stair stepper, elliptical training or walking on a treadmill can also be introduced in this phase.

Phase 3 takes 2 to 24 weeks, and phase 4 ranges from 2 to 12 weeks. In phase 3, proprioceptive training and balance exercises, running, plyometric exercises and jump training are introduced. In phase 4, resistance training, sport-specific exercises for neuromuscular control and proprioception training are started. Moreover, agility exercises, sprinting, cutting drills, and plyometrics can also be added to the rehabilitation protocol in this phase. Gradual return to sports practice starts in this phase. The effectiveness of different strategies and approaches in ACL postoperative rehabilitation directly impacts on the outcomes of the reconstruction. In a recent systematic review**,** Nelson et. al. (2021) **[66**] reported that vibration training has been described as an exciting approach to the process of neuroplasticity involved in ACL reconstruction, improving strength, neuromuscular control and knee stability. Moreover, the short- and long-term clinical benefits of accelerated rehabilitation are not so consistent compared to traditional ones and need further investigation. Open kinetic chain exercises in the initial phases of rehabilitation remain controversial, while closed kinetic chain exercises are commonly recommended in the initial postoperative phase. In relation to neuromuscular stimulation and water exercises, the authors found moderate benefits in the early rehabilitation stages. Table 2 presents the main goals of the postoperative strategy of ACL reconstruction and implemented phases.

There are four fields where clinical studies regarding the effectiveness of rehabilitation programs directly on the functional outcome, whether in prevention or return to sport following ACL injuries.

TABLE 2 - MAIN GOALS IN POSTOPERATIVE REHABILITATION OF ACL RECONSTRUCTION

MAIN GOALS IN POSTOPERATIVE REHABILITATION OF ACL RECONSTRUCTION	
PHASE 1 (until 5-week postoperative)	
pain relief, diminish swelling, and inflammatory response to surgery	
restore normal knee range of motion	passive and active exercises
isometric exercises of quadriceps and hamstrings	
Cryotherapy	
additional measures	transcutaneous (TENS) and neuromuscular (NMES) electrical nerve stimulation, hip abduction and adduction exercises, knee and patella mobilization, gait training and ankle exercises
PHASE 2 (until 12-week postoperative)	
restore full active and passive range of motion of the knee	
proprioception exercises	
neuromuscular training	
PHASE 3 (until 24-week postoperative)	
proprioceptive and balance exercises,	
plyometric exercises	
jump training	
Running	
PHASE 4 (until 24-week postoperative)	

resistance training
neuromuscular control and proprioception
sport-specific exercise (sprinting, cutting drills, and plyometrics)

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Prevention of ACL injuries in Athletes

Studies on the prevention of ACL injuries started around the turn of the century, with Hewett et al. demonstrating the higher incidence of ACL injuries in women, with biomechanical factors being essential variables. Evidence-based guidelines based on longitudinal studies with thousands of young female athletes under the age of 20 suggest that the inclusion of pre-season programs and pre-workout warm-up involving strengthening of the hip, thigh using, among other modalities of muscle contraction, plyometrics, reduced by 64% the incidence of ACL injuries and by 30% severe knee injuries [67].

TIPS AND TRICKS	
PREOPERATIVE REHABILITATION OF ACL	**REHABILITATION ACHIEVEMENT**
	▪ minimize knee pain, swelling, and inflammation following injury ▪ better quadriceps motor control ▪ reestablish full knee range of motion (ROM) ▪ prevent anterior knee pain and quadriceps inhibition in the early postoperative phase ▪ reduce the occurrence of episodes of knee instability and consequence of new injuries ▪ opportunity to inform and discuss with the patient the pro and cons of conservative and operative management of ACL injury

- minimize knee pain, swelling, and inflammation following surgical trauma

POSTOPERATIVE ACL REHABILITATION

- early mobilization
- reestablish and improve neuromuscular control
- reestablish full knee range of motion
- knee proprioception, plyometrics
- gradual return to pre-injury physical or sports activities level

PREVENTING COMPLICATIONS IN ACL POSTOPERATIVE REHABILITATION

- respect the biological time frames of the graft
- attention to patient's emotional status during rehabilitation
- reestablish quadriceps motor control and range of motion
- manage patients's expectations based on their ACL injury pattern

Criteria for returning to sport

Patients with ACL injuries wish to return to the same pre-injury level after surgery or conservative treatment. Graft maturity post-reconstruction may play a role in failure rate when athletes return to play too quickly; various modern explanations include inadequate graft maturation, decreased psychologic readiness and confidence, poor core control, inadequate rehabilitation of coordination, and fitness. There are remarkable differences between professional athletes compared to recreational athletes. For example, professional soccer players exhibit return rates at the same pre-injury level of 83% (6), while recreational athletes have significantly lower rates at 55% [68].

After analyzing ACL biomechanical risk factors in football players**,** Dauokas et al. [**69**] identified that players who sustained a lower-limb injury within the previous 12 months showed an increased maximum knee valgus angle and decreased minimum knee flexion

angle at initial landing contact compared to players with no history of lower limb injuries within the previous 12 months, and concluded that ACL rehabilitation and return to sport should focus on restoring knee kinematics.

In addition, the graft rupture rate has been between 20-23% in the same knee or contralateral knee in a young population [70]. To decrease the rates of graft re-rupture and increase the rates of return to sport at the same pre-injury level, rehabilitation specialists have focused on elaborating intensive rehabilitation and test battery protocols for return to sport to be performed 6 to 10 months after surgery [71]. These test batteries should include functional questionnaires, kinesiophobia questionnaires, limb strength and symmetry tests, arthrometry ligament laxity tests, different unipodal jump tests, and agility tests. Recent systematic reviews and meta-analyses give conflicting results, as only 23% of patients can pass all test batteries. In addition, as a predictive value, the return to sport tests shows a 60% reduction in the risk of reinjury to the operated knee, but a 235% increase in the risk of injury to the contralateral knee [71]. These findings are based on a few high-quality studies which cannot be fully generalized yet to produce widely accepted strategies to optimize return to sport at the pre-injury level.

Analyzing the postoperative outcomes - Patient's voice (PROM)

In all areas of modern medicine, health care professionals must be aware of patients' voice and opinions, as they play an essential role in developing and refining a management plan. Therefore, adequate tools should allow to collect solid and valid data on the treatment received from the patient's point of view. Patient-Reported Outcomes Measures – PROMs should allow to analyze and compare outcomes, highlight changes, and improve treatment plans However, it should be considered that the demands and expectations of athletes differ from those of the general population. Therefore, **a PROM instrument tailored to capture the athletes and sports practitioners' perception of the whole treatment process is necessary** [72].

VALIDATED OUTCOME MEASURES AND CLASSIFICATIONS
CLINICAL ESCORES
IKDC
MARX ACTIVITY RATING SCALE
LYSHOLM SCORE
TEGNER ACTIVITY SCALE
4-DOMAIN Sports PROM
FUNCTIONAL EVALUATION
HOP TEST
ISOKINETIC EVALUATION

CONSIDERATIONS IN ACL REHABILITATION

Postoperative rehabilitation following ACL reconstruction is still relatively heterogeneous. It has gone through several phases, including the most conservative protocol by Paulos et al.[**56**], in the early 1980s, whose discharge criteria was a 9 to 12-month postoperative period, and the accelerated protocol by Shelbourne et al., in the early 1990s. Evidence-based practice points to the fact that rehabilitation after ACL reconstruction (ACLR) should be carried out progressively, respecting the physiological process of biological maturation of the graft. The rehabilitatiove goals should not just be time-based [**73**], and include objective functional parameters [**74**] and psychosocial aspects.

Over time, new approaches have improved rehabilitation, accelerating knee function recovery pre- and postoperatively. Since then, the advances in knee joint biomechanics, kinetics, biology, and new technologies (surgical instruments, fixation devices) have

guided the development of rehabilitation. The current foundations for ACL rehabilitation have five main fields, with the final goals to correct undesirable knee kinematics adaptations following ACL injury either in the preoperative or perioperative condition [**75**], such as restoring passive and active knee range of motion, quadriceps activation and strengthening, training of neuromuscular control, and return to sports practice (discharge criteria).

An ACL-deficient knee is more vulnerable to repeated episodes of uncomfortable and painful joint instability, tested using the pivot shift and reported by ACL deficient patients as knee "giving-way", a phenomenon that occurs when an extended ACL-deficient knee is charged by valgus stress and moves to slight flexion. The pivot shift sign involves knee joint movements in more than one plane and is more pronounced when the knee is under weight-bearing conditions, clinically manifested by rotatory instability. In a laboratory *in vivo* study, Ferrer et al. **[76]** reported lower torque values of internal rotation at the beginning and mid-stance time intervals and higher values in the crossover task toward the end of the stance phase, and also an avoidance pattern when performing a pivoting-jump task comparing ACL-deficient knees with a control group.

As knee instability is recurrent, patients unconsciously adopt a slight flexion of the knee to avoid the pivot shift phenomenon. However, this strategy will increase the shear forces on the knee joint, predisposing to new or additional meniscus and osteochondral injuries.

A knee extension deficit is undesirable, and is reported in 4% to 35% of patients with ACL deficiency [**77**]. A lower knee extension range could be harmful to the patient's daily living activities, such as walking, climbing and descending stairs, sitting and standing, as well as running. A deficit of only 5° of the knee extension could result in an abnormal gait from increased joint load, patellofemoral pain, and quadriceps weakness, and lower muscle torque at the extremes of knee extension [**53**], and increase the risk of knee osteoarthritis [**78**]. Moreover, in the postoperative period, a knee extension deficit may also predispose to graft failure [**79**], given its greater vulnerability to mechanical stress and shearing forces resulting from such deficit.

A retrospective cohort study showed that failure to achieve full knee extension in the early postoperative period was a significant risk factor in developing the "cyclops" syndrome –

a nodule of fibrovascular tissue formed in the anterior portion of the ACL graft [**80**]. The symptomatic knee extension deficit results from the impact of the "cyclops" lesion against the intercondylar space.

These clinical findings reinforce the importance of starting physiotherapy as soon as the diagnosis of ACL injury is confirmed. Consequently, one of the primary goals in rehabilitation is to reach full knee extension, comparable to that of the non-injured knee as quickly as possible, and physiological quadriceps muscle activation [**75, 81]**. Moreover, even starting up to 6 weeks preoperatively, physiotherapy produces positive results, leading to a faster return to sport [**81**].

Therefore, restoring full knee extension after ACLR is of paramount importance, and should be an early goal of rehabilitation. In a cross-sectional study with 74 individuals after ACLR, Noll et al. [**82]** demonstrated that the pattern of knee extension ROM achieved at four weeks postoperatively has a strong correlation with the knee ROM at 12 weeks.

Biggs et al. [**83**] reported complete knee extension in 100% of participants using a specific protocol focused on ROM recovery started immediately after the surgery. Isberg et al. [**84**] demonstrated no functional impairment or graft laxity after ACLR when knee extension was introduced immediately in the early postoperative phase.

In a randomized controlled study, Yazdi et al. [**85**] reported improving knee extension in two weeks when manoeuvres of knee extension were performed during ACL reconstruction. However, there was no difference at 6, 12 or 24 weeks compared to participants who did not receive this intervention.

Wilk and Arrigo [**86**] applied clinical physiotherapeutic techniques to restore knee extension such as hamstring stretching in the operated lower limb, thigh and calf, maintaining knee extension with a rolled up towel under the ankle for 10-15 minutes, four times a day, totaling 60 minutes. Biggs et al. [**83**] proposed knee extension performed by the patient in a sitting position pulling a towel tied to the foot while stabilizing the proximal portion of the knee.

Patellar mobility is a vital point to be assessed during postoperative ACL rehabilitation. Restricted or absent patella motion may cause knee pain and discomfort in the operated

knee. This complication may result from the scar tissue adhering to the patellar retinaculum and its fat pad, causing patellar tendon retraction and reduction of overall knee ROM comprising the complete knee extension and patellar movements. It reinforces the importance of starting patellar mobilizations (lateromedial and superior-inferior), anti-inflammatory measures, reducing oedema, which also play an essential role in restoring knee extension postoperatively.[**86**]

Quadriceps muscle deficit is a common barrier to the restoration of knee function. The leading cause is still arthrogenic muscle inhibition (AMI), where the quadriceps muscle contraction fails as a consequence of neural inhibition. These mechanisms can come from changes in the resting motor threshold, changes in the triggering of joint sensory receptors, spinal reflex and abnormal cortical activity [**87**]. Therefore, quadriceps activation and strengthening are imperative, acting as turning points of ACL rehabilitation**.**

A review of the level of evidence of the main interventions against arthrogenic muscle inhibition (AMI) showed that cryotherapy and exercises for quadriceps and hamstrings muscles are adequate measures, with moderate evidence against arthrogenic muscle inhibition (AMI).[**87**]

In addition, the quadriceps muscles activation should start in the first few days after the ACL R with open-kinetic chain exercises (i.e. exercises performed with the foot free, not fixed to on object or ground), isometric exercises or elevation (straight leg raise - SLR) without long-term functional impairment [**84, 88**]

Fukuda et al. (2013) [**89**] used a protocol for quadriceps muscles training performed in a controlled angle extension chair (90°-45°) in patients with hamstring grafts, comparing early training initiation (4 weeks) to late training (12 weeks), and found no difference in functional variables or graft laxity at a 17-month follow-up.

Closed-kinetic chain (CKC) exercises have been related to less pain and lower risk of graft loosening.

After the third week, and depending on the patient's tolerance, eccentric exercises performed within limited ROM can be started because they produce better strength

development than concentric ones [**75, 90**] give some preference to CKC exercises, starting the modalities in OKC exercises (except SLR and isometrics) after six weeks, again within limited ROM.

CKC and OKC exercises play an essential role in quadriceps muscle activation and strengthening. Furthermore, when neuromuscular electrical stimulation (NMES) is associated, it is more effective in strengthening the quadriceps muscle group than rehabilitation alone. [**75**]

Recently, Toth et al. (2020) [**91**] randomized 25 individuals with ACL injury, comparing the use of NMES and placebo NMES. In this study, all patients used placebo NMES or NMES for three weeks, preoperatively, and for three weeks, postoperatively, starting 72 hours after surgery, for 60 minutes, five days a week. The results demonstrate decreased atrophy in type II muscle fibers and preservation of contractility in type I muscle fibers.

Therefore, strengthening or initial activation of quadriceps muscles must be carried out promptly and progressed according to tolerance to biological responses of the graft and the patient.

Neuromuscular control is a critical aim to achieve the success of ACL rehabilitation. In addition to quadriceps strengthening, other strategies allow to improve the limb's motor control, aiming to develop dynamic unconscious joint motor control. Ghaderi et al. (2020) [**92**] demonstrated that neuro-training control could be beneficial even after rehabilitation. On the other hand, recent systematic reviews [**58**, **75**] recommend the use of neuromuscular control training (NCT) in rehabilitation protocols, although there is no specific NCT intervention[**93**].

Returning to sports practice is the main focus of the ACLR. However, preventing new injury and re-rupturing after the ACLR is also a concern for both the medical team and the Athlete as it can reach 5% in the ipsilateral limb and 10% in the contralateral limb for the ACLR. [94] The actual rate of return to the pre-injury sports level does not exceed 65%, while the rate of athletes who return to their desired at a competitive level longer than two years drops to 38%. [75]

Vila et al. [**95**] followed elite soccer athletes who suffered ACL injuries for up to 19 years: most reinjuries occurred within two years after returning to the sport, both on ipsilateral to the ACLR and contralaterally. At the end of the follow-up, almost 20% of the athletes had suffered an ACL re-rupture.

The final phase of ACLR rehabilitation is aimed at establishing the patient's ability to return to sports practice. In the literature, clinical practice guides [**96**], as well as systematic reviews [**58**], have presented rehabilitation protocols which consider the individual's skills in sports, and their physical and emotional aspects [52]. Therefore, it reinforces the importance to include physical test batteries such as hop tests [**96**] as well as applying specific PROMs such as IKDC, KOOS, Lysholm [**75**], **4-DOMAIN SPORTS PROM** [**97**] to assess the mental health of individuals [**50**], to try and identify the patient's capability to return to sport, support sports practice to minimize further ligament rupture.

MAJOR PITFALLS OF ACL REHABILITATION

- delay and inaccurate diagnosis of associated ligament injuries
- **neglecting** the biological time frames of the graft
- **absence of a careful evaluation of** patients' response during rehabilitation
- inadequate management of patient's expectations

GEOGRAPHICAL DIFFERENCES IN ACL REHABILITATION

Brazil

Worldwide, ACL rehabilitation protocols have followed the advances in ACL surgical techniques and instruments, biomechanical studies, and a better understanding of graft healing and its integration to the bone tunnel. Firstly, a sizeable scientific production has occurred at centers in the United States, Europe and Australia. With world globalization, knowledge and experiences on ACL rehabilitation have become more available, especially

with the advent of the internet, increasing this capacity exponentially, and allowing physicians and physiotherapists to access quality literature anywhere worldwide.

In Brazil, the rehabilitation of ACL insufficiency has converged into a consensus regarding preoperative and postoperative approaches, closely connected to the literature updates. Based on large university centers, many research groups have been carrying out studies on the rehabilitation of ACL insufficiency, allowing Brazil to achieve a place in the hall of references on this subject. Moreover, since telerehabilitation has been introduced to the rehabilitation protocol, it has become popular in Brazil as a valuable alternative tool to offer information to patients and continue their rehabilitation even in pandemic times.

EUROPE

Europe is composed of many states, each with their own peculiarities. In this respect, there cannot be a Europe-wide approach. In general, the Nordic states have produced scientifically valid strong research in this field, and have shown, for example, that conservative management of ACL injuries can be feasible in selected individuals, and that structured rehabilitation produces consistently favourable results. In countries where a National Health Service is strongly radicated, and a finite expenditure health expenditure is available, research has focused on the health economics of given procedures. In this context, therefore, it is not surprising that in such countries it has been established that home rehabilitation is feasible, and can produce results similar to what achieved following formal rehabilitation in dedicated settings.

Often, in Southern Europe research has focused on ‘the fastest return to sport’ paradigm, and it is therefore not surprising that reports have emerged of elite athletes return to first team duties in less than 100 days. Though eye catching, these reports do not necessarily stress that elite athletes are genetically gifted, are superbly trained and highly motivated: it is therefore understandable that they may be able to return to high level sport participation, but this does not imply that their feats are the norm in the weekend warriors.

AUSTRALIA

Management of ACL injuries within Australia has largely historically paralleled practices described in this review, as Australian surgeons have often studied overseas in North

America and the UK, and have also looked to literature from these regions for guidance. As such there has been a similar evolution from the era of open surgery with postoperative immobilization and very restricted rehabilitation protocols in the 1970's and '80's, to less invasive arthroscopic techniques with more accelerated rehabilitation protocols thereafter.

Whilst traditional rehabilitation protocols have been largely time-based, with set time frames for progression through stages of the program and return to play, more recent protocols have emphasized safe return to sport, and performance-based progression through the sequential phases of rehabilitation. This has been driven by recognition of the need to minimise the high rate of reinjury, particularly in younger populations, and rehabilitation programs have therefore been developed around regular testing, using assessments that have high level evidence for predicting success of return to sport and risk of reinjury. What has also been recognized is the need to respect additional meniscal or chondral pathology that may require modification of rehabilitation time frame expectations. Well-structured preoperative injury rehabilitation, followed with individualized, performance-based postoperative rehabilitation and a graduated return to training and ultimately competition is a fundamental principle of managing these patients.

A comprehensive postoperative testing protocol has both objective and subjective elements. Subjectively patients complete PROMS to measure performance and confidence (IKDC and ACL-RSI) and objective measures that include isokinetic strength testing, balance and agility testing, laximetry and high resolution MRI scans. In our practice high resolution MRI scans at 12 months postoperatively have proven useful in assessing the entire joint, but particularly assessing graft signal. Recent studies have demonstrated a relationship between increased graft signal and the risk of re-rupture, as well as improvements in signal in certain patients between 1 and 2 years, lending some credibility to possibly recommending a delay in return to sport in these patients [98]. Overall, we believe that once patients have completed the appropriate rehabilitation program, and successfully met the above objective and subjective criteria, their chance of successful return to sport with minimised reinjury risk has been optimized.

Future perspectives

Regarding the future of rehabilitation protocols for ACL insufficiency, biomechanical studies and technological advances could play an essential role in developing new approaches; however, neuromotor control, early knee mobilization, quadriceps activation should remain at the heart of rehabilitation protocols.

Preventing an ACL injury and reinjury will remain major topics in rehabilitation. Studies addressing physical demands, potential muscle imbalances, inappropriate sports gestures, and injury risk factors related to each sports modality will contribute to develop new rehabilitation protocols and prevent their occurrence.

The application of a PROM tailored for sports practitioners may meet **the expectations in the patient's reports by** offering a more detailed analysis of rehabilitation, and also helping to monitor and evaluate treatment outcomes, contributing **to guide changes in ACL rehabilitation protocol.**

Return to sports after ACL reconstruction will remain a crucial rehabilitation protocol aim; the development of a comprehensive analysis of physical demands related to each modality of sport, level of sports training and competition, and assessment of athlete's biotype will continue to be the primary references to establish a customized strategy for return to sport.

The care of the mental health of athletes should receive closer attention in a rehabilitation protocol, guiding the outcomes evaluation and helping to develop new rehabilitation strategies.

Covid-19 has changed the world dynamics, and, as a consequence, **telerehabilitation has come to the forefront. This new approach in rehabilitation should continue in the future as a valuable tool for ACL rehabilitation strategies** as it allows several physiotherapists to be connected and discuss patients' rehabilitation protocols, and for patients to be followed and evaluated from afar.

FUTURE PERSPECTIVES IN ACL POSTOPERATIVE REHABILITATION
▪ neuromotor control, early knee mobilization, quadriceps activation should remain at the heart of rehabilitation protocols ▪ advances in prevention measures in ACL injury and reinjury ▪ PROM tailored for sports practitioners may meet their expectations and contribute to improve rehabilitation protocols ▪ new approaches to accelerate return to sports after ACL reconstruction ▪ closer attention to Athlete's mental health care ▪ telerehabilitation

To sum up, the rehabilitation protocols following ACL injury have markedly changed since the 1960's. Rehabilitation plays an essential role in managing ACL injuries, but it cannot be fully standardized pre- or postoperatively. Pre- and postoperative rehabilitation should be based on an accurate clinical diagnosis, patients' understanding of their injury, graft tissue biology and biomechanics, surgical technique, and the patient's physical demands and expectations.

Acknowledgments "We wish to thank Ana Karina Castro Zandona Rocha Piedade for the help given in preparing the Figure 1."

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BOX 1 - KEY ARTICLES

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BOX 5 - FUTURE PERSPECTIVES IN ACL POSTOPERATIVE REHABILITATION

- development of new strategies to restore neuromotor control, early knee mobilization, quadriceps activation should remain at the heart of rehabilitation protocols
- investing on advances in prevention measures in ACL injury and reinjury
- improvements in PROM tailored for sports practitioners may meet their expectations and contribute to improve rehabilitation protocols
- development of new approaches to accelerate return to sports after ACL reconstruction
- closer attention to Athlete's mental health care (considering their aims as athletes, social conditions, recurrent sports injuries, emotional lability)
- in clinical practice, telerehabilitation will be more present as an alternative to assess patients and guide health professionals involved in ACL postoperative rehabilitation, particularly in cases when presential evaluation cannot be carried out

BOX 2 - TIPS AND TRICKS

PREOPERATIVE REHABILITATION OF ACL REHABILITATION ACHIEVEMENT

- minimize knee pain, swelling, and inflammation following injury
- restablish full knee range of motion (ROM
- achieve better quadriceps motor control
- prevent anterior knee pain and quadriceps inhibition in the early postoperative phase
- **resistance training to gain muscle mass and strength close to 90% of the contralateral limb**
- prevent anterior knee pain and quadriceps inhibition in the early postoperative phase
- reduce the occurrence of episodes of knee instability and new injuries
- inform and discuss with the patient the pro and cons of conservative and operative management of ACL injury
- optimally prepare for surgery

POSTOPERATIVE ACL REHABILITATION

- focus in resolving arthrogenic muscle inhibition

- early knee mobilization and weight-bearing
- optimize loading to maximize quadriceps muscle function
- restore full knee range of motion
- reestablish and improve neuromuscular control
- rebuild knee proprioception and plyometricability
- gradually return to pre-injury physical or sports activities level

PREVENTING COMPLICATIONS IN ACL POSTOPERATIVE REHABILITATION

- respect the biological time frames for graft healing and integration
- reestablish quadriceps motor control and range of motion
- evaluate the patients' emotional status during rehabilitation (discussing their expectations of the treatment, outcomes and, future projects of work and life
- manage patients's expectations based on their ACL injury pattern

BOX 3 - VALIDATED OUTCOME MEASURES AND CLASSIFICATIONS

CLINICAL SCORES

IKDC (standard documentation system for knee ligament injuries)

MARX ACTIVITY RATING SCALE

LYSHOLM SCORE (correlation of symptoms and functional criteria)

TEGNER ACTIVITY SCALE

4-DOMAIN Sports PROM (PROM tailored for athletes and highly sports practitioners)

FUNCTIONAL EVALUATION

HOP TEST (variation of single-legged hop tests for distance, time, hop and stop, crossed hops to assess the dynamic knee stability during the rehabilitation and predict knee function on returning to sport)

ISOKINETIC EVALUATION OF QUADRCIPES AND HAMSTRINGS (balance between flexors and extensors of the knee)

- **BOX 4 - MAJOR PITFALLS OF ACL REHABILITATION**

- delay and inaccurate diagnosis of associated ligament injuries
- **neglecting** the biological time frames of the graft
- **absence of a careful evaluation of** patients' response during rehabilitation
- inadequate management of patient's expectations

Conflict of interest

Campinas, November 19th, 2021

The undersigned authors hereby approve the submission of article **REHABILITATION FOLLOWING SURGICAL RECONSTRUCTION FOR ANTERIOR CRUCIATE LIGAMENT INSUFFICIENCY: WHAT HAS CHANGED SINCE THE 1960S? - STATE OF THE ART,** and the subsequent transfer of all their copyrights by the Journal of ISAKOS, in order to allow its publication. The authors further attest that the work represents an original material, which does not infringe any third party copyright, and that no part of this work has been published or will be submitted for publication in another journal.

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