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Marc Dauty[1,2,3], Pierre Menu[1,2,3], Olivier Mesland[1,2] and Alban Fouasson-Chailloux[1,2,3]

[1]CHU Nantes, Physical Medicine and Rehabilitation Center, University Hospital of Nantes, France;

[2]CHU Nantes, Service de Médecine du Sport, University Hospital of Nantes, France;

[3]INSERM UMR U1229/RMeS, Regenerative Medicine and Skeleton – Nantes University, France

Corresponding author: Alban Fouasson-Chailloux

MPR Locomotrice et Respiratoire, CHU de Nantes, Hôpital St Jacques, 85 rue Saint Jacques, 44093 Nantes, Cedex 1.

E-mail: alban.fouassonchailloux@chu-nantes.fr

Tel: +33 240 846 211

Abstracts

Arthrofibrosis is a devastating complication after Anterior Cruciate Ligament reconstruction (ACLr) characterized by a muscle weakness secondary to an arthrogenic muscle inhibition process. The loss of knee isokinetic strength due to arthrogenic muscle inhibition may be more important after arthrofibrosis, compared to an ACLr population with no complication. The isokinetic strength deficit [Limb Symmetry Index (LSI) at 60 and 180°/s of angular speed] was measured at 4, 7 and 12 post-operative months. Knee function, return to running and return to sport were evaluated. A comparison of the Quadriceps and the Hamstring LSI between patients with arthrofibrosis and those without post-operative complication was performed according to time and taking into consideration the type of surgical procedure. 539 primary ACLr patients were assessed. The arthrofibrosis group presented at 4, 7 et 12 post-operative months a Quadriceps LSI significantly lower compared to the control group, without influence of the graft procedure (LSI: 38, 53, 68% vs 63, 73, 85% at 60°/s respectively). The Hamstring LSI was significantly lower at 4 and 7 post-operative months, but comparable at 12 months with an influence of the Hamstring procedure. Knee function was significantly lower at 4 and 7 post-operative months. Few arthrofibrosis ACLr patients returned to running at 7 post-operative months (6.8% vs 69.9%; $p<0.0001$). An important and durable Quadriceps muscle weakness occurred after arthrofibrosis, whatever the type of graft procedure. This is explained by an Arthrogenic muscle inhibition which compromised the return to sport at the same level until 12 post-operative months.

Key Terms: Knee, ACL reconstruction, Isokinetic, Arthrogenic muscle inhibition.

Introduction

Each year, many patients have anterior cruciate ligament reconstruction (ACLr), in order to return to sport[19,27]. The process of post-operative recovery takes time to obtain a painless and movable knee which associates stability and strength recovery[5,6]. A medical follow-up is recommended to assess the recovery process in order to return to sport at the same level[2]. A quadricipital strength deficit of 30% (Limb Symmetric Index (LSI) of 70%) between the operated and the non-operated side may allow the return to running[28]. A symmetrical strength of the quadriceps (LSI ≥ 90%) would be preferable to return to a competitive sport involving contacts and pivoting movements[7].

Usually, muscular strength is reliably and reproducibly assessed with an isokinetic dynamometer[13]. The LSI highlights the arthrogenic muscle inhibition which predominates on the quadriceps on the operated side, because of post-operative joint swelling and local inflammation[29]. A gradual improvement over several months is expected during the post-operative follow-up after ACLr[38]. Yet, the LSI can be particularly reduced and takes long time to recover in case of post-operative complications such as anterior knee pain, posterior knee pain or arthrofibrosis[4]. Moreover, the type of graft may influence the hamstring arthrogenic inhibition in case of hamstring[3].

The arthrofibrosis represents a formidable post-operative complication with a variable incidence of 4 to 38%[8]. It is explained by a joint invasion of fibrous tissues responsible for a joint ankyloses. Three topographies are described: intercondylar, suprapatellar or lateral, and supracondylar[12]. It is secondary to a fibroblastic and endothelial proliferation - a dense type I, II and IV collagen fibers formation depending on an overexpression of cytokines such as TGF-β, platelet-derived growth factor and fibroblastic growth factor[9,11,18].

Clinically, knee range of motion decreases, which is easily observable, and enables the surgeon to propose a mobilization under general anesthesia or an early arthrolysis[1,15,22,31,40].

Different types of arthrofibrosis have been described in the reference classification of Shelbourne et al [8,33]. Type 1 corresponds to an isolated knee extension decrease inferior to 10° (due to an insufficient rehabilitation?). Type 2 is characterized by an isolated knee extension decrease superior to 10°, usually secondary to a « Cyclops syndrome » [14,18,39]. Types 3 and 4 have a decrease of the extension and the flexion associated to a decrease or an absence of patella mobility, described as « Infrapatellar contracture syndrome »[23,24]. « Complex Regional Pain Syndrome » has also been used to describe these 2 last types [3,18,21].

A strength deficit, difficult to improve by rehabilitation, has also been described in case of arthrofibrosis[33]. However, this strength deficit is almost never measured, while it is certainly responsible for difficulties to return to daily activities or previous sport [21]. It is the consequence of the arthrogenic muscle inhibition, which may be associated to a mechanical part due to the joint stiffness.

The main objective of this work was to assess if the arthrogenic muscle inhibition (in accordance with the Quadriceps and Hamstring LSI) was higher in a group of patients with arthrofibrosis compared to a control ACLr group at 4 and 12 months after surgery. We also evaluated arthrofibrosis consequences according to the number of physiotherapy sessions performed before 4 months, according to the function of the operated knee and according to the return to running and to sport at the same level.

Materials and Methods

Population

Since 2005, all our patients operated on an ACLr performed an accelerated post-operative rehabilitation (Early full weight-bearing with crutches, early passive and active knee extension)[17,32]. Cycling was proposed at the 2nd post-operative month and the practice of jogging at the 3rd one by the orthopedic surgeon[22]. At 4 months after surgery, the follow-up was performed by an independent physician of Physical Medicine and Rehabilitation, to assess the isokinetic strength recovery of the quadriceps and the hamstrings. The objective of this isokinetic evaluation was to detect the consequences of any post-operative complications on the knee muscle strength and to advise the return to sport until competition[3]. Yet, some patients developed arthrofibrosis with difficulties of hamstrings and quadriceps strength recovery, despite continuing rehabilitation care. Return to sport at the same level was in these cases compromised. So, from a historical cohort between 2008 and 2018, we retrospectively included all the patients who underwent a primary ACLr (Bone-Patella-Tendon-Bone (BPTB) or Hamstring (H) procedure) with or without meniscus lesion or extra articular tenosis, and performed isokinetic tests at 4, 7 and 12 months after surgery. We excluded patients who had an associated osteotomy, an ACLr revision, a concomitant other ligament reconstruction, a posterior cruciate ligament injury or reconstruction, a knee arthrolysis, a malposition of the drill tunnels on post-operative x-rays or a Cyclops syndrome surgery. We also excluded ACLr patients who had a post-operative infection, a knee swelling, an anterior or posterior knee pain without ROM reduction or a contralateral knee pathology. Patients who performed less than 3 isokinetic tests during the follow-up were not included.

We identified 2 ACLr groups of patients at 4 months after surgery: an arthrofibrosis ACLr group which had the type 3 of the Shelbourne et al.'s classification[33] and a control ACLr group without complications. Diagnosis criteria were, at 4 months, a reduction of the knee

extension superior to 10° and a reduction of the knee flexion superior to 25°, and no knee instability. This association of clinical signs present at 4 months enabled us to exclude surgical failures that might have induced a loss of knee flexion or extension, but not both at the same time (incorrect position of the bone tunnels or excess of graft tension)[11,18,20,30].

Isokinetic evaluation

All the first isokinetic measurements were performed at the 4th postoperative month after ACLr, using a CybexNorm® isokinetic dynamometer (Ronkonkoma, NY, USA). All subjects were seated with a hip angle of 85°. The mechanical axis of the dynamometer was aligned with the lateral epicondyle of the knee. The trunk and the thigh were stabilized with belts. The knee range of motion was 100° (100 to 0° = maximal knee extension). Torque was gravity-corrected at 45° of knee flexion and the dynamometer calibration was monthly performed in accordance with the manufacturer's instructions. Every session was preceded by familiarization with the isokinetic movements (3 submaximal movements). The patients were tested over 3 maximal repetitions at the angular speed of 60°/s followed by 5 maximal repetitions at 180°/s. A 30-second recovery period was allowed between both series. The non-operated knee was always first evaluated after instruction and with verbal encouragement and visual feedback. We considered the maximal strength in Newton-meter (Nm) of the different repetitions. All evaluation tests were conducted by the same PM&R physician. The main parameter was the strength deficit, defined by the Limb Symmetry Index (LSI) for the knee extensors (Quadriceps) and the knee flexors (Hamstrings). The LSI was expressed in percentage and calculated with the formulae: maximal strength of the non-operated knee / maximal strength of the operated knee) x 100[28]. The LSI enabled us to compare the external load produced on the healthy side and the one produced on the operated side. A Quadriceps and Hamstrings LSI lower on the operated side was the sign of the arthrogenic muscle

inhibition in case of arthrofibrosis. The reliability of Quadriceps and Hamstring maximal strength is considered as excellent (ICC: 0.93-0.98) and this of LSI as low (ICC: 0.43-78)[13].

At 4 months after surgery, the number of physiotherapy sessions was noticed. The function of the operated knee was assessed with the Lysholm score[35]. The return to running was considered effective at 7 months if the patients were able to run at least 15 minutes. The type of sport and the level were described with the Tegner score, before and after[36]. The knee range of motion (ROM) has been measured at 4 and 7 months after surgery, and expressed in degrees in the group with arthrofibrosis.

Ethics

Applicable institutional and governmental regulations concerning ethics were followed during the course of this research. The data report form was declared to the French data protection authority (CNIL) and to the Research Department of the University Hospital. Since data were collected retrospectively and that patients' management was not modified, according to French law, this study did not need to be approved by a research ethics committee (articles L.1121-1 paragraph 1 and R1121-2, Public Health code).

Statistical analysis

Statistical analysis was performed using the SPSS 23.0® software package (IBM corp. Ireland). The quantitative variables were expressed by average and standard deviation. The categorical variables were expressed by median, maximum and minimum values, or frequency. The comparison between arthrofibrosis and control ACLr groups was assessed by the Student's *t* test and the χ^2 test. Non parametric Spearman correlations between the muscle LSI and the Lysholm and the Tegner scores were searched at the 7th postoperative month for both groups. The arthrogenic muscle inhibition was established by two-way repeated-

measures ANOVA [3 times (4 vs 7 vs 12 months) x 2 knees (ACLr vs non-operative)] of the Quadriceps and Hamstring isokinetic strength for the 2 angular speeds (60 and 180°/s). arthofibrosis and graft procedures types were studied as factors between patients. Firstly, the normal distribution of different 3 times of strength measurements was verified by the Kolmogorov-Smirnov test. Secondly, a correction of Greenhouse-Geisser was used if the Mauchly test of sphericity of variance/covariance matrix was not respected. A Bonferoni post-hoc test was used to establish difference between isokinetic parameters depending of different times of isokinetic assessment and of operative or non-operative knees. Results were considered significant at $p<0.05$.

Results

908 patients with ACLr had criteria of inclusion, and 85 cases of stage 3 arthrofibrosis were clinically diagnosed, that is to say an incidence of 9.4% (Figure).

203 patients have been excluded and 160 dropped out the study, including 26 cases of arthrofibrosis among which 4 cases underwent a knee arthrolysis at 4 months after surgery. The proportion of patients lost to follow-up (30.5 vs 22.0%; p=0.5), the anthropometric and surgical parameters were not different between the group of patients with arthrofibrosis and those without. 539 patients have been studied with 59 cases of arthrofibrosis and 480 control ACLr patients. We assessed 384 men and 155 women; their mean age was 25+/-7 years old.

Before ACL traumatism, the most practiced sports were soccer (46.8%), basketball (19.3%) and handball (12.6%), that is to say pivoting sports with contact in nearly 78.7% of the cases. The median Tegner score was 7.0 [4 - 10] before ACLr. The ACLr had been performed by 13 different surgeons, 198 +/- 282 days from the ACL traumatism, with 176 BPTB procedures and 363 H procedures, associated to 114 meniscus surgeries and 45 extra-articular tenodesis.

Isokinetic evaluations have been performed at 131 +/- 13 days, 210 +/- 16 days and 348 +/- 21 days.

The arthrofibrosis ACLr group and the control group were not different concerning anthropometric parameters (Table I). Four months after surgery, the arthrofibrosis ACLr group had performed significantly more sessions of physiotherapy than the control ACLr group ($p<0.0001$). All the patients with arthrofibrosis had continued sessions of physiotherapy after 4 months in order to improve their knee ROM. Between the 4^{th} and the 7^{th} months after surgery the knee ROM increased by 20.0° +/- 6.0, 2.0° +/- 0.9 for the knee extension and 17.0° +/- 5.0° for the flexion. The Lysholm score was lower in the arthrofibrosis ACLr group at 4 and 7 post-operative months, but it was similar at 12 months after surgery (Table I). At the 7^{th} month after surgery, only 6.8% of the patients with arthrofibrosis had returned to running whereas 69.9% of the patients in the control group had returned ($p<0.0001$; Table 1). The level of sport was significantly lower in the arthrofibrosis ACLr group at 4, 7 and 12 months after surgery (Table I). The Quadriceps and the Hamstring LSI were also lower at 4 and 7 months after surgery in the arthrofibrosis group (Table 2). At 12 post-operative months, the Quadriceps LSI remained lower whereas the Hamstring LSI was comparable to the control group. At 7 post-operative months, the Quadriceps LSI at 60 and 180°/s were significantly correlated with the sport level in the arthrofibrosis ACLr group ($r = 0.329$ and $r = 0.321$, respectively; $p < 0.01$) and in the control ACLr group ($r = 0.301$ and $r = 0.31$, respectively; $p < 0.01$). Yet, the Lysholm score was not correlated with the muscles LSI.

The arthrogenic muscle inhibition of the quadriceps was significant on the operated side independently of the type of the graft procedure, whereas concerning the hamstrings, the degree of arthrogenic muscle inhibition was dependent on the surgical procedure (Table 3).

Discussion

Arthrofibrosis of the knee is a disabling and severe complication after ACLr[31,33]. We have reported an incidence of nearly 10%, that can be explained because we studied all the cases of arthrofibrosis, including those not operated. Considering only the operated cases of arthrofibrosis under-estimates the incidence of this complication[31]. Indeed, all the cases of arthrofibrosis may not be diagnosed or operated or may be lost of follow-up[8].

The arthrofibrosis is responsible for a strength deficit difficult to improve despite rehabilitation[1,33]. This deficit of strength is rarely studied while it may be responsible for the impossibility to return to sport at the same level, just like the loss of knee ROM. The main originality of our study was to assess the evolution of the Quadriceps and Hamstring LSI and their consequences on the return to sport in case of arthrofibrosis. We have shown that in case of arthrofibrosis, the Quadriceps LSI was low, but also the Hamstring LSI in smaller proportions. The Quadriceps LSI remained low 12 months after surgery despite continuing rehabilitation; running was rarely practiced before 7 months after surgery and the return to sport was low.

Our results are difficult to compare because few studies have evaluated the isokinetic LSI of the knee in case of arthrofibrosis after ACLr. Over 25 years ago, Shelbourne et al. had shown that the patients that had been operated before 21 days post-injury had a low quadriceps LSI of 51%, at 4 months post-surgery, due to more frequent cases of [34]. In 1996, Shelbourne et al. showed a low Quadriceps LSI of 72% in case of cyclops syndrome, of 67 and 73% in case of type 3 and 4 of arthrofibrosis at 12 months after ACLr[33]. The Quadriceps LSI of the arthrofibrosis ACLr group were of 68 and 74% at the angular speeds of 60 and 180°/s. Previous authors had shown the evolution of the isokinetic strength according to the complications of the hamstring procedures[3]. The arthrofibrosis was the most serious complication in terms of Quadriceps LSI. According to 7 cases of arthrofibrosis, named at that time « diffuse pain limited joint motion », we showed a low Quadriceps LSI at 4 months

after surgery (42% at 60°/s), which remained low at 12 post-operative months (61% at 60°/s). A low Hamstring LSI was also present at 4 months after surgery (51% at 60°/s) but then, it was comparable to the control group at 12 months (89% at 60°/s). The return to sport was also difficult, none of the 7 cases had returned to sport at the same level, 12 months after surgery[3].

In case of ACLr, the low LSI is the consequence of the arthrogenic muscle inhibition[29]. The reason is not clear, but it could be secondary to the swelling and the pain after surgery[29]. These symptoms would stimulate the knee articular sensory receptors which would modulate the spinal and supra-spinal centers[16]. The spinal reflex pathways contribute to the arthrogenic muscle inhibition, especially the nonreciprocal inhibitory pathway (Ib), the flexion reflex and the gamma-loop. The supraspinal may also play an important role in the muscle inhibition[16,25]. That would generate a muscular atrophy and an ineffective muscle strengthening as if a muscle proportion could not be activated[10,37]. Yet, 4 months after surgery, these clinical signs have disappeared, at the time of the isokinetic test. The arthrogenic muscle inhibition is also present on the non-operated side[16,26,29,38]. We have confirmed this phenomenon on the non-operated knee of the ACLr control patients and we have noticed no increase of this phenomenon in case of arthrofibrosis.

On the operated side, the arthrogenic muscle inhibition may have been associated to a mechanical component. Indeed, concerning the arthrogenic hamstring inhibition, the transmission of the muscular force to achieve knee flexion could be reduced due to the removal of the semi-tendinosus tendon during the Hamstring procedure[4]. A mechanical component could also be associated to the arthrogenic quadriceps inhibition because of the joint stiffness due to the intra-articular fibrosis development. Yet, this explanation has not been proven.

Our study has also some limits. The ROM of the arthrofibrosis ACLr group have not been compared to those of the ACLr group. Indeed, in the absence of complications, the ROM are

quite symmetrical between the operated and the non-operated knees from the 4th months after surgery. The increase of 20° of the ROM in the arthrofibrosis ACLr group, may have explained why the functional knee scores (Lysholm score) was comparable between the 2 groups at the 12th post-operative month. However, the quadriceps LSI remained lower in the arthrofibrosis ACLr group, despite a favorable evolution. The post-operative follow-up was certainly too short to know the final evolution of the arthrogenic muscle inhibition in case of arthrofibrosis. Strength recovery generally takes more than 12 months. A 24-month follow-up may be useful to know potential sequels of the arthrofibrosis, in terms of strength loss, return to sport and osteoarthritis evolution[21].

Conclusion

Arthrofibrosis is a serious complication after ACLr because of the intensity of the post-operative arthrogenic muscle inhibition. It is responsible for a long-term strength deficit of the quadriceps, still present 12 months after surgery. The mechanical component may be added due to the knee joint stiffness. According to Lysholm score, the knee function improves at 12 months. But the return to running is unusual before 7 post-operative months, despite the continuation of the rehabilitation care. Likewise, the return to a pivoting and contact sport is still compromised 1 year after surgery. These findings open perspectives for the management of arthrofibrosis. Particular attention should be paid to the fight against the arthrogenic quadriceps inhibition. The treatment may combine technics of neural rehabilitation, such as contralateral lower-limb strengthening, transcutaneous electrical nerve stimulation or electrical neuromuscular stimulation. The interest of the surgical revision should be considered according to this type of rehabilitation and the delay from the surgery.

References

1. Calloway SP, Soppe CJ, Mandelbaum BR. Clinical Outcomes After Arthroscopic Release of Patellofemoral Arthrofibrosis in Patients With Prior Anterior Cruciate Ligament Reconstruction. *Arthroscopy*. 2018;34(5):1603-1607. doi:10.1016/j.arthro.2017.12.011

2. Cavanaugh JT, Powers M. ACL Rehabilitation Progression: Where Are We Now? *Curr Rev Musculoskelet Med*. 2017;10(3):289-296. doi:10.1007/s12178-017-9426-3

3. Dauty M, Tortelier L, Huguet D, Potiron-Josse M, Dubois C. Consequences of pain on isokinetic performance after anterior cruciate ligament reconstruction using a semitendinosus and gracilis autograft. *Rev Chir Orthop Reparatrice Appar Mot*. 2006;92(5):455-463.

4. Dauty M, Tortellier L, Rochcongar P. Isokinetic and anterior cruciate ligament reconstruction with hamstrings or patella tendon graft: analysis of literature. *Int J Sports Med*. 2005;26(7):599-606. doi:10.1055/s-2004-821342

5. Davies GJ, McCarty E, Provencher M, Manske RC. ACL Return to Sport Guidelines and Criteria. *Curr Rev Musculoskelet Med*. 2017;10(3):307-314. doi:10.1007/s12178-017-9420-9

6. Dingenen B, Gokeler A. Optimization of the Return-to-Sport Paradigm After Anterior Cruciate Ligament Reconstruction: A Critical Step Back to Move Forward. *Sports Med*. 2017;47(8):1487-1500. doi:10.1007/s40279-017-0674-6

7. Edwards PK, Ebert JR, Joss B, et al. Patient Characteristics and Predictors of Return to Sport at 12 Months After Anterior Cruciate Ligament Reconstruction: The Importance of Patient Age and Postoperative Rehabilitation. *Orthop J Sports Med*. 2018;6(9):2325967118797575. doi:10.1177/2325967118797575

8. Ekhtiari S, Horner NS, de Sa D, et al. Arthrofibrosis after ACL reconstruction is best treated in a step-wise approach with early recognition and intervention: a systematic review. *Knee Surg Sports Traumatol Arthrosc*. 2017;25(12):3929-3937. doi:10.1007/s00167-017-4482-1

9. Fischer K, van der Bom JG, Mauser-Bunschoten EP, et al. The effects of postponing prophylactic treatment on long-term outcome in patients with severe hemophilia. *Blood*. 2002;99(7):2337-2341.

10. Fukunaga T, Johnson CD, Nicholas SJ, McHugh MP. Muscle hypotrophy, not inhibition, is responsible for quadriceps weakness during rehabilitation after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2019;27(2):573-579. doi:10.1007/s00167-018-5166-1

11. Gillespie MJ, Friedland john, Dehaven K. Arthrofibrosis: Etiology,classification, histopathology, and treatment. *Operative Techniques in Sports Medicine*. 1998;6(2):102-110.

12. Hughston JC. Complications of anterior cruciate ligament surgery. *Orthop Clin North Am*. 1985;16(2):237-240.

13. Impellizzeri FM, Bizzini M, Rampinini E, Cereda F, Maffiuletti NA. Reliability of isokinetic strength imbalance ratios measured using the Cybex NORM dynamometer. *Clin Physiol Funct Imaging*. 2008;28(2):113-119. doi:10.1111/j.1475-097X.2007.00786.x

14. Jackson DW, Schaefer RK. Cyclops syndrome: loss of extension following intra-articular anterior cruciate ligament reconstruction. *Arthroscopy*. 1990;6(3):171-178. doi:10.1016/0749-8063(90)90072-l

15. Klein W, Shah N, Gassen A. Arthroscopic management of postoperative arthrofibrosis of the knee joint: indication, technique, and results. *Arthroscopy*. 1994;10(6):591-597. doi:10.1016/s0749-8063(05)80053-2

16. Kuenze CM, Hertel J, Weltman A, Diduch D, Saliba SA, Hart JM. Persistent neuromuscular and corticomotor quadriceps asymmetry after anterior cruciate ligament reconstruction. *J Athl Train*. 2015;50(3):303-312. doi:10.4085/1062-6050-49.5.06

17. MacDonald PB, Hedden D, Pacin O, Huebert D. Effects of an accelerated rehabilitation program after anterior cruciate ligament reconstruction with combined semitendinosus-gracilis autograft and a ligament augmentation device. *Am J Sports Med*. 1995;23(5):588-592. doi:10.1177/036354659502300512

18. Magit D, Wolff A, Sutton K, Medvecky MJ. Arthrofibrosis of the knee. *J Am Acad Orthop Surg*. 2007;15(11):682-694. doi:10.5435/00124635-200711000-00007

19. Mall NA, Chalmers PN, Moric M, et al. Incidence and trends of anterior cruciate ligament reconstruction in the United States. *Am J Sports Med*. 2014;42(10):2363-2370. doi:10.1177/0363546514542796

20. Markolf KL, Hame S, Hunter DM, et al. Effects of femoral tunnel placement on knee laxity and forces in an anterior cruciate ligament graft. *J Orthop Res*. 2002;20(5):1016-1024. doi:10.1016/S0736-0266(02)00035-9

21. Mayr HO, Weig TG, Plitz W. Arthrofibrosis following ACL reconstruction--reasons and outcome. *Arch Orthop Trauma Surg*. 2004;124(8):518-522. doi:10.1007/s00402-004-0718-x

22. Myer GD, Paterno MV, Ford KR, Quatman CE, Hewett TE. Rehabilitation after anterior cruciate ligament reconstruction: criteria-based progression through the return-to-sport phase. *J Orthop Sports Phys Ther*. 2006;36(6):385-402. doi:10.2519/jospt.2006.2222

23. Paulos LE, Rosenberg TD, Drawbert J, Manning J, Abbott P. Infrapatellar contracture syndrome. An unrecognized cause of knee stiffness with patella entrapment and patella infera. *Am J Sports Med*. 1987;15(4):331-341. doi:10.1177/036354658701500407

24. Paulos LE, Wnorowski DC, Greenwald AE. Infrapatellar contracture syndrome. Diagnosis, treatment, and long-term followup. *Am J Sports Med*. 1994;22(4):440-449. doi:10.1177/036354659402200402

25. Perraton L, Clark R, Crossley K, et al. Impaired voluntary quadriceps force control following anterior cruciate ligament reconstruction: relationship with knee function.

Knee Surg Sports Traumatol Arthrosc. 2017;25(5):1424-1431. doi:10.1007/s00167-015-3937-5

26. Pietrosimone BG, Lepley AS, Ericksen HM, Clements A, Sohn DH, Gribble PA. Neural Excitability Alterations After Anterior Cruciate Ligament Reconstruction. *J Athl Train*. 2015;50(6):665-674. doi:10.4085/1062-6050-50.1.11

27. Rahr-Wagner L, Lind M. The Danish Knee Ligament Reconstruction Registry. *Clin Epidemiol*. 2016;8:531-535. doi:10.2147/CLEP.S100670

28. Rambaud AJM, Ardern CL, Thoreux P, Regnaux J-P, Edouard P. Criteria for return to running after anterior cruciate ligament reconstruction: a scoping review. *Br J Sports Med*. Published online May 2, 2018. doi:10.1136/bjsports-2017-098602

29. Rice DA, McNair PJ. Quadriceps Arthrogenic Muscle Inhibition: Neural Mechanisms and Treatment Perspectives. *Seminars in Arthritis and Rheumatism*. 2010;40(3):250-266. doi:10.1016/j.semarthrit.2009.10.001

30. Romano VM, Graf BK, Keene JS, Lange RH. Anterior cruciate ligament reconstruction. The effect of tibial tunnel placement on range of motion. *Am J Sports Med*. 1993;21(3):415-418. doi:10.1177/036354659302100315

31. Sanders TL, Kremers HM, Bryan AJ, Kremers WK, Stuart MJ, Krych AJ. Procedural intervention for arthrofibrosis after ACL reconstruction: trends over two decades. *Knee Surg Sports Traumatol Arthrosc*. 2017;25(2):532-537. doi:10.1007/s00167-015-3799-x

32. Shelbourne KD, Nitz P. Accelerated rehabilitation after anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 1992;15(6):256-264. doi:10.2519/jospt.1992.15.6.256

33. Shelbourne KD, Patel DV, Martini DJ. Classification and management of arthrofibrosis of the knee after anterior cruciate ligament reconstruction. *Am J Sports Med*. 1996;24(6):857-862. doi:10.1177/036354659602400625

34. Shelbourne KD, Wilckens JH, Mollabashy A, DeCarlo M. Arthrofibrosis in acute anterior cruciate ligament reconstruction. The effect of timing of reconstruction and rehabilitation. *Am J Sports Med*. 1991;19(4):332-336. doi:10.1177/036354659101900402

35. Tegner Y, Lysholm J. Rating systems in the evaluation of knee ligament injuries. *Clin Orthop Relat Res*. 1985;(198):43-49.

36. Tegner Y, Lysholm J, Odensten M, Gillquist J. Evaluation of cruciate ligament injuries. A review. *Acta Orthop Scand*. 1988;59(3):336-341.

37. Thomas AC, Wojtys EM, Brandon C, Palmieri-Smith RM. Muscle atrophy contributes to quadriceps weakness after anterior cruciate ligament reconstruction. *J Sci Med Sport*. 2016;19(1):7-11. doi:10.1016/j.jsams.2014.12.009

38. Urbach D, Nebelung W, Becker R, Awiszus F. Effects of reconstruction of the anterior cruciate ligament on voluntary activation of quadriceps femoris a prospective twitch

interpolation study. *J Bone Joint Surg Br*. 2001;83(8):1104-1110. doi:10.1302/0301-620x.83b8.11618

39. Wang J, Ao Y. Analysis of different kinds of cyclops lesions with or without extension loss. *Arthroscopy*. 2009;25(6):626-631. doi:10.1016/j.arthro.2008.12.006

40. Worsham J, Lowe WR, Copa D, et al. Subsequent Surgery for Loss of Motion After Anterior Cruciate Ligament Reconstruction Does Not Influence Function at 2 Years: A Matched Case-Control Analysis. *Am J Sports Med*. 2019;47(11):2550-2556. doi:10.1177/0363546519863347

TABLE 1 Comparison between Arthrofibrosis and control ACLr patient groups

	Arthrofibrosis ACLr group	Control ACLr group	p-value
Age (Year), mean+/-SD[A]	25 +/- 7	25 +/- 6	0.86
Gender n(%)[B]			
Male	39 (66.1%)	345 (71.9%)	0.36
Female	20 (33.9%)	135 (28.1%)	
Weight (Kg) (mean+/-SD)[A]	71 +/- 12	72 +/- 12	0.70
Height (cm) (mean+/-SD)[A]	171 +/- 8	173 +/- 9	0.56
Graft procedure n(%)[B]			
H procedure	33 (55.9%)	330 (68.8%)	0.06
BPTB procedure	26 (44.1%)	150 (31.3%)	
Meniscus procedure n(%)[B]			
Yes	12 (20.3%)	102 (21.3%)	0.99
No	47 (79.7%)	378 (78.8%)	
Extra-articular tenodesis n(%)[B]			
Yes	4 (6.7%)	41 (8.5%)	0.63
No	55 (93.3%)	436 (91.5%)	
Physiotherapy (n sessions+/-SD)[A]	54 +/- 33	41 +/- 18	<0.0001
Lysholm score (mean+-SD)[C]			
4 months	86 +/- 9 [b]	96 +/- 7	<0.0001
7 months	92 +/- 8 [b]	97 +/- 6	<0.001
12 months	94 +/- 7 [b]	97 +/- 5	0.04
Tegner score (M [min-max])[C]			
Before ACLr	7 [4-10][a]	7 [4-10][a]	0.16
4 months	4 [3-4][a,b]	4 [3-7][a,b]	<0.01
7 months	4 [3-6][a,b,c]	5 [3-10][a,b,c]	<0.0001
12 months	4 [3-9][a,b,c]	5 [4-10][a,b,c]	<0.001
RTS at 7 months n(%)[B]			
No RTS	39 (66.1%)	35 (7.3%)	
Bicycling	16 (27.1%)	109 (22.8%)	<0.0001*
Footing	4 (6.8%)	335 (69.9%)	

Abbreviations: ACLr: Anterior Cruciate Ligament reconstruction; RTS: Return to Sport; SD: Standard deviation; M [min-max]: Median [minimal and maximal values].

[A]Student *t* test; [B]χ^2 test, [C]Repeated-measured ANOVA.

[a]significant difference between before ACLr and 4 months and 7 months and 12 months.

[b]significant difference between 4 months and 7 months and 12 months.

[c]significant difference between and 7 months and 12 months.

TABLE 2 Limb Symmetry Index comparison at 4 months, 7 months and 12 months after ACL reconstruction (repeated-measured ANOVA).

	Arthrofibrosis ACLr group	Control ACLr group	p-value
LSI Q60 (%)			
4 months	38 +/- 12[a]	63 +/- 14[a]	<0.0001
7 months	53 +/- 14[a]	73 +/- 14[a]	<0.0001
12 months	68 +/- 13[a]	85 +/- 11[a]	<0.0001
LSI Q180 (%)			
4 months	48 +/- 14[a]	73 +/- 16[a]	<0.0001
7 months	60 +/- 17[a]	79 +/- 12[a]	<0.0001
12 months	74 +/- 11[a]	89 +/- 11[a]	<0.0001
LSI H60 (%)			
4 months	66 +/- 16[a]	88 +/- 14[b]	<0.0001
7 months	86 +/- 16[a]	93 +/- 12[b]	0.01
12 months	92 +/- 16[a]	93 +/- 13	0.70
LSI H180 (%)			
4 months	77 +/- 25[a]	93 +/- 17[b]	<0.0001
7 months	84 +/- 23[a]	96 +/- 17[b]	<0.001
12 months	92 +/- 13[a]	96 +/- 14	0.14

Abbreviations: LSI: Limb Symmetry Index; Q: Quadriceps; H: Hamstring; 60: 60° angular speed; 180: 180° angular speed.

[a] significant difference between 4 months and 7 months and 12 months

[b] significant difference between 4 months and 7 months

TABLE 3 Arthrogenic muscle inhibition of ACLr and non-operative knees during the evolution in arthrofibrosis and control ACLr groups (two-way repeated-measured ANOVA)

	Arthrofibrosis ACLr group		Control ACLr group	
Graft procedure	H procedure (n=33)	BPTB procedure (n=26)	H procedure (n=330)	BPTB procedure (n=150)
ACLr Q60 (Nm)				
4 months	72 +/- 32 ^{a§*}	79 +/- 26 ^{a§*}	128 +/- 42 ^{a§*}	120 +/- 34 ^{a§*}
7 months	106 +/- 52 ^{a§*}	104 +/- 25 ^{a§*}	146 +/- 41 ^{a§*}	141 +/- 37 ^{a§*}
12 months	130 +/- 52 ^{a§*}	146 +/- 34 ^{a§*}	160 +/- 44 ^{a§*}	162 +/- 38 ^{a§*}
ACLr Q180 (Nm)				
4 months	58 +/- 28 ^{a§*}	63 +/- 18 ^{a§*}	91 +/- 27 ^{a§*}	88 +/- 21 ^{a§*}
7 months	81 +/- 37 ^{a§*}	81 +/- 16 ^{a§*}	104 +/- 22 ^{a§*}	100 +/- 23 ^{a§*}
12 months	98 +/- 34 ^{a§*}	107 +/- 22 ^{a§*}	109 +/- 30 ^{a§*}	113 +/- 25 ^{a§*}
ACLr H60 (Nm)				
4 months	66 +/- 26 ^{a§β*}	75 +/- 21 ^{a§β*}	83 +/- 23 ^{a§β*}	100 +/- 24 ^{a§β*}
7 months	87 +/- 31 ^{a§β*}	106 +/- 20 ^{a§β*}	97 +/- 26 ^{a§β*}	115 +/- 26 ^{a§β*}
12 months	95 +/- 28 ^{a§β*}	123 +/- 39 ^{a§β}	102 +/- 27 ^{a§β*}	120 +/- 25 ^{a§β}
ACLr H180 (Nm)				
4 months	56 +/- 18 ^{a§β*}	59 +/- 14 ^{a§β*}	63 +/- 18 ^{a§β*}	76 +/- 17 ^{a§β*}
7 months	64 +/- 21 ^{a§β*}	84 +/- 14 ^{a§β}	73 +/- 11 ^{a§β*}	86 +/- 24 ^{a§β}
12 months	72 +/- 19 ^{a§β}	91 +/- 18 ^{a§β}	76 +/- 20 ^{a§β}	89 +/- 19 ^{a§β}
Nop Q60 (Nm)				
4 months	191 +/- 42 ^{a§}	196 +/- 40 ^{a§}	188 +/- 47 ^{a§}	199 +/- 40§
7 months	193 +/- 59 ^{a§}	199 +/- 45 ^{a§}	194 +/- 47^{a§}	199 +/- 41§
12 months	196 +/- 54 ^{a§}	210 +/- 47 ^{a§}	196 +/- 46^{a§}	211 +/- 41§
Nop Q180 (Nm)				
4 months	124 +/- 31 ^{a§}	125 +/- 24 ^{a§}	120 +- 33 ^{a§}	127 +/- 31 ^{a§}
7 months	127 +/- 35 ^{a§}	127 +/- 24 ^{a§}	128 +- 30 ^{a§}	132 +/- 28 ^{a§}
12 months	136 +/- 37 ^{a§}	134 +/- 25 ^{a§}	136 +- 31 ^{a§}	135 +/- 28 ^{a§}
Nop H60 (Nm)				
4 months	97 +/- 25 ^{a§β}	115 +/- 25 ^{a§β}	102 +- 26 ^{a§β}	109 +/- 22 ^{a§β}
7 months	103 +/- 27 ^{a§β}	122 +/- 27 ^{a§β}	112 +- 20 ^{a§β}	118 +/- 24 ^{a§β}
12 months	108 +/- 29 ^{a§β}	130 +/- 32 ^{a§β}	118 +- 29 ^{a§β}	131 +/- 25 ^{a§β}
Nop H180 (Nm)				
4 months	70 +/- 16 ^{a§β}	84 +/- 16 ^{a§β}	75 +- 20 ^{a§β}	82 +/- 17 ^{a§β}
7 months	76 +/- 19 ^{a§β}	100 +/- 18 ^{a§β}	84 +- 22 ^{a§β}	96 +/- 18 ^{a§β}
12 months	81 +/- 18 ^{a§β}	98 +/- 24 ^{a§β}	86 +- 22 ^{a§β}	100 +/- 22 ^{a§β}

Abbreviations: Q: Quadriceps; H: Hamstring; 60: 60° angular speed; 180: 180° angular speed; ACLr: Anterior Cruciate Ligament reconstruction; BPTB: Bone-Patellar-Tendon-Bone procedure; Nop: non-operated knee.

[a]Significant difference between time of isokinetic measurements

[§]Significant difference between the operated and the non-operated knee

[β]Significant difference between H and BPTB procedure

*Significant difference between arthrofibrosis and control ACLr group

Figure: Flowchart