CR’S TAL study: Criteria for Return to Sport after ACL reconstruction with lower re-injury risk. A prospective observational study protocol

Journal: BMJ Open

Manuscript ID: bmjopen-2016-015087

Article Type: Protocol

Date Submitted by the Author: 10-Nov-2016

Complete List of Authors:
Rambaud, Alexandre; Universite Jean Monnet Saint-Etienne, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424); Centre de kinésithérapie du Pôle Sportif;
SEMA Y, Bertrand; Universite Jean Monnet Saint-Etienne Faculte de Medecine Jacques Lisfranc, Department of Orthopaedic and Trauma Surgery; Universite Jean Monnet Saint-Etienne, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424)
Testa, Rodolphe; Universite Jean Monnet Saint-Etienne, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424)
Samozino, Pierre; Universite Savoie Mont-Blanc, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424)
Morin, Jean-Benoît; Universite de Nice Sophia Antipolis, Laboratory of Human Motricity, Education Sport and Health (EA 6312)
Rossi, Jérémy; Universite Jean Monnet Saint-Etienne, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424)
Philippot, Rémi; Centre Hospitalier Universitaire de Saint-Etienne, Department of Orthopaedic and Trauma Surgery; Universite Jean Monnet Saint-Etienne, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424)
Edouard, Pascal; Centre Hospitalier Universitaire de Saint-Etienne, Department of Clinical and Exercise Physiology, Sports Medicine Unit; Universite Jean Monnet Saint-Etienne, Laboratory of Human Motricity, Education Sport and Health (EA 6312)

Primary Subject Heading: Sports and exercise medicine

Secondary Subject Heading: Rehabilitation medicine

Keywords: Anterior Cruciate Ligament Reconstruction, injury prevention, Risk factors, Biomechanics, Return to Sport
CR’STAL study: Criteria for Return to Sport after ACL reconstruction with lower re-injury risk. A prospective observational study protocol

Alexandre JM RAMBAUD1 2, Bertrand SEMAY1 3*, Rodolphe TESTA1, Pierre SAMOZINO4, Jean-Benoît MORIN5, Jérémy ROSSI1, Rémi PHILIPPOT1 3, Pascal EDOUARD1 6

1 Inter-university Laboratory of Human Movement Biology (LIBM EA 7424), University of Lyon, University Jean Monnet. Saint Etienne, France
2 Physiotherapy Clinic of the Sport Center, La Talaudière, France
3 Department of Orthopaedic and Trauma Surgery, University Hospital Center of Saint-Etienne, hôpital Nord, Saint-Etienne, France
4 Inter-university Laboratory of Human Movement Biology (LIBM EA 7424), University Savoie Mont Blanc, Le Bourget-du-Lac, France
5 Laboratory of Human Motricity, Education Sport and Health (EA 6312), University of Nice Sophia Antipolis, Nice, France
6 Department of Clinical and Exercise Physiology, Sports Medicine Unit, University Hospital of Saint-Etienne, Faculty of Medicine, Saint-Etienne. France

Corresponding Author:
Alexandre JM RAMBAUD, LIBM, University of Lyon, Campus Santé Innovations IRMIS, 10 rue de la Marandière, 42270 Saint-Priest en Jarez, France.
Email: alexandre.rambaud.kine@gmail.com +33 (0)4 77 30 76 55

*These authors contributed equally to this work.

Keywords:
Anterior Cruciate Ligament Reconstruction, Return to Sport, Biomechanics, risk factors; injury prevention
ABSTRACT

Introduction:

After an Anterior Cruciate Ligament (ACL) tear, if the patient requires good knee stability, an ACL Reconstruction (ACLR) could be performed. After an ACLR, the decision to return to sport is important. Many assessments have been used to determine an optimal timeline for a return to sport after ACLR, such as subjective and objective parameters, but none have been validated.

The aim of the present study is to test the relationships between reinjury risk and subjective and objective criteria in order to determine which criteria or combination of criteria could be predictive for a return to sport with the lowest possible risk of reinjury.

Methods and analysis

This study is a prospective cohort, single-center trial, with repeated assessments at 6, 9 and 12 months post-ACL surgical reconstruction and including a 3-year follow-up of patients’ sporting activity and injuries. 50 patients will be included to test one explanatory variable. Postural control analysis, knee laxity, modified star excursion balance test, running and sprinting biomechanics, Hop Tests and isokinetic tests will all be used. The primary outcome will be any reinjury during the follow-up, defined as a graft rupture, a contralateral ACL rupture, or any injury necessitating an interruption of training with a medical consultation. Two groups will be constituted during the follow-up, using reinjured and non-reinjured patients, and univariate and multivariate analyzes will be performed.

Ethics and dissemination
The results of this study will be disseminated through peer-reviewed publications and scientific presentations. Ethical approval was obtained through the University Hospital of Saint-Etienne Ethics Committee (Reference number IRBN522015/CHUSTE).

STRENGTHS AND LIMITATIONS OF THIS STUDY:

- This is the first study analyzing several parameters (usual and innovative) and their association to determine the best decision making model to determine the time to return to sport after ALCR.

- This study has been designed with evaluations over 6 months (at 6, 9 and 12 months post-ACLR) in order to analyse data from the usual time to return to pivot-sports training (6-9 months) to the time to return to competition (generally 9-12 months).

- The study includes only young competitive athletes, which is the population with higher reinjury risk, however the findings could not be applied to the general population.

- This screening protocol seeks to assess all the elements involved in the return to sport after ACLR with knee-specific and task-specific objective measurements associated with subjective assessment of knee function and psychometric capabilities.

- The design and objectives of this study will require a significant number of patients, however, we chose this specific population, who is very motivated to return to sport, to limit dropouts.
INTRODUCTION

Anterior cruciate ligament (ACL) tears represent a public health challenge.[1] The incidence of ACL rupture has been reported as 60-71 per 100,000 subjects.[2,3] It is often associated with meniscal tears (30%-75%) and cartilage lesions (25-29%).[4,5] In the United States, around 200,000 ACL Reconstructions (ACLR) are performed each year,[6,7] and the cost of ACLR is estimated to be between $32,000 and $50,000 per patient.[1] In addition, an ACL tear often gives rise to problems like post-traumatic osteoarthritis; this could lead to an increase in knee surgery in the future and will surely generate middle- and long-term problems for the patient, at a significant cost to society. In this context, prevention (primary, secondary and tertiary) of ACL tears represents a very relevant current challenge and a major orientation for orthopaedics and sports medicine research.[1]

Most at-risk are young, active subjects, playing pivot-shift sports at competition level. The risk of ACL tears varies with age (higher risk in subjects aged under 30)[3] and sex (higher risk in women)[2,3,8]. The frequency of ACL tears depends on the type of sport, with these being seen mainly in pivot-shift sports (e.g. a higher risk in soccer than basketball) and at higher activity levels (higher risk for professional compared to recreational players).[9]

After the injury, the most frequent question asked by the patient is: “when can I get back to my sport?” If the patient with an ACL tear is considered to be at a high risk of knee instability (young, high level athletes in a pivoting and/or contact sport), an ACLR may be performed, followed by a period of rehabilitation. The ACLR usually uses an autograft tendon: the central-third bone-patellar tendon-bone[10] or the semitendinosus tendon either alone or with the gracilis tendon.[11] No technique has shown superiority to any other for overall functional outcome (i.e. clinical condition of the knee, time to return to sport, and/or long term consequences and risk of secondary lesions).[12–14] After surgical reconstruction,
a rehabilitation program is set up to allow patients to return to a painless and fully functional
daily life.[15–18] However, the patient’s aim is to return to his sport, and a successful ACLR
is one where the patient retrieves the same level of sporting performance as before the injury.
[19]. Consequently, the decision of when to return to sport is an important one if the patient is
to achieve his goal and a challenge in the context of secondary and tertiary prevention.
The return to sport, especially with pivoting or contact sports, exposes the athlete to a risk of
reinjury: the reinjury rate for the ipsilateral ACL is 3.5% to 13.0% and for the contralateral
ACL is 4.4% to 9.0%.[5,6,20,21] A new injury after an ACLR may affect the joint (rupture of
the graft or contralateral ACL, chondral and/or meniscal lesion) or be a musculoskeletal
injury. Koulouris et al.[22] reported, in elite soccer athletes, an association between a history
of ACLR and hamstring reinjuries.
An early return to sport exposes the patient to a high risk of reinjury,[23–26] but returning to
sport too late seems to decrease the chances of returning to the pre-injury level of
performance. Many factors affect this return to sport and fewer than 1 in 6 return to
competitive sport following ACLR.[5,26,27] The longer the patient waits to return to
competition, the more his socio-professional and familial environment will diminish his
motivation to return to competitive sport.[28] It is obviously necessary to define the optimal
timeline for return to sport and to achieve this, to define and validate the optimal criteria
permitting a return to sport; this will both minimize the risk of reinjury and optimize the
return to sport.
Many techniques and many criteria have been used in clinical studies to determine the optimal
moment for a return to sport after ACLR:[23,28,29] the most used is the post-operative
timeline, either alone or with: muscle strength, knee laxity, knee assessment form, or
functional tests. Fitzgerald et al.[30] described and validated objective criteria to return to
sport in non-operated patients:[31] functional tests like Hop Tests (single, cross-over, triple),
quadriceps strength and self-reported knee function. However, to the best of our knowledge, there are no clearly validated criteria for a return to sport after ACLR. This decision is currently based on multiple criteria[23,28,29] mostly using the post-operative time frame needed for the biological integration of the graft.[32,33] Barber and Noyes,[23] in a systematic review, described how this decision is associated with subjective criteria ("satisfactory clinical examination", "stable knee", "normal joint function", self-reported knee function (subjective IKDC)) and objective criteria. Yet only 19% of studies[23] have used objective criteria like: muscular strength, knee laxity, the limb symmetry index (LSI) or functional tests (Hop Tests, Star Excursion Balance Tests). It is surprising that the more objective tests are the least used while the least objective tests are the most used criteria.

Among the objective criteria, testing isokinetic muscular strength is a clear measure of strength recovery [34,35]. Functional testing and biomechanical analysis of running or sprinting, allows evaluation of lower limb function in a context close to that of sport. After an ACLR, weakness of the quadriceps disturbs the pattern of walking; this is known as “Quad-Avoidance”. [36,37] This altered pattern may persist when running and modify the stiffness of the lower limb and step length. Functional tests and biomechanical analysis would highlight both this altered pattern during the stance phase of running and the functional asymmetry of the patient. This altered pattern could be one of the parameters involved in the decreased athletic ability of patients and the increased risk of injury. Using a non-motorized treadmill fitted with force sensors, Brown and Brughelli[38] evaluated the sprint of a rugby player after ACLR during the period of return to sport (between the return to training and competition). An asymmetry of the Ground Reaction Force (GRF) persisted (horizontal force: 13%, vertical force: 7%) while the isokinetic muscular strength testing appeared normal. They concluded that an evaluation of sprint mechanics complemented the usual functional assessments. This analysis, in line with sports reality,[39] could detect an asymmetry during the return to sport...
phase (6-12 months). This sport-specific assessment seems very relevant to the decision to return to sport. This new approach could also help explain the many failures in returning to sport, despite LSI scores close to 100% with both isokinetic and Hop tests. The predictive values of all these tests have not yet been validated for detecting the risk of reinjury in sports after an ACLR. This sprint running and running biomechanics approach could help more clearly define the criteria necessary to assess a safe return to sport after an ACLR in a high-risk population.

In this context, the determination of valid criteria or an association of criteria to aid in the decision making process regarding a return to sport without risk of reinjury or associated lesions (muscles or ligaments of the lower limbs) is of major interest in the monitoring of patients with ACLR who want to return to a competitive pivoting sport. The aim of the present study is therefore to test the relationships between reinjury risk and subjective and objective criteria in order to determine which criteria or combination of criteria could be predictive for a return to sport with the lowest possible risk of reinjury.

METHODS

The present study is a prospective cohort single-center trial, with repeated measures at 6, 9 and 12 months post-operatively after an ACLR and follow-up of the return to sport and reinjury for 3 years after the ACLR. The study design is shown in Fig 1.

Please insert Fig 1.
Study patients

Potential subjects will be drawn consecutively from among the patients of the Sports Medicine Unit or the Orthopaedic Surgery and Traumatology department of the local University Hospital; subjects included in the study must meet the criteria for inclusion/exclusion shown in Table 1. All study patients will undergo post-surgical rehabilitation in the same Physiotherapy Clinic using the protocol recommended in the literature [16–18] (for more information about the protocol please see S1 Appendix. ACL Reconstruction Rehabilitation Protocol).

Table 1 Inclusion and exclusion criteria for patients

<table>
<thead>
<tr>
<th>Inclusion criteria</th>
<th>Exclusion criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>➢ Participation in pivot and/or contact sports and with intensive sporting activity before the ACL tear:</td>
<td>➢ Bilateral lower limb pathologies</td>
</tr>
<tr>
<td>- with a Marx scale score above 11 before the injury</td>
<td>➢ Recurrence of ACL rupture (with a MRI diagnostic)</td>
</tr>
<tr>
<td>- with a Tegner score above 4 before the injury</td>
<td>➢ Contraindications to carrying out a test, i.e.:</td>
</tr>
<tr>
<td>(competition training with more than 3 training sessions per week before the injury)</td>
<td>➢ Postoperative time less than 6 months</td>
</tr>
<tr>
<td>➢ Unilateral tear</td>
<td>➢ Persistence of knee pain (score &gt;3 at Numeric Pain Rating Scales)</td>
</tr>
<tr>
<td></td>
<td>➢ Persistence of a joint effusion (patellar tap test positive)</td>
</tr>
<tr>
<td></td>
<td>➢ Incomplete range of motion (Range of motion &lt; 90% of contralateral side)</td>
</tr>
<tr>
<td></td>
<td>➢ Abnormal walk (observable gait deviations during the walk)</td>
</tr>
<tr>
<td></td>
<td>➢ Allografts</td>
</tr>
<tr>
<td></td>
<td>➢ Skeletal immature</td>
</tr>
<tr>
<td></td>
<td>➢ Older than 35 years</td>
</tr>
</tbody>
</table>

Assessment procedure

All tests will be performed in the same place and all patients will be tested at the same time of day between 2 pm and 6 pm. 48 hours before each evaluation session, patients will receive an email reminding them of the test procedure and asking them to complete a subjective questionnaire online (IKDC, TSK11 and SANE).
Informed consent will be obtained from all subjects before testing begins and a standardized explanation of the assessment procedure given to the patients. Each test session will include, in the same order, a medical check-up, postural control analysis, knee laxity measurements, Star Excursion Balance Test modified, biomechanical running and sprint analysis, Hop Tests and isokinetic tests, with 5-minut rest between each test. Before the biomechanical analysis begins, patients will warm-up with 10 minutes of cycling to raise muscle temperature. A specific warm up activity will be included before each new activity. The isokinetic evaluation is at the end of the battery to avoid tiredness affecting the results of the other tests.

Subjective evaluation using questionnaires

The first questionnaire is the IKDC, an algo-functional questionnaire commonly used for ACLR follow-up.[40,41] A score above 90% is considered a criterion for a return to sport.[42] The patient will then complete the Tampa Scale of Kinesiophobia-11 (TSK11). This questionnaire, containing 11 questions (choice between 5 answers), is used to estimate a patient’s fear of movement and reinjury giving a score from 11 to 55.[43–45] A score below 20 indicates low pain-avoidance and could also allow a return to sport.[46] The patient will also be asked to estimate his knee recovery on a scale (from 0 to 100) with a single assessment numeric evaluation (SANE).[41,47]

Medical check-up

Firstly, we will check if the online questionnaires have been done, and the presence of inclusion criteria and absence of exclusion criteria. The assessor will fill out the demographic information in the observation book (gender, age, weight, height, sport, training frequency
and Marx's score before the ACL tear), a timeline for a return to running, sport-specific
training and competitive play where possible, and finally the ACLR surgeon and technique
used. The clinical examination will follow the IKDC-2000 grid.[40]

Postural control analysis

A WinPosturo® (Medicapteurs, Balma, France) stabilometry platform will be used with the
WinPosture® software (Medicapteur, Balma, France) to determine variations in the center of
pressure (CoP). The force plate, which measures 530 × 460 × 35 mm has three pressure
gauges (hysteresis < 0.2%), with a sensitivity of 90 points per Newton. The sampling
frequency will be fixed at 40 Hz with the platform recalibrated before each session. The
assessment will be conducted in an isolated room, in a noise-free environment, with a hard,
flat floor, following the recommendations of the American Academy of Neurology
(AAN)[48] and the study by Ruhe et al.[49] The standardized position of the feet will be:
oriented 15° laterally to the sagittal plane. The patient will have to breathe normally and stare
at a point 1.5 m in front him, at eye level, the arms relaxed along the body. The patient will be
in sportswear and socks.

Four measurements, knees in extension, separated by 30 seconds of recovery in a sitting
position, will be performed:
- bipedal position, eyes open (60s)
- bipedal position, eyes closed (60s)
- balancing on the healthy leg (30s)
- balancing on the operated leg (30s)

The values of total CoP (CoP in mm), CoP velocity (in mm.s⁻¹), standard derivations of
CoP (SDx and SDY), and CoP sway area (in mm²) will be recorded. Kouvelioti et al. showed
good or excellent reproducibility of all these variables using a similar assessment protocol (Intraclass Correlation Coefficient (ICC) range from 0.68 to 0.91). [50]

**Knee laxity measurements**

The GNRB® system (Genourob, Laval, France) is a non-invasive arthrometer that provides comparative bilateral measurements of knee laxity. This system is reliable and reproducible (ICC range from 0.77 to 0.91) [51–53] The patient will lie on a standard examination table in the supine position, with the knee at 20° flexion and 0° of rotation (Fig 2). The lower is immobilized in a thermoformed shell, adaptable for different leg lengths, at the patella and the foot with a force of about 65±5N controlled by a force sensor with a precision of 0.1 mm. The analysis will begin with the healthy leg, with a push to 134N and 3 pushes to 250N. The same procedure is then repeated on the operated limb. The displacement of the anterior tibial tubercle relative to the femur is measured. The drawer shift/pressure curve is determined by the displacement (with 0.1 mm precision) and the slope of the curve (Slp in degree) which defines ligamentous laxity. The push to 250 N with the largest displacement (D_ap in mm) and Slp will be retained. The difference between the operated and healthy limb will be calculated for D_ap and Slp.

Please insert Fig 2.

**Modified Star Excursion Balance Test**

The patient, shoeless, will be asked to stand on one leg, starting with the healthy limb, without lifting the heel and with hands on hips and perform the following exercise as described in the
literature:[54–56] to reach maximally to touch a point as far as possible in 3 directions, along
i) an antero-posterior axis ii) the postero-lateral axis and finally iii) the postero-medial axis,
returning to the initial position between each movement. Two attempts and 2 measurements
will be made for each direction. The longest distance (in cm) will be noted for each direction.
The reliability is high with ICC from 0.83 to 0.96.[57]

Running and sprinting mechanics

Patients will choose either a cycle ergometer and/or jogging for a 10-15 general warm-up,
followed by a specific sprint warm-up included sprint drills and short sprints. On a motorized
instrumented treadmill (ADAL3D-WR; Medical Development, HEF Tecmachine,
Andrezieux-Boutheon, France), with four piezoelectric force transducers (KI 9077b, Kistler,
Winterthur, Switzerland), on a hard, flat surface in a quiet room, the patient will be then
undergo the biomechanical evaluations first for running and then sprinting with a one minute
between them (Fig 3). The reliability is high with ICC from 0.85 to 0.90.[58]

For the running biomechanical evaluation, each patient will run for three minutes at 3.33 m.s\(^{-1}\)
(12 km.h\(^{-1}\)) and, without the patient being informed of the exact moment of data recording, 20
sec of biomechanical parameters will be recorded. Mechanical data will be sampled at 1000
Hz. After appropriate filtering (Butterworth-type 30 Hz low-pass filter, 2\(^{nd}\) order),
instantaneous data of vertical force will be averaged for each support phase (vertical force
above 30 N) over the 20-s \(F_{V,R}\), and expressed in N and body weight (BW). For each step,
contact \(t_c\) and aerial \(t_a\) times will be calculated. Spring–mass parameters, like vertical
stiffness \(k_{v_{en}}\) in kN m\(^{-1}\) and leg stiffness \(k_{leg}\) in kN m\(^{-1}\), will be calculated using the
computation method proposed by Morin et al.[59] The lower limb leg length will be the
distance behind the great trochanter to ground distance in a standing position. The stride
length ($l_{\text{stride}}$ in m) will be calculated as: $l_{\text{stride}} = (t_c + t_a) \cdot v$

For the sprint running biomechanical evaluation, each patient will first be familiarized with
sprinting on a treadmill by three 6-sec sprints separated by 1 minute of rest. The patient is
fitted with a leather weightlifting belt attached via a rigid tether (0.6 cm in diameter) to the
wall (Figure 3), as described by Morin et al.[58] The constant motor torque will be set to
160% of the default torque, i.e. the motor torque necessary to overcome the friction on the
treadmill belt due to the subject’s body weight. The default torque will be measured by
making the subjects stand still and by increasing the driving torque until a movement of the
treadmill belt greater than 2 cm is observed over 5 s. Motor torque of 160% of the default
value will be selected after several preliminary measurements comparing various torques, as
this will allow subjects to sprint in a comfortable manner and produce maximal effort without
risking a loss of balance. Once the patient is correctly attached, he will be required to lean
forward in a typical crouched sprint-start position with their preferred foot forward. This
starting position will be used and standardized throughout the sprint series. After a 3-s
countdown, the treadmill will be released, and the treadmill belt will begin to accelerate as
subjects apply a positive horizontal force. With patients strongly encouraged to produce their
maximum intensity, two sprints will be recorded separated by a 1-minute rest period. The data
used for analysis will be: instantaneous data of vertical, net horizontal and total GRF averaged
for each support phase (vertical force above 30 N) over 6-s sprints ($F_{V_{\text{sprint}}}, F_{H_{\text{sprint}}}, F_{\text{tot}_{\text{sprint}}}$
respectively), and expressed in N and BW. For each step, the ratio of forces applied on the
ground (RF) will be calculated as the ratio of $F_{H_{\text{sprint}}}$ to $F_{\text{tot}_{\text{sprint}}}$ for one contact as follows:

$$RF = F_{H_{\text{sprint}}} \cdot \frac{1}{F_{\text{tot}_{\text{sprint}}}} \text{ (expressed in %)}$$

[60] Then, mean and maximal values of ratio forces
for the 6-s sprint will be computed (RF-mean and RF-max, respectively). The index of force
application technique ($D_{RF}$) representing the decrement in RF with increasing speed (S) will
be computed as the slope of the linear RF-speed relationship calculated from the step-averaged values between the second step and the step at top speed.[60] Therefore, the higher the DRF (i.e. a flat RF-speed relationship), the more RF will be maintained despite increasing velocity, and vice versa.[61] Lastly, for each 6-s sprint, performance will be described through mean and maximal running speeds (S and S-max, respectively).

Please insert Fig 3.

**Hop Tests:**
The patient will be asked to perform the following exercises, as described by Noyes and al.[62] (Fig 4.):

- **Single One-Leg Hop Test** on the healthy limb and then the operated limb, with the arms crossed, hands on shoulders. The patient will perform one hop, as far as possible, with a controlled, balanced landing (minimum 3 seconds). If the patient cannot maintain the landing position, makes extra hops, or does not keep his hands on his shoulders, then the hop test will be considered a failure.

- **Triple One-Leg Hop Test** on the healthy limb and then the operated limb with the arms in any position. The patient will perform 3 consecutive hops as far as possible. The last hop position must be maintained for a minimum of 3 seconds as with the **Single One-Leg Hop Test**.

- **Cross-over One-Leg Hop Test** on the healthy limb and then the operated limb with the arms in any position. The test is carried out on a 6.5 m strip of carpet with a central line 15 cm in width. The patient is asked to make three hops, the first laterally, crossing the line on each hop. Landing after the final hop must be as with the **Single One-Leg Hop Test**.
Patients start from single limb stance. Every attempt will include at least 3 jumps and will continue until the patient progresses. The best distance for each leg and each hop test will be recorded for analysis (in cm). The reliability is high with ICC from 0.84 to 0.92. [63]

Please insert Fig 4.

Isokinetic assessment

As the resulting tiredness could affect the other tests if done earlier in the battery, the isokinetic quadriceps and hamstring muscle strength assessment will be performed last. They will be done on a Con-Trex® Multi-Joint dynamometer (CMV AG, Dübendorf, Switzerland) and controlled by Con-Trex Software. The installation is described elsewhere in the literature.[64,65] The subject will be seated with the hip joint at about 85° and strapped in place at the chest, pelvis and mid-thigh to avoid postural compensation during the assessment. The contralateral limb will be fixed to a support at the ankle. The axis of the dynamometer will be perfectly aligned with the rotation axis (lateral femoral epicondyle) of the knee joint. A resistive support will be strapped to the leg, at 2-3 cm proximal to the ankle joint line. The range of knee motion will be set from 80° for a safe, comfortable, comparative assessment. The gravity correction will be used. Assessment will begin with the healthy knee, and then the operated knee, and each series of repetitions will be followed by one minute of rest. The assessment is summarized in Table 2.

Table 2 Isokinetic assessment design

<table>
<thead>
<tr>
<th></th>
<th>Repetitions</th>
<th>Angular velocity and mode of contraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>First specific warm-up</td>
<td>↓ 6 sub-maximal</td>
<td>120 °/s in concentric</td>
</tr>
<tr>
<td>Second specific warm-up</td>
<td>↓ 6 sub-maximal</td>
<td>120 °/s in concentric</td>
</tr>
</tbody>
</table>
Habituation session ↓ 3 sub-maximal 60 °/s in concentric

Maximal test session with encouragement ↓ 3 maximal 60 °/s in concentric

Maximal test session with encouragement ↓ 3 maximal 120 °/s in concentric

Habituation session ↓ 3 sub-maximal 30°/s in eccentric

Maximal test session with encouragement ↓ 3 maximal 30°/s in eccentric

The isokinetic assessment will be performed in this order, using gravity corrections, at a range of motion of 5°-85°, and measuring peak torque for each test session. A 1-minute rest will be allowed between each session.

Torque, position and angular velocity data will be recorded from the isokinetic dynamometer with a sampling rate of 100 Hz. After appropriate filtering, for concentric and eccentric strength trials, the software will calculate a large number of parameters, but we will retain only the absolute peak torque, the most reproducible parameter (ICC > 0.96).[64]

The peak torque normalized to the body weight (Nm/kg) value will be recorded for each mode and speed of contraction for the Quadriceps (Q) and Hamstring (H). The Q/H ratio will be calculated for each mode and speed of contraction on the operated side, with a ratio ≥ 60% considered to be physiologically sufficient to obtain joint control. A mixed functional ratio, associating the eccentric performance of the flexor (at 30°/s) and the concentric performance of the extensor (at 240°/s) will also be calculated, as reported by Croisier and al.[65]

Follow-up after ACL surgical reconstruction

Patients’ follow-up will continue until 36 months post-operatively. After the evaluation at 12 months post-surgery patient follow-up will continue for a further 2 years. The researchers will attempt to follow-up all patients by phone interview every 6 months to determine the date of
return to running, to pivoting sport-specific training, and to pivoting sport competition, as
well as the date and the nature of any reinjury that may occur. We will also collect the Tegner
score at 3-years post-ACLR.

**Method of accounting for missing, unused or invalid data**

A patient’s participation in the study will cease if significant complications appear when
performing the tests and all data collected before that point will be analyzed.

**Power and simple size considerations**

Assuming the rate of ACL reinjury to be 0.20% after an ACLR (ipsi or contralateral ACL
injury),[3] considering a 10% dropout rate, and that 10 cases (reinjury) are needed to test one
explanatory variable, it is necessary to include 50 patients to test one explanatory variable for
95% power and a Type-I error rate (alpha) of 0.05.

**Primary outcome**

The main criterion for assessment is the occurrence of reinjury during the 3-year follow-up. A
reinjury is defined as a rupture of the transplant or the contralateral ACL, or any injury
requiring the sporting activity to cease and necessitating a consultation and/or medical care.

**Statistical analyses**

Means and standard deviations will be calculated, and the normal distribution of values will
be checked. The explanatory variables are reported in Table 3.
### Table 3 Exploratory variables and their clinical relevance

<table>
<thead>
<tr>
<th>Categories of criteria</th>
<th>Explanatory variables</th>
<th>variables</th>
<th>unit</th>
<th>range</th>
<th>criterion to return to sport</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marx pre injury</td>
<td>Marx_preinj</td>
<td>numeric discrete</td>
<td>0-16</td>
<td></td>
<td></td>
<td>Anderson et al. [42]</td>
</tr>
<tr>
<td>Tegner pre injury</td>
<td>Tegner_preinj</td>
<td>numeric discrete</td>
<td>0-10</td>
<td></td>
<td></td>
<td>Myer et al. [66]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lentz et al. [46]</td>
</tr>
<tr>
<td>self-report measures</td>
<td>IKDC</td>
<td>ikdc_score</td>
<td>numeric continuous</td>
<td>0-100</td>
<td>&gt;90%</td>
<td>Zwolski et al. [67]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;70%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;87.5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;95%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TSK-11</td>
<td>TSK_score</td>
<td>numeric discrete</td>
<td>11-55</td>
<td>&lt;20</td>
<td>Lentz et al. [46]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SANE</td>
<td>SANE_score</td>
<td>numeric continuous</td>
<td>0-100</td>
<td>&gt;75</td>
<td>Ellman et al. [68]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Postural control analysis</td>
<td>CoP_biped_longer</td>
<td>numeric continuous</td>
<td>mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LSI_CoP_longer</td>
<td>numeric continuous</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CoP_biped_velocity</td>
<td>numeric continuous</td>
<td>mm.s⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LSI_CoP_velocity</td>
<td>numeric continuous</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CoP_biped_area</td>
<td>numeric continuous</td>
<td>mm²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LSI_CoP_area</td>
<td>numeric continuous</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee laxity measurements</td>
<td>Slp_diff</td>
<td>numeric continuous</td>
<td>mm</td>
<td>&lt;3mm</td>
<td></td>
<td>Lynch et al. [19]</td>
</tr>
<tr>
<td></td>
<td>Dap_diff</td>
<td>numeric continuous</td>
<td>mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEBT</td>
<td>LSI_SEBT_ant</td>
<td>numeric continuous</td>
<td>%</td>
<td></td>
<td>Composite score ≥95%</td>
<td>Gribble et al. [56]</td>
</tr>
<tr>
<td>Postero-lateral distance</td>
<td>LSI_SEBT_PostLat</td>
<td>numeric</td>
<td>continuous</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------------</td>
<td>------------------</td>
<td>---------</td>
<td>------------</td>
<td>---</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Postero-lateral distance</td>
<td>LSI_SEBT_PostLMed</td>
<td>numeric</td>
<td>continuous</td>
<td>%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Running and Sprinting mechanics</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Leg stiffness</td>
<td>LSI_Kleg</td>
<td>numeric</td>
<td>continuous</td>
<td>%</td>
</tr>
<tr>
<td>stride length</td>
<td>LSI_stride</td>
<td>numeric</td>
<td>continuous</td>
<td>%</td>
</tr>
<tr>
<td>Sprint vertical force</td>
<td>LSI_Fv_sprint</td>
<td>numeric</td>
<td>continuous</td>
<td>%</td>
</tr>
<tr>
<td>Sprint horizontal force</td>
<td>LSI_Fh_sprint</td>
<td>numeric</td>
<td>continuous</td>
<td>%</td>
</tr>
<tr>
<td>Sprint total Force</td>
<td>LSI_Ftot_sprint</td>
<td>numeric</td>
<td>continuous</td>
<td>%</td>
</tr>
<tr>
<td>Sprint ratio of forces</td>
<td>LSI_RF_sprint</td>
<td>numeric</td>
<td>continuous</td>
<td>%</td>
</tr>
<tr>
<td>Sprint DRF</td>
<td>LSI_DRF_sprint</td>
<td>numeric</td>
<td>continuous</td>
<td>%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hop tests</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Single One-Leg Hop Test</td>
<td>LSI_SOLHT</td>
<td>numeric</td>
<td>continuous</td>
<td>%</td>
</tr>
<tr>
<td>Triple One-Leg Hop Test</td>
<td>LSI_TOLHT</td>
<td>numeric</td>
<td>continuous</td>
<td>%</td>
</tr>
<tr>
<td>Cross-over One-Leg Hop Test</td>
<td>LSI_COOLHT</td>
<td>numeric</td>
<td>continuous</td>
<td>%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Isokinetic assessment</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadriceps peak tork at 60°/s BW</td>
<td>Q60_inj</td>
<td>numeric</td>
<td>continuous</td>
<td>N/kg</td>
</tr>
<tr>
<td>Quadriceps peak tork at 240°/s BW</td>
<td>Q240_inj</td>
<td>numeric</td>
<td>continuous</td>
<td>N/kg</td>
</tr>
<tr>
<td>Quadriceps peak tork at 30°/s BW</td>
<td>Q30_inj</td>
<td>numeric</td>
<td>continuous</td>
<td>N/kg</td>
</tr>
<tr>
<td>Hamstring peak tork at 60°/s BW</td>
<td>JJ60_inj</td>
<td>numeric</td>
<td>continuous</td>
<td>N/kg</td>
</tr>
<tr>
<td>Hamstring peak tork at 60°/s BW</td>
<td>JJ240_inj</td>
<td>numeric</td>
<td>continuous</td>
<td>N/kg</td>
</tr>
</tbody>
</table>

- LSI of all tests ≥90% Fitzgerald et al.[69]
- Barber-Westin and Noyes [23]
- Quadriceps LSI ≥85
- Hamstring LSI = 100%
- Ellman et al. [68]
- Ellman et al. [64]
- Lynch et al. [19]
- Barber-Westin and Noyes [23]
- Barber-Westin and Noyes [23]
- Quadriceps torque: body weight ratio > 55%
- Hhamstring/Quadriceps strength ratio >70%
- Quadriceps LSI ≥90%
- Hamstring LSI ≥90 %
<table>
<thead>
<tr>
<th>Conditioning Test</th>
<th>Measure Code</th>
<th>Type</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>240°/s BW</td>
<td>IJ240_hea</td>
<td>numeric</td>
<td>N/kg</td>
</tr>
<tr>
<td>Hamstring peak tork at 30°/s BW</td>
<td>IJ30_inj</td>
<td>numeric</td>
<td>N/kg</td>
</tr>
<tr>
<td>Mixed functional ratio</td>
<td>MFR_inj</td>
<td>numeric</td>
<td>N/kg</td>
</tr>
<tr>
<td>Follow-up</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marx 3 years postop</td>
<td>Marx_3y</td>
<td>numeric</td>
<td>discrete</td>
</tr>
<tr>
<td>Tegner 3 years postop</td>
<td>Tegner_3y</td>
<td>numeric</td>
<td>discrete</td>
</tr>
<tr>
<td>SANE 3 years postop</td>
<td>SANE_score_3y</td>
<td>numeric</td>
<td>continuous</td>
</tr>
</tbody>
</table>

LSI = leg operated / leg healthy, Slp_diff = Slp_operated - Slp_healthy, Dap_diff = Dap_operated - Dap_healthy, RF = Fh_sprint / Ftot_sprint, MRF = IJ30 / Q 240
An analysis of the evolution between 6, 9 and 12 months after an ACLR of the explanatory variables between the reinjured patients and non-reinjured patients using an ANOVA for repeated measures with two factor (time and groups) will be performed.

An analysis of correlation will be performed with all explanatory variables. Then explanatory variables will be included for univariate and multivariate analyses based on statistical criteria and clinical relevance.

Concerning our research into predictive factors, we will do a univariate analysis with independence variables to determine the predictive values, and then, logistic regression and a post-hoc REGW (Ryan-Einot-Gabriel-Welsch) tests will be done whenever possible. For the multiple models will be performed using backward elimination of nonsignificant variables (ie, variable with p≥0.02 were eliminated stepwise). Covariate variables will be entered in the models, but only independent variables will be used. All variables which will be validated criteria to return to sport or biomechanical significant to avoid wacky variables. We will also standardize as possible our independent variables and we will calculate the variance inflation factor for each variables of the multiple model.

The main conclusions drawn from this trial will be tested with p-values at the standard 0.05 level. Statistical analyses will be performed using R (http://www.R-project.org).

ETHICS AND DISSEMINATION

The present study has been approved by the local Ethical Committee (IRBN522015/CHUSTE). Prior to enrolment in the study, all subjects will be asked to give their informed consent. The patient can decide at any time to be released from the study and they will be informed of this in the information leaflet. His/her data will then be deleted from the data collection file. Leaving the study will have no incidence on the normal monitoring
protocol of patients post-surgery. The results of this trial will be disseminated via presentation at local, national and international conferences, peer-reviewed journals.

DISCUSSION

After ACLR, long-term problems like reinjuries or osteoarthritis highlight the importance of secondary and tertiary prevention. The management of return to sport is a public health challenge because these decisions are made during a period with a high risk of reinjury. Many criteria to allow a return to sport are proposed in clinical studies and used in clinical practice but no evidence-based criteria exist. In this study, we have chosen to use many criteria described in the literature and to continue monitoring during the return to sport phase. Repeating these assessments will enable us to observe the recovery kinetics of many of these criteria, linking them to the biomechanical assessments. This study is the first clinical trial aiming to analyze the criteria used for a return to sport, and adds biomechanical evaluation using force sensors when running. This analysis, mimicking sporting reality,[39] will detect any asymmetry during the return to sport phase (6 - 12 months), a point that standard evaluation procedures do not address. This evaluation is highly specific for the analysis of patients in the return to sport phase and consequently, useful to the decision of when this phase can safely start. These assessments will provide a great deal of specific data. They will allow multivariate statistical analyses and should determine the most robust criteria for a return to sport with a reduced risk of reinjury. With fewer injuries during the return to sport, we can expect improved overall recovery, and better protection of the knee against the consequences of an ACL tear. Less premature osteoarthritis and fewer reinjuries after ACLR
means not only improved function of the joint after ACLR but also generate less health care
costs for society as a whole.
Acknowledgements

The authors are grateful to the study participants, hospital staff and study staff (Léa Feuillassier, Alex Pavoine)

Contributors

AJMR, BS and PE designed the CRSTAL study and contributed to development of the study protocol. AJMR drafted the manuscript. BS submitted to ethic committee. AJMR, BS, RT, PS, JBM, RP and PE assisted in drafting the manuscript. All authors read and approved the final manuscript.

Conflict of interest

None declared.

Ethics approval

Ethical approval was obtained through the University Hospital of Saint-Etienne Ethics Committee (Reference number IRBN522015/CHUSTE).

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.
References


Barber-Westin SD, Noyes FR. Objective Criteria for Return to Athletics After Anterior Cruciate Ligament Reconstruction and Subsequent Reinjury Rates: A


Undheim MB, Cosgrave C, King E, et al. Isokinetic muscle strength and readiness to return to sport following anterior cruciate ligament reconstruction: is there an


Figure 1. The study design:

Figure 2. Knee laxity measurement position and the GNRB® system.

Figure 3. A runner fitted with a leather weightlifting belt (D) attached with a rigid tether (C) to the wall mounting bracket (A and B) sprinting on a motorized treadmill.

Figure 4. Hop Tests: A: Single One-Leg Hop Test, B: Triple One-Leg Hop Test, and C: Cross-over One-Leg Hop Test.
Fig 1. The study design

338x190mm (96 x 96 DPI)
Fig 2. Knee laxity measurement position and the GNRB® system.

699x990mm (90 x 90 DPI)
A runner fitted with a leather weightlifting belt (D) attached with a rigid tether (C) to the wall mounting bracket (A and B) sprinting on a motorized treadmill.

250x126mm (96 x 96 DPI)
Fig 4. Hop Tests: A: Single One-Leg Hop Test, B: Triple One-Leg Hop Test, and C: Cross-over One-Leg Hop Test

210x188mm (96 x 96 DPI)
Appendix 1

Phase 1

Acute Management/Early Motion and Basic Movement Retraining

This phase begins immediately after surgery and continues for 3 weeks.

Goals

1. Achieve full active knee extension equal to the uninvolved side with active Vaste Medialis recruitment.
2. Eliminate swelling
3. Restore the ability to control the leg while weight bearing
4. Achieve at least 90° of knee flexion
5. Be able to to straight leg raise.
6. Normalize walking pattern with the assistance of crutches and/or brace

If hamstring graft, no active hamstring exercises until 2 weeks and no open-chain resisted hamstring curls until 4 weeks post-op.
Type of exercises:

- Range of Motion (ROM) Exercises
- Soft tissue treatments to patella, patella tendon, incisions, and posterior musculature to improve range of motion and decrease fibrosis.
- Muscle Activation with quad sets, straight leg raises and double leg mini squats
- Core Body Training
- Ambulation like diagonal weight shifting, backward stepping and step-overs

Phase 2

Basic Strength and Proprioception

This phase begins 3 weeks after surgery. It will usually take 3-5 weeks to achieve the goals in this phase.

Goals

1. Restore proper body alignment and control with basic movements, such as walking without assistance, squats, stationary lunges and single-leg balance
2. Build lower extremity and core body strength

3. Develop increased proprioception, starting with stationary postures and then progressing to movements

4. Achieve active range of motion equal to the uninvolved Knee

Type of exercises:

- Range of Motion (ROM) and stationary bike

- Soft tissue treatments

- Gait Drills

- Functional Strengthening (add weight or resistance with exercises), Single-leg/unilateral workouts (i.e. on weight machines, squats, side and forward step-downs).

- Increase depth of balance exercises

- Core Body and increase intensity with aerobic machines.

Carefully monitor exercises for signs of diminished eccentric control, weakness, or poor ability to stabilize against varus / valgus moment with loading exercises.
Phase 3

Dynamic Neuromotor Strength, Endurance and Coordination

This phase can be initiated when the goals of phase 2 are met. On average this will begin 8 weeks after surgery.

Goals

1. Increase the strength of the involved leg.
2. Develop eccentric neuromuscular control to allow acceptance of impact activities without increasing symptoms
3. Develop dynamic flexibility to allow for proper alignment during activities of increasing speed.
4. Full range of motion is expected

Type of exercises:

- Range of Motion

- Dynamic Agility Drills: begin with small strides at low velocity, gradually progressing the velocity.
- Functional Strengthening. The recommended strengthening exercises are closed chain: squat, lunge.

- Landing and Takeoff Drills: before initiating impact activities the patient should not have any swelling, have full knee extension, be able to balance on one leg for 10 seconds and be able to perform a single leg squat to approximately 45-60° of knee flexion with good posture and control.

- Balance exercises with challenge postural control and duration: balance board activities, swim strokes, single leg balance with your eyes closed

- Core Body and cardiovascular conditioning

Phase 4

Athletic Enhancement and Return to Activity

This phase can be initiated when the goals of Phase 3 are met. This phase will usually begin 12-16 weeks after surgery.

Goals

1. Progress from double leg impact control to single leg impact control.
2. Develop proper technique and appropriate neuromuscular control with start and stop movements and change of direction movements.

3. Eliminate apprehension that may exist with complex movements related to sports.

**Type of exercises:**

- **Dynamic Warm Up:** will help with increasing core body temperature, mental alertness, elasticity of the muscular system and activation of your neuro-muscular system.

- **Multi-planar Landing Control and Neuromuscular Reaction:** Jump rotations, fast feet and lunge, multi-planar leap and land, stop and go, hopping.

- **Functional movements and strengthening:** one legged squat, single leg deadlift, lateral lunge walk, power step up.

- **Advanced Core Training and begin for jogging.**
Criteria for Return to Sport after Anterior Cruciate Ligament reconstruction with lower re-injury risk (CR’STAL study): A prospective observational study

<table>
<thead>
<tr>
<th>Journal:</th>
<th>BMJ Open</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuscript ID</td>
<td>bmjopen-2016-015087.R1</td>
</tr>
<tr>
<td>Article Type:</td>
<td>Protocol</td>
</tr>
<tr>
<td>Date Submitted by the Author:</td>
<td>20-Jan-2017</td>
</tr>
<tr>
<td>Complete List of Authors:</td>
<td>Rambaud, Alexandre; Universite Jean Monnet Saint-Etienne, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424); Centre de kinésithérapie du Pôle Sportif, SEMAY, Bertrand; Universite Jean Monnet Saint-Etienne Faculte de Medecine Jacques Lisfranc, Department of Orthopaedic and Trauma Surgery; Universite Jean Monnet Saint-Etienne, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424) Testa, Rodolphe; Universite Jean Monnet Saint-Etienne, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424) Samozino, Pierre; Universite Savoie Mont-Blanc, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424) Morin, Jean-Benoit; Universite Cote d’Azur, LAMHESI Rossi, Jérémy; Universite Jean Monnet Saint-Etienne, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424) Philippot, Rémi; Centre Hospitalier Universitaire de Saint-Etienne, Department of Orthopaedic and Trauma Surgery; Universite Jean Monnet Saint-Etienne, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424) Edouard, Pascal; Centre Hospitalier Universitaire de Saint-Etienne, Department of Clinical and Exercise Physiology, Sports Medicine Unit; Universite Jean Monnet Saint-Etienne, Laboratory of Human Motricity, Education Sport and Health (EA 6312)</td>
</tr>
</tbody>
</table>

**Primary Subject Heading**: Sports and exercise medicine

**Secondary Subject Heading**: Rehabilitation medicine

**Keywords**: Anterior Cruciate Ligament Reconstruction, injury prevention, Risk factors, Biomechanics, Return to Sport
Criteria for Return to Sport after Anterior Cruciate Ligament reconstruction with lower re-injury risk (CR’STAL study): A prospective observational study protocol

Alexandre JM RAMBAUD1,2, Bertrand SEMAY1,3*, Rodolphe TESTA1, Pierre SAMOZINO4, Jean-Benoît MORIN5, Jérémy ROSSI1, Rémi PHILIPPOT1,3, Pascal EDOUARD1,6

---

1 Inter-university Laboratory of Human Movement Biology (LIBM EA 7424), University of Lyon, University Jean Monnet, Saint Etienne, France
2 Physiotherapy Clinic of the Sport Center, La Talaudière, France
3 Department of Orthopaedic and Trauma Surgery, University Hospital Center of Saint-Etienne, Hôpital Nord, Saint-Etienne, France
4 Inter-university Laboratory of Human Movement Biology (LIBM EA 7424), University Savoie Mont Blanc, Le Bourget-du-Lac, France
5 Université Côte d’Azur, LAMHESS, Nice, France
6 Department of Clinical and Exercise Physiology, Sports Medicine Unit, University Hospital of Saint-Etienne, Faculty of Medicine, Saint-Etienne, France

---

Corresponding Author:
Alexandre JM RAMBAUD, LIBM, University of Lyon, Campus Santé Innovations IRMIS, 10 rue de la Marandière, 42270 Saint-Priest en Jarez, France.
Email: alexandre.rambaud.kine@gmail.com +33 (0)4 77 30 76 55
*These authors contributed equally to this work.

Keywords:

Anterior Cruciate Ligament Reconstruction, Return to Sport, Biomechanics, risk factors; injury prevention
ABSTRACT

Introduction:

The decision regarding when to return to sport after an Anterior Cruciate Ligament Reconstruction (ACLR) is an important one. Using a variety of subjective and objective parameters various attempts have been made to determine an optimal timeline for a return to sport after ACLR, but none have been validated.

The aim of the present study is to test the relationships between the risk of reinjury and objective measurement of subjective and objective parameters to determine which criteria or combination of criteria could be predictive of a return to sport with the lowest possible risk of reinjury.

Methods and analysis

This study is a prospective cohort, single-center study, with repeated assessments at 6, 9 and 12 months post-ACL surgical reconstruction and including a 3-year follow-up of patients’ sporting activity and injuries. 250 patients will be included to test explanatory variables. Postural control analysis, knee laxity, questionnaires (IKDC, TSK11, ACLR-RSI, SANE), modified Star Excursion Balance Tests, running and sprinting biomechanics, Hop Tests and isokinetic tests will all be used. The primary outcome will be any reinjury during the follow-up period, defined as a graft rupture, a contralateral ACL rupture, or any injury necessitating an interruption of training and requiring a medical consultation. Two groups will be
constituted during the follow-up, separating reinjured from non-reinjured patients. In addition, classic analysis and Data Mining approaches will be used to build predictive models.

Ethics and dissemination

The results of this study will be disseminated through peer-reviewed publications and scientific presentations. Ethical approval was obtained through the University Hospital of Saint-Etienne Ethics Committee (Reference number IRBN522015/CHUSTE).
STRENGTHS AND LIMITATIONS OF THIS STUDY:

● This is the first study to associate the analysis of several parameters (both habitual and innovative, considered both singly and in combination) with an exploratory data analysis (Data Mining), to formulate the best decision-making model for determining the optimal time for a return to sport after ACLR.

● This study has been designed to include evaluations at 6, 9 and 12 months post-ACLR in order to include and analyze data from the usual time when athletes return to pivot-sport training (6-9 months) and the time when they can return to competition (generally 9-12 months).

● The study includes only young competitive athletes, which is the population with the highest risk of reinjury. These findings would not necessarily be applicable to the general population.

● This screening protocol seeks to assess elements involved in the return to sport after ACLR with knee-specific and task-specific objective measurements associated with subjective assessment of knee function and psychometric capabilities.

● The design and objectives of this study will require a significant number of patients, but since this population is highly motivated to return to sport, we are convinced that this choice will limit dropouts.
INTRODUCTION

Anterior cruciate ligament (ACL) tears represent a public health challenge with an incidence reported as 60-71 per 100,000 subjects. ACL tears often give rise to problems like post-traumatic osteoarthritis; that could lead to middle- and long-term problems for the patient, a potential increase in knee surgery in the future and consequently a significant cost to society. In this context, appropriate treatment of ACL tears and secondary and tertiary prevention among young pivot-shift athletes represent very relevant challenges and a major orientation for orthopedics and sports medicine research.

After an injury (ACL tear), the most frequent question asked by the patient is: “when can I get back to my sport?” If the patient with an ACL tear is considered to be at a high risk of knee instability (young, high-level athletes in a pivoting and/or contact sport), an ACLR is the current clinical standard. After surgical reconstruction, a rehabilitation program is set up to allow patients to return to a painless and fully functional daily life. In patients aiming to return to sport, the rehabilitation program must continue until this is possible.

The consensus is that a successful ACLR is one where the patient can return to the same level of sporting activity as before the injury and a recent patient satisfaction survey confirms that a patient who can resume his sporting activity is more likely to be satisfied with the outcome of the ACLR. Consequently, the decision of when to return to sport is an important one for patient satisfaction and challenging in the context of secondary and tertiary prevention.

The return to sport, especially with pivoting or contact sports, exposes the athlete to a risk of reinjury: the reinjury rate for the ipsilateral ACL is 3.5% to 13.0% and for the contralateral
ACL is 4.4% to 9.0%. A new injury after an ACLR may affect the joint (rupture of the graft or contralateral ACL, chondral and/or meniscal lesion) or be a musculoskeletal injury. Many factors have been implicated in reinjury risk, including sex, age, activity level, graft placement, graft type, time from surgery, and deficits in neuromuscular and biomechanical control of the lower limb.

An early return to sport exposes the patient to a high risk of reinjury, but returning to sport too late seems to decrease the chances of returning to the pre-injury level of performance. In their updated review, Ardern and al. had shown that on average 80% of patients returned to sport, while only 55% returned to competitive levels after ACLR. Thus, the decision to return to sport is both important and challenging.

Therefore, it is obviously necessary to define an optimal individualized timeline for a return to sport and to define and validate the optimal criterion obtained from explanatory variables permitting a return to sport. It is vitally important to determine this optimal individualized timeline as this could both minimize the risk of reinjury and optimize the return to sport.

Many techniques and many criteria have been used in clinical studies to determine the optimal moment for a return to sport after ACLR. The most used is the post-operative timeline, either alone or with: muscle strength, knee laxity, knee assessment form, or functional tests. However, to the best of our knowledge, there are no clearly validated criteria for a return to sport after ACLR. This decision is currently based on multiple criteria mostly using the post-operative time frame needed for the biological integration of the graft.

Barber-Westin and Noyes, in a systematic review, described how this decision is associated with subjective parameters ("satisfactory clinical examination", "stable knee", "normal joint function", self-reported knee function (subjective IKDC (The International
Knee Documentation Committee\textsuperscript{43} and objective criteria. Only 19\% of studies\textsuperscript{32} have used objective criteria such as: muscular strength, knee laxity, the limb symmetry index (LSI) or functional tests (Hop Tests, Star Excursion Balance Tests).

Among the objective criteria, testing isokinetic muscular strength is a clear measure of strength recovery\textsuperscript{44,45} and seems to be central in objective assessment of a readiness to return to sport\textsuperscript{35,40}. In two recent studies, Krytsis and al.\textsuperscript{40} and Grindem and al.\textsuperscript{35} report the risk-factors for injury during a return to sport (RTS) using two similar sets of objective measures as discharge criteria for returning to sport. These two studies highlight the major interest for an individualized decision about RTS after ACLR. While pushing back the RTS from the 6th to the 9th month after surgery can reduce the risk of reinjury by 51\% for each month\textsuperscript{35}, the use of a test battery (Hop Tests, Running-t-test, and isokinetic strength assessment) was able to identify patients at lower risk of reinjury\textsuperscript{40}. However, contextual factors such as a positive attitude and fear of injury have not been assessed either in these studies or in the literature as predictors of re-injury although it is well known that these factors influence the capacity to return to sport, especially at the same level of participation\textsuperscript{46}.

Functional testing and biomechanical analysis of running or sprinting allows evaluation of lower limb function in a context close to that of sport. After an ACLR, weakness of the quadriceps disturbs the pattern of walking; this is known as “Quad-Avoidance”\textsuperscript{47,48}. This altered pattern may persist when running and modify the stiffness of the lower limb and step length. Functional tests and biomechanical analysis would highlight both this altered pattern during the stance phase of running and the functional asymmetry of the patient. This altered pattern could be one of the parameters involved in the decreased athletic ability of patients and the increased risk of injury. Using a non-motorized treadmill fitted with force sensors,
Brown and Brughelli\textsuperscript{49} evaluated the sprint of a rugby player after ACLR during the period of return to sport (between the return to training and competition). An asymmetry of the Ground Reaction Force (GRF) persisted (horizontal force: 13\%, vertical force: 7\%) while the isokinetic muscular strength testing appeared normal. They concluded that an evaluation of sprint mechanics complemented the usual functional assessments. This analysis, in line with sports reality,\textsuperscript{50} could detect an asymmetry during the return to sport phase (6-12 months). This sport-specific assessment seems very relevant to the decision to return to sport; indeed, a good gait with efficient biomechanical performance in the sagittal plan is an essential step for a return to pivoting/cutting sports. This new approach could also help explain the many failures in returning to sport, despite LSI scores close to 100\% with both isokinetic and Hop Tests. The predictive values of all these tests have not yet been validated for detecting the risk of reinjury in sports after an ACLR. This sprint running and running biomechanics approach could help more clearly define the criteria necessary to assess a safe return to sport after an ACLR in a high-risk population.

In this context, the determination of valid criteria or an association of criteria to aid in the decision-making process regarding a return to sport without risk of reinjury or associated lesions (muscles or ligaments of the lower limbs) is of major interest in the monitoring of patients with ACLR who want to return to a competitive pivoting sport. The aim of the present study is therefore to test the relationships between reinjury risk and objective measures of subjective and objective parameters in order to determine which criteria or combination of criteria could be predictive for a return to sport with the lowest possible risk of reinjury.
METHODS

The present study is a prospective cohort single-center study, with repeated measures at 6, 9
and 12 months post-operatively after an ACLR and follow-up of the return to sport and
reinjury for 3 years after the ACLR. The research started in January 2015, and is due to be
completed in December 2020. The study design is shown in Fig 1.

Please insert Fig 1.

Study patients

Potential subjects will be drawn consecutively from among the patients of the Sports Medicine
Unit or the Orthopedic Surgery and Traumatology department of the local University
Hospital. Subjects included in the study must meet the criteria for inclusion/exclusion shown
in Table 1. All study patients will undergo post-surgical rehabilitation in the same
Physiotherapy Clinic using the protocol recommended in the literature (for more
information about the protocol please see S1 Appendix. ACL Reconstruction Rehabilitation
Protocol).

Table 1 Inclusion and exclusion criteria for patients
## Inclusion criteria

- Participation in pivot and/or contact sports and with intensive sporting activity before the ACL tear:
  - with a Marx scale score above 11 before the injury
  - with a Tegner score above 4 before the injury
  (competition training with more than 3 training sessions per week before the injury)
- Unilateral tear

## Exclusion criteria

- Bilateral lower limb pathologies
- Recurrence of ACL rupture (with a MRI diagnostic)
- Contraindications for carrying out a test, i.e.:
  - Postoperative time less than 6 months
  - Persistence of knee pain (score >3 at Numeric Pain Rating Scales)
  - Persistence of a joint effusion (positive patellar tap test)
  - Incomplete range of motion (Range of motion < 90% on contralateral side)
  - Abnormal walk (observable gait deviations during the walk)
  - Allografts
  - Skeletal immaturity
  - Older than 35 years

## Assessment procedure

All tests will be performed in the same place and all patients will be tested at the same time of day between 2 pm and 6 pm. Forty-eight hours before each evaluation session, patients will receive an email reminding them of the test procedure and asking them to complete a subjective questionnaire online (IKDC, TSK11, ACL-RSI and SANE).

Informed consent will be obtained from all subjects before testing begins and a standardized explanation of the assessment procedure given to the patients. Each test session will include, in the same order, a medical check-up, postural control analysis, knee laxity measurements, a modified Star Excursion Balance Test, biomechanical running and sprint analysis, Hop Tests and isokinetic tests, with a 5-minute rest between each test. Before the biomechanical analysis begins, patients will warm-up with 10 minutes of cycling to raise muscle temperature. A
specific warm up activity will be included before each new activity. The isokinetic evaluation is at the end of the battery to avoid tiredness affecting the results of the other tests.

**Evaluation of subjective parameters by questionnaires**

The first questionnaire is the IKDC, an algo-functional questionnaire commonly used for ACLR follow-up. An IKDC within the 15th percentile of healthy subjects is considered as criteria for a return to sport. The patient will then complete the Tampa Scale of Kinesiophobia-11 (TSK11). This questionnaire, containing 11 questions (choice between 5 answers), is used to estimate a patient’s fear of movement and reinjury giving a score from 11 to 55. A score below 20 indicates low pain avoidance and could also allow a return to sport. The last questionnaire the patient is asked to complete is the ACL-Return to Sport after injury (ACL-RSI). This 12-item scale measures three specific psychological constructs – emotions, confidence in performance, and risk appraisal – on a scale from 0 to 100. This scale is a predictive parameter for a successful return to sport after ACLR.

The patient will also be asked to estimate his knee recovery on a scale (from 0 to 100) with a single assessment numeric evaluation (SANE).

**Medical check-up**

Firstly, we will check if the online questionnaires have been done, and the presence of inclusion criteria and absence of exclusion criteria. The assessor will fill out the demographic information in the observation book (sex, age, weight, height, sport, training frequency and
Marx’s score before the ACL tear), a timeline for a return to running, sport-specific training
and competitive play where possible, and finally the ACLR surgeon and technique used. The
clinical examination will follow the IKDC-2000 grid\textsuperscript{52}.

Postural control analysis

A WinPosturo\textsuperscript{®} (Medicapteurs, Balma, France) stabilometry platform will be used with the
WinPosture\textsuperscript{®} software (Medicapteur, Balma, France) to determine variations in the center of
pressure (CoP). The force plate, which measures 530 × 460 × 35 mm has three pressure
gauges (hysteresis < 0\textperthousand 2%), with a sensitivity of 90 points per Newton. The sampling
frequency will be fixed at 40 Hz with the platform recalibrated before each session. The
assessment will be conducted in an isolated room, in a noise-free environment, with a hard,
flat floor, following the recommendations of the American Academy of Neurology (AAN)\textsuperscript{61}
and the study of Ruhe et al.\textsuperscript{62}. The standardized position of the feet will be: oriented 15°
laterally to the sagittal plane. The patient will have to breathe normally and stare at a point 1.5
m in front him, at eye level, the arms relaxed along the body. The patient will be in
sportswear and socks.

Four measurements, knees in extension, separated by 30 seconds of recovery in a sitting
position, will be performed:

- bipedal position, eyes open (60s)
- bipedal position, eyes closed (60s)
- Single-leg squat following by balancing on the healthy leg (30s)\textsuperscript{36}
- Single-leg squat following by balancing on the operated leg (30s)\textsuperscript{36}
The values of total CoP path (CoP in mm), CoP velocity (in mm.s\(^{-1}\)), standard derivations of CoP (SDx and SDY), and CoP sway area (in mm\(^2\)) will be recorded. Kouvelioti et al. showed good or excellent reproducibility of all these variables using a similar assessment protocol (Intraclass Correlation Coefficient (ICC) range from 0.68 to 0.91).

Knee laxity measurements

The GNRB® system (Genourob, Laval, France) is a non-invasive arthrometer that provides comparative bilateral measurements of knee laxity. This system is reliable and reproducible (ICC range from 0.77 to 0.91 \(^{64-66}\)). The patient will lie on a standard examination table in the supine position, with the knee at 20° flexion and 0° of rotation (Fig 2). The lower limb is immobilized in a thermoformed shell, adaptable for different leg lengths, at the patella and the foot with a force of about 65±5N controlled by a force sensor with a precision of 0.1 mm. The analysis will begin with the healthy leg, with a push to 134N and 3 pushes to 250N. The same procedure is then repeated on the operated limb. The displacement of the anterior tibial tubercle relative to the femur is measured. The drawer shift/pressure curve is determined by the displacement (with 0.1 mm precision) and the slope of the curve (\(Slp\) in degree) which defines ligamentous laxity. The push to 250 N with the largest displacement (\(D_{ap}\) in mm) and \(Slp\) will be retained. The difference between the operated and healthy limb will be calculated for \(D_{ap}\) and \(Slp\).

Please insert Fig 2.
Modified Star Excursion Balance Test

The patient, shoeless, will be asked to stand on one leg, starting with the healthy limb, without lifting the heel and with hands on hips and perform the following exercise as described in the literature: \textsuperscript{67-69} to reach maximally to touch a point as far as possible in 3 directions, along i) an antero-posterior axis ii) the postero-lateral axis and finally iii) the postero-medial axis, returning to the initial position between each movement. Two attempts and 2 measurements will be made for each direction. The longest distance (in cm) will be noted for each direction. The reliability is high with ICC from 0.83 to 0.96 \textsuperscript{70}.

Running and sprinting mechanics

Patients will choose either a cycle ergometer and/or jogging for a 10-15 general warm-up, followed by a specific sprint warm-up included sprint drills and short sprints. On a motorized instrumented treadmill (ADAL3D-WR; Medical Development, HEF Tecmachine, Andrezieux-Boutheon, France), with four piezoelectric force transducers (KI 9077b, Kistler, Winterthur, Switzerland), on a hard, flat surface in a quiet room, the patient will be then undergo the biomechanical evaluations first for running and then sprinting with a one minute rest between them (Fig 3). The reliability is high with ICC from 0.85 to 0.90 \textsuperscript{71}.

For the running biomechanical evaluation, each patient will run for three minutes at 3.33 m.s\textsuperscript{-1} (12 km.h\textsuperscript{-1}) and, without the patient being informed of the exact moment of data recording, 20 sec of biomechanical parameters will be recorded. Mechanical data will be sampled at 1000 Hz. After appropriate filtering (Butterworth-type 30 Hz low-pass filter, 2\textsuperscript{nd} order),
For peer review only

instantaneous data of vertical force will be averaged for each support phase (vertical force above 30 N) over the 20-s ($F_{VR}$), and expressed in N and body weight (BW). For each step, contact ($t_c$) and aerial ($t_a$) times will be calculated. Spring–mass parameters, like vertical stiffness ($k_{vert}$ in kN m$^{-1}$) and leg stiffness ($k_{leg}$ in kN m$^{-1}$), will be calculated using the computation method proposed by Morin et al.[59] The lower limb leg length will be the distance behind the great trochanter to ground distance in a standing position. The stride length ($l_{stride}$ in m) will be calculated as: $l_{stride} = (t_c + t_a) \cdot v$.

For the sprint running biomechanical evaluation, each patient will first be familiarized with sprinting on a treadmill by three 6-sec sprints separated by 1 minute of rest. The patient is fitted with a leather weightlifting belt attached via a rigid tether (0.6 cm in diameter) to the wall (Figure 3), as described by Morin et al. [72] The constant motor torque will be set to 160% of the default torque, i.e. the motor torque necessary to overcome the friction on the treadmill belt due to the subject’s body weight. The default torque will be measured by making the subjects stand still and by increasing the driving torque until a movement of the treadmill belt greater than 2 cm is observed over 5 s. Motor torque of 160% of the default value will be selected after several preliminary measurements comparing various torques, as this will allow subjects to sprint in a comfortable manner and produce maximal effort without risking a loss of balance. Once the patient is correctly attached, he will be required to lean forward in a typical crouched sprint-start position with their preferred foot forward. This starting position will be used and standardized throughout the sprint series. After a 3-sec countdown, the treadmill will be released, and the treadmill belt will begin to accelerate as subjects apply a positive horizontal force. With patients strongly encouraged to produce their maximum intensity, two sprints will be recorded separated by a 1-minute rest period. The data used for
analysis will be: instantaneous data of vertical, net horizontal and total GRF averaged for each support phase (vertical force above 30 N) over 6-s sprints ($F_{V\text{sprint}}$, $F_{H\text{sprint}}$, $F_{t\text{ot}\text{sprint}}$ respectively), and expressed in N and BW. For each step, the ratio of forces applied on the ground (RF) will be calculated as the ratio of $F_{H\text{sprint}}$ to $F_{t\text{ot}\text{sprint}}$ for one contact as follows:

$$RF = \frac{F_{H\text{sprint}}}{F_{t\text{ot}\text{sprint}}} - 1$$ (expressed in %).

Then, mean and maximal values of ratio forces for the 6-s sprint will be computed (RF-mean and RF-max, respectively). The index of force application technique ($D_{RF}$) representing the decrement in RF with increasing speed (S) will be computed as the slope of the linear RF-speed relationship calculated from the step-averaged values between the second step and the step at top speed. Therefore, the higher the DRF (i.e. a flat RF-speed relationship), the more RF will be maintained despite increasing velocity, and vice versa. Lastly, for each 6-s sprint, performance will be described through mean and maximal running speeds ($S$ and $S$-max, respectively).

Please insert Fig 3.

Hop Tests:

The patient will be asked to perform the following exercises, as described by Noyes and al. (Fig 4.):

- Single One-Leg Hop Test on the healthy limb and then the operated limb, with the arms crossed, hands on shoulders. The patient will perform one hop, as far as possible, with a controlled, balanced landing (minimum 3 seconds). If the patient cannot maintain the landing position, makes extra hops, or does not keep his hands on his shoulders, then the Hop Test will be considered a failure.
- **Triple One-Leg Hop Test** on the healthy limb and then the operated limb with the arms in any position. The patient will perform 3 consecutive hops as far as possible. The last hop position must be maintained for a minimum of 3 seconds as with the *Single One-Leg Hop Test*.

- **Cross-over One-Leg Hop Test** on the healthy limb and then the operated limb with the arms in any position. The test is carried out on a 6.5 m strip of carpet with a central line 15 cm in width. The patient is asked to make three hops, the first laterally, crossing the line on each hop. Landing after the final hop must be as with the *Single One-Leg Hop Test*. The *Cross-over One-Leg Hop Test* allows assessment of the cutting movement capabilities of the patient.

  It imposes both predominant sagittal plane and rotation forces on the frontal plane of the knee. In addition, the test highlights any instability in the knee, but also tests muscle extensibility, muscle strength and power, proprioception, neuromuscular control, dynamic balance, and agility.

Patients start from single limb stance. Every attempt will include at least 3 jumps and will continue until the patient progresses. The best distance for each leg and each Hop Test will be recorded for analysis (in cm). The reliability is high with ICC from 0.84 to 0.92.

Please insert Fig 4.

**Isokinetic assessment**

As the resulting tiredness could affect the other tests if done earlier in the battery, the isokinetic quadriceps and hamstring muscle strength assessment will be performed last. They
will be done on a Con-Trex® Multi-Joint dynamometer (CMV AG, Dübendorf, Switzerland) and controlled by Con-Trex Software. The installation is described elsewhere in the literature.  

The subject will be seated with the hip joint at about 85° and strapped in place at the chest, pelvis and mid-thigh to avoid postural compensation during the assessment. The contralateral limb will be fixed to a support at the ankle. The axis of the dynamometer will be perfectly aligned with the rotation axis (lateral femoral epicondyle) of the knee joint. Resistive support will be strapped to the leg, at 2-3 cm proximal to the ankle joint line. The range of knee motion will be set from 80° for a safe, comfortable, comparative assessment. The gravity correction will be used. Assessment will begin with the healthy knee, and then the operated knee, and each series of repetitions will be followed by one minute of rest. The assessment is summarized in Table 2.

<table>
<thead>
<tr>
<th>Repetitions</th>
<th>Angular velocity and mode of contraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>First specific warm-up</td>
<td>↓ 6 sub-maximal 120 °/s in concentric</td>
</tr>
<tr>
<td>Second specific warm-up</td>
<td>↓ 6 sub-maximal 120 °/s in concentric</td>
</tr>
<tr>
<td>Habituation session</td>
<td>↓ 3 sub-maximal 60 °/s in concentric</td>
</tr>
<tr>
<td>Maximal test session with encouragement</td>
<td>↓ 3 maximal 60 °/s in concentric</td>
</tr>
<tr>
<td>Maximal test session with encouragement</td>
<td>↓ 3 maximal 120 °/s in concentric</td>
</tr>
<tr>
<td>Habituation session</td>
<td>↓ 3 sub-maximal 30°/s in eccentric</td>
</tr>
<tr>
<td>Maximal test session with encouragement</td>
<td>↓ 3 maximal 30°/s in eccentric</td>
</tr>
</tbody>
</table>
The isokinetic assessment will be performed in this order, using gravity corrections, at a range of motion of 5°-85°, and measuring peak torque for each test session. A 1-minute rest will be allowed between each session.

Torque, position and angular velocity data will be recorded from the isokinetic dynamometer with a sampling rate of 100 Hz. After appropriate filtering, for concentric and eccentric strength trials, the software will calculate a large number of parameters, but we will retain only the absolute peak torque, the most reproducible parameter (ICC > 0.96)\(^7\). The peak torque value normalized to the body weight (Nm/kg) will be recorded for each mode and speed of contraction for the Quadriceps (Q) and Hamstring (H). The Q/H ratio will be calculated for each mode and speed of contraction on the operated side, with a ratio ≥ 60% considered to be physiologically sufficient to obtain joint control. A mixed functional ratio, associating the eccentric performance of the flexor (at 30°/s) and the concentric performance of the extensor (at 240°/s) will also be calculated, as reported by Croisier and al.\(^8\).

**Follow-up after ACL surgical reconstruction**

Patient follow-up will continue until 36 months post-operatively. After the evaluation at 12-months post-surgery patient follow-up will continue for a further 2 years. The researchers will attempt to follow-up all patients by phone interview every 6 months to determine the date of return to running, to pivoting sport-specific training, and to pivoting sport competition, as well as the date and the nature of any reinjury that may occur. We will also collect the Tegner score at 3-years post-ACLR.
The decision for clearance to a return to sport will be made by a sport-physician, blinded to all the tests results except the isokinetics results. This decision will be taken after considering the time from surgery, clinical experience and the isokinetics results.

**Primary outcome**

The main criterion for assessment is the occurrence of reinjury during the 3-year follow-up. A reinjury is defined as a rupture of the transplant or the contralateral ACL, or any injury requiring the sporting activity to cease and necessitating a consultation and/or medical care.

**Method of accounting for missing, unused or invalid data**

A patient’s participation in the study will cease if significant complications appear when performing the tests and all data collected before that point will be analyzed.

**Power and sample size considerations**

Assuming the rate of ACL reinjury to be 20% after an ACLR (ipsi or contralateral ACL injury)\(^3\), considering a 10% dropout rat, and that 10 cases (reinjury) are needed to test one explanatory variable, it is necessary to include 50 patients to test one explanatory variable for 95% power and a Type-I error rate (alpha) of 0.05. Given the very specific population and the optimized follow up, we hope that we will have a low percentage of dropouts. Depending on the results of the Data Mining procedures on the variables presented in table 3, we will choose a maximum of 5 variables to construct the model. We will therefore need to include 250 patients.
Statistical analyses

Exploratory data analysis will be performed, following five steps adapted from Data Mining processes: 80 81 1) Identification of study objectives, 2) Data acquisition, 3) Data evaluation and preparation, 4) Data analysis and modeling, 5) Results, interpretation and validation.

In step 3, we will analyze the data quality checking that there are no inconsistencies, errors, duplicates or "aberrant" data. We will also verify the overall consistency of the data.

In step 4, classification and selection of variables reported in Table 3 will define the explanatory variables required to build the models. We will choose the best data analysis taking into account the characteristic of the model variables.

Lastly, in step 5, the model(s) will be analyzed and compared in order to define as precisely as possible the explanatory variables and the most suitable model. The p-value will be adjusted if necessary and other methods could be used (Akaike information criterion (AIC) or Bayesian information criterion (BIC)). The parameters of the model will then be analyzed in order to define their clinical relevance.

The use of this exploratory data analysis will be based on by some of the work in medical research to use Data Mining 80 82. However, this method does not exclude the classical statistical analyses for the creation of a model. Lasting, depending on our variables, we will use the appropriate statistical tests. After performing a correlation matrix and calculating colinearity using linear regression, we will calculate several Generalized Linear
Models if possible: Linear Regression, Generalized Estimating Equations, Generalized Linear Mixed Model, depending on the characteristics of our variables.

Statistical analyses will be performed using R (http://www.R-project.org).

Table 3. Explanatory variables

<table>
<thead>
<tr>
<th>Categories of criteria</th>
<th>Explanatory variables</th>
<th>unit or range</th>
<th>Calculated data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Marx pre injury</td>
<td>0-16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tegner pre injury</td>
<td>0-10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>self-reported measures</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>IKDC</td>
<td>0-100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TSK-11</td>
<td>11-55</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SANE</td>
<td>0-100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Postural control analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Center of pressure (CoP)</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Center of pressure (CoV)</td>
<td>mm.s-1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Center of pressure (CoP)</td>
<td>mm²</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Knee laxity measurements</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>GnRB slope</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GnRB anteroposterior displacement</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SEBT</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Anterior distance</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Postero-lateral distance</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Postero-lateral distance</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>composite SEBT score</td>
<td>%</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Running and Sprinting mechanics</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LSI Leg stiffness</td>
<td>%</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>LSI stride length</td>
<td>%</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>LSI Sprint vertical force</td>
<td>%</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>LSI Sprint horizontal force</td>
<td>%</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>LSI Sprint total Force</td>
<td>%</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>LSI Sprint ratio of forces</td>
<td>%</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>LSI Sprint DRF</td>
<td>%</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Hop Tests</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LSI Single One-Leg Hop Test</td>
<td>%</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>LSI Triple One-Leg Hop Test</td>
<td>%</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>LSI Cross-over One-Leg Hop Test</td>
<td>%</td>
<td>X</td>
</tr>
</tbody>
</table>
![Image of a page from a document]

**Isokinetic assessment**

<table>
<thead>
<tr>
<th></th>
<th>Quadriceps peak torque at 60°/s BW</th>
<th>N/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quadriceps peak torque at 240°/s BW</td>
<td>N/kg</td>
</tr>
<tr>
<td></td>
<td>Quadriceps peak torque at 30°/s BW</td>
<td>N/kg</td>
</tr>
<tr>
<td></td>
<td>Hamstring peak torque at 60°/s BW</td>
<td>N/kg</td>
</tr>
<tr>
<td></td>
<td>Hamstring peak torque at 240°/s BW</td>
<td>N/kg</td>
</tr>
<tr>
<td></td>
<td>Hamstring peak torque at 30°/s BW</td>
<td>N/kg</td>
</tr>
</tbody>
</table>

| Mixed Functional Ratio | % | X |

<table>
<thead>
<tr>
<th>Follow-up</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Marx 3 years postop</td>
<td>0-16</td>
<td></td>
</tr>
<tr>
<td>Tegner 3 years postop</td>
<td>0-10</td>
<td></td>
</tr>
<tr>
<td>SANE 3 years postop</td>
<td>0-100</td>
<td></td>
</tr>
</tbody>
</table>

LSI = operated leg/healthy leg, Mixed Functional Ratio = IJ30/Q 240

**ETHICS AND DISSEMINATION**

The present study has been approved by the local Ethical Committee (IRBN522015/CHUSTE) and will be recorded on ClinicalTrials.gov. Prior to enrolment in the study, all subjects will be asked to give their informed consent. The patient can decide at any time to be released from the study and they will be informed of this in the information leaflet. His/her data will then be deleted from the data collection file. Leaving the study will have no incidence on the normal monitoring protocol of patients post-surgery. The results of this study will be disseminated via presentation at local, national and international conferences and peer-reviewed journals.

**DISCUSSION**

After ACLR, long-term problems like reinjuries or osteoarthritis highlight the importance of secondary and tertiary prevention. The management of return to sport is a public health
challenge because these decisions are made during a period with a high risk of reinjury. Many
criteria to allow a return to sport are proposed in clinical studies and used in clinical practice
but no evidence-based criteria exist. In this study, we have chosen to use many criteria
described in the literature, to use a new exploratory data analysis allowing creation of new
explanatory variables explaining the return to sport without injury, and to continue monitoring
all these variables during the return to sport phase. Repeating these assessments will enable us
to observe the recovery kinetics of many of these criteria, linking them to the biomechanical
assessments.

However, the main limitation of this study is the utilization of one of these criteria
(isokinetics) to clear the patient to return to sport participation. This selection bias will be
taken into account when the rate of re-injury has been evaluated, and will be considered when
interpreting our results.

This study is the first clinical study aiming to analyze the criteria used for a return to sport,
and adds biomechanical evaluation using force sensors when running. This analysis,
mimicking sporting reality\(^{50}\) will detect any asymmetry during the return to sport phase (6 -
12 months), a point that standard evaluation procedures do not address. This evaluation is
highly specific for the analysis of patients in the return to sport phase and consequently,
useful to the decision of when this phase can safely start. These assessments will provide a
great deal of specific data.

Moreover, data mining will be used to build a predictive model if possible. Data mining will
allow us to find models and patterns from the available data. It includes descriptive data
mining algorithms for finding interesting patterns in the data, like associations, clusters and
subgroups.
The aim of our model, if possible, is Predictive modeling to build a predictive model for a target variable, based on explanatory variables. But data Mining also includes Attribute selection and most machine learning algorithms allow us to learn which are the most appropriate attributes (predictor variables) to use for making decisions. Most methods for Attribute selection involve the space of attributes for the subset which is most likely to predict the best class.

The use of this exploratory data analysis will be inspired by some of the work done by Combes & Azema. and Esfandiari et al. 2014. On the other hand, this method does not exclude the classical statistical analyses for the creation of a model. These new criteria will allow an individualization of the return to sport decision accordingly to a global patient condition assessment. This optimization could limit the risk of reinjury, and so minimized associated long-term knee-problems.
Acknowledgements

The authors are grateful to the study participants, hospital staff and study staff, and especially Léa Feuillassier, Alex Pavoine, Antoine Dany.

Contributors

AJMR, BS and PE designed the CRSTAL study and contributed to development of the study protocol. AJMR and BS drafted the manuscript. BS submitted to ethic committee. AJMR, BS, RT, PS, JBM, RP and PE assisted in drafting the manuscript. All authors read and approved the final manuscript.

Conflict of interest

None declared.

Ethics approval

Ethical approval was obtained through the University Hospital of Saint-Etienne Ethics Committee (Reference number IRBN522015/CHUSTE).

Funding

This research received no specific grant from any funding agency in the public, commercial, or not- for-profit sectors.
References


Figure 1. The study design:

Figure 2. Knee laxity measurement position and the GNRB® system.

Figure 3. A runner fitted with a leather weightlifting belt (D) attached with a rigid tether (C) to the wall mounting bracket (A and B) sprinting on a motorized treadmill.

Figure 4. Hop Tests: A: Single One-Leg Hop Test, B: Triple One-Leg Hop Test, and C: Cross-over One-Leg Hop Test.
Fig 1. The study design

71x40mm (300 x 300 DPI)
Fig 2. Knee laxity measurement position and the GNRB® system.

395x559mm (300 x 300 DPI)
A runner fitted with a leather weightlifting belt (D) attached with a rigid tether (C) to the wall mounting bracket (A and B) sprinting on a motorized treadmill.

51x26mm (300 x 300 DPI)
Fig 4. Hop Tests: A: Single One-Leg Hop Test, B: Triple One-Leg Hop Test, and C: Cross-over One-Leg Hop Test

68x61mm (300 x 300 DPI)
Postoperative rehabilitation [1-3]

Phase 1

Acute Management/Early Motion and Basic Movement Retraining

Goals
1. Achieve full active knee extension equal to the uninvolved side with active Vastus Medialis recruitment.
2. Eliminate swelling.
3. Restore the ability to control the leg while weight bearing.
4. Achieve at least 90° of knee flexion.
5. Be able to straight leg raise.
6. Normalize walking patterns with the assistance of crutches and/or a brace.

If hamstring graft, no active hamstring exercises until 2 weeks and no open chain resisted hamstring curls until 4 weeks post-op.

Type of exercises:
—Range of Motion (ROM) Exercises (Heel-slides to improve knee flexion.)
—Soft tissue treatments to patella, patella tendon, incisions, and posterior musculature to improve range of motion and decrease fibrosis.
—Muscle Activation with quad sets, straight leg raises and double leg mini squats (ROM 0–60°). Use manual facilitation techniques or electrostimulation when voluntary contraction of the quadriceps is not possible.
—Core Body Training and Neuromuscular Training. Encourage a correct quality of performance (e.g. trunk lateroflexion, hip- and knee flexion, dynamic knee valgus and...
knee-over-toe) during strength training and walking. Use implicit learning techniques instead of explicit learning techniques.

—Ambulation like diagonal weight shifting, backward stepping and step-overs

Criteria to start phase 2:

—Closed wound
—No knee pain with phase 1 exercises (VAS)
—Minimal synovitis or effusion
—Normal mobility (left-right) of the patellofemoral joint
—Knee extension of at least 0° and a 120–130° flexion
—Voluntary control of the quadriceps
—Active dynamic gait pattern without crutches
—Correct qualitative performance of phase 1 exercises.

Phase 2

Basic Strength and Proprioception

Goals

1. Restore proper body alignment and control with basic movements, such as walking without assistance, squats, stationary lunges and single-leg balance.
2. Build lower extremities and core body strength
3. Develop increased proprioception, starting with stationary postures and then progressing to movements.
4. Achieve active range of motion equal to the uninvolved Knee.

Type of exercises:

—Range of Motion (ROM) and stationary bike
—Soft tissue treatments
For peer review only - http://bmjopen.bmj.com/site/about/guidelines.xhtml

— Gait Drills
— Functional Strengthening (add weight or resistance with exercises), Single-leg/unilateral workouts (i.e. on weight machines, squats, side and forward step-downs).
— increase depth of balance exercises
— Neuromuscular training: Increase difficulty of neuromuscular and perturbation training
— Core Body and increase intensity with aerobic machines.

Carefully monitor exercises for signs of diminished eccentric control, weakness, or poor ability to stabilize against varus/valgus moment with loading exercises.

Criteria to start phase 3:
— Correct qualitative performance of phase 2 exercises
— Limb Symmetry Index (LSI) >80% for quadriceps and hamstring strength
— LSI >80% for a hop test battery, preferably using the hop test battery of Gustavsson

Phase 3

Dynamic Neuromotor Strength, Endurance and Coordination

Goals
1. Increase the strength of the involved leg.
2. Develop eccentric neuromuscular control to allow acceptance of impact activities without increasing symptoms.
3. Develop dynamic flexibility to allow for proper alignment during activities of increasing speed.
4. Full range of motion is expected.

Type of exercises:
— Range of Motion
Dynamic Agility Drills: begin with small strides at low velocity, gradually increasing the velocity.

Functional Strengthening. The recommended strengthening exercises are closed chain: squat, lunge.

Landing and Takeoff Drills: before initiating impact activities the patient should not have any swelling, have full knee extension, be able to balance on one leg for 10 seconds and be able to perform a single leg squat to approximately 45–60° of knee flexion with good posture and control.

Balance exercises with challenge postural control and duration: balance board activities, swim strokes, single leg balance with eyes closed

- Core Body and cardiovascular conditioning

Phase 4

Athletic Enhancement and Return to Activity

This phase can be initiated when the goals of Phase 3 are met. This phase will usually begin 12–16 weeks after surgery.

Goals

1. Progress from double leg impact control to single leg impact control.
2. Develop proper technique and appropriate neuromuscular control with start and stop movements and change of direction movements.
3. Eliminate apprehension that may exist with complex movements related to sports.

Type of exercises:

- Dynamic Warm Up: will help with increasing core body temperature, mental alertness, elasticity of the muscular system and activation of the neuromuscular system.
- Multi-planar Landing Control and Neuromuscular Reaction: Jump rotations, fast feet and lunge, multi-planar leap and land, stop and go, hopping.
—Functional movements and strengthening: one-legged squat, single leg dead lift, lateral lunge walk, power step up.

—Advanced Core Training and begin for jogging.

Reference


# Criteria for Return to Sport after Anterior Cruciate Ligament reconstruction with lower re-injury risk (CR’STAL study): A prospective observational study

<table>
<thead>
<tr>
<th>Journal:</th>
<th>BMJ Open</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuscript ID</td>
<td>bmjopen-2016-015087.R2</td>
</tr>
<tr>
<td>Article Type:</td>
<td>Protocol</td>
</tr>
<tr>
<td>Date Submitted by the Author:</td>
<td>21-Mar-2017</td>
</tr>
<tr>
<td>Complete List of Authors:</td>
<td>Rambaud, Alexandre; Universite Jean Monnet Saint-Etienne, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424); Centre de kinésithérapie du Pôle Sportif, SEMAY, Bertrand ; Universite Jean Monnet Saint-Etienne Faculte de Medecine Jacques Lisfranc, Department of Orthopaedic and Trauma Surgery ; Universite Jean Monnet Saint-Etienne, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424) Samozino, Pierre; Universite Savoie Mont-Blanc, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424) Morin, Jean-Benoît; Universite Cote d’Azur, LAMHESSTesta, Rodolphe; Universite Jean Monnet Saint-Etienne, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424) Philippot, Rémi; Centre Hospitalier Universitaire de Saint-Etienne, Department of Orthopaedic and Trauma Surgery; Universite Jean Monnet Saint-Etienne, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424) Rossi, Jérémy; Universite Jean Monnet Saint-Etienne, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424) Edouard, Pascal; Centre Hospitalier Universitaire de Saint-Etienne, Department of Clinical and Exercise Physiology, Sports Medicine Unit; Universite Jean Monnet Saint-Etienne, Laboratory of Human Motricity, Education Sport and Health (EA 6312)</td>
</tr>
<tr>
<td>Primary Subject Heading:</td>
<td>Sports and exercise medicine</td>
</tr>
<tr>
<td>Secondary Subject Heading:</td>
<td>Rehabilitation medicine</td>
</tr>
<tr>
<td>Keywords:</td>
<td>Anterior Cruciate Ligament Reconstruction, injury prevention, Risk factors, Biomechanics, Return to Sport</td>
</tr>
</tbody>
</table>
Criteria for Return to Sport after Anterior Cruciate Ligament reconstruction with lower re-injury risk (CR’STAL study): A prospective observational study

Alexandre JM RAMBAUD1 2, Bertrand SEMAY1 3*, Pierre SAMOZINO4, Jean-Benoît MORIN5, Rodolphe TESTA1, Rémi PHILIPPOT1 3, Jérémy ROSSI1, Pascal EDOUARD1 6

1 Inter-university Laboratory of Human Movement Biology (LIBM EA 7424), University of Lyon, University Jean Monnet, Saint Etienne, France
2 Physiotherapy Clinic of the Sport Center, La Talaudière, France
3 Department of Orthopaedic and Trauma Surgery, University Hospital Center of Saint-Etienne, Hôpital Nord, Saint-Etienne, France
4 Inter-university Laboratory of Human Movement Biology (LIBM EA 7424), University Savoie Mont Blanc, Le Bourget-du-Lac, France
5 Université Côte d’Azur, LAMHESS, Nice, France
6 Department of Clinical and Exercise Physiology, Sports Medicine Unit, University Hospital of Saint-Etienne, Faculty of Medicine, Saint-Etienne, France

Corresponding Author:
Alexandre JM RAMBAUD, LIBM, University of Lyon, Campus Santé Innovations IRMIS, 10 rue de la Marandière, 42270 Saint-Priest en Jarez, France.
Email: alexandre.rambaud.kine@gmail.com +33 (0)4 77 30 76 55
*These authors contributed equally to this work.

Keywords:

Anterior Cruciate Ligament Reconstruction, Return to Sport, Biomechanics, risk factors; injury prevention
ABSTRACT

Introduction:

The decision regarding when to return to sport after an Anterior Cruciate Ligament Reconstruction (ACLR) is an important one. Using a variety of subjective and objective parameters, various attempts have been made to determine an optimal timeline for a return to sport after ACLR, but none have been validated.

The aim of the present study is therefore to determine which criteria or combination of criteria could allow to return to sport with the lowest possible risk of reinjury.

Methods and analysis

This study is a prospective cohort, single-center study, with repeated assessments at 6, 9 and 12 months post-ACLR surgical reconstruction and including a 3-year follow-up of patients’ sporting activity and reinjuries. 275 patients will be included to test explanatory variables. Postural control analysis, knee laxity, questionnaires (IKDC, TSK11, ACLR-RSI, SANE), modified Star Excursion Balance Tests, running and sprinting biomechanics, Hop Tests and isokinetic tests will all be used. The primary outcome will be any reinjury during the follow-up period, defined as a graft rupture, a contralateral ACL rupture, or any injury necessitating an interruption of training and requiring a medical consultation. Two groups will be constituted during the follow-up, separating reinjured from non-reinjured patients. In addition, classic analysis and Data Mining approaches will be used to build predictive models.
Ethics and dissemination

The results of this study will be disseminated through peer-reviewed publications and scientific presentations. Ethical approval was obtained through the University Hospital of Saint-Etienne Ethics Committee (Reference number IRBN522015/CHUSTE).
STRENGTHS AND LIMITATIONS OF THIS STUDY:

● This is the first study to associate the analysis of several parameters (both habitual and innovative, considered both singly and in combination) with an exploratory data analysis (Data Mining), to formulate the best decision-making model for determining the optimal time for a return to sport after ACLR.

● This study has been designed to include evaluations at 6, 9 and 12 months post-ACLR in order to include and analyze data from the usual time when athletes return to pivot-sport training (6-9 months) and the time when they can return to competition (generally 9-12 months).

   • The study includes only young competitive athletes, which is the population with the highest risk of reinjury, but also with the highest chance to return to sport at the pre-injury level. These findings would not necessarily be applicable to the general population.

● This screening protocol seeks to assess elements involved in the return to sport after ACLR with knee-specific and task-specific objective measurements associated with subjective assessment of knee function and psychometric capabilities.

● The design and objectives of this study will require a significant number of patients, but since this population is highly motivated to return to sport, we are convinced that this choice will limit dropouts.
INTRODUCTION

Anterior cruciate ligament (ACL) tears represent a public health challenge with an incidence reported as 60-71 per 100,000 subjects. ACL tears often give rise to problems like post-traumatic osteoarthritis; that could lead to middle- and long-term problems for the patient, a potential increase in knee surgery in the future and consequently a significant cost to society. In this context, appropriate treatment of ACL tears and secondary and tertiary prevention among young pivot-shift athletes represent very relevant challenges and a major orientation for orthopedics and sports medicine research.

After an injury, and especially ACL tear, one of the most frequent questions asked by the patient is: “when can I get back to my sport?”. ACL Reconstruction (ACLR) is the current clinical standard for patients with an ACL tear and considered to be at a high risk of knee instability (young, high-level athletes in a pivoting and/or contact sport). After surgical reconstruction, a rehabilitation program is set up to allow patients to return to a painless and fully functional daily life. In patients aiming to return to sport, the rehabilitation program must continue until this is possible.

To consider an ACLR successful, the patient should be able to return to the same level of sporting activity as before the injury. Moreover, a recent patient satisfaction survey confirms that a patient who can resume his sporting activity is more likely to be satisfied with the outcome of the ACLR. However, in their updated review, Ardern and al. had shown that on average 80% of patients returned to sport, while only 55% returned to competitive levels after ACLR. Theses mitigated results highlight the fact that the return to sport (RTS) represents an important challenge after ACLR, and that current practices should be improved in this aim.
After ACLR, rehabilitation should be optimal to allow athletes’ RTS, and the decision of when RTS is an important one for patient satisfaction and challenging in the context of secondary and tertiary prevention. Indeed, more the time to RTS is delayed, more the patient motivation and his psychological readiness could be poorer, decreasing as well his chance to return to sport at the same level, but on the other hand an early return to sport exposes the patient to a high risk of reinjury. RTS, especially with pivoting or contact sports, exposes the athlete to a risk of reinjury: Wiggins et al., in a systematic review and meta-analysis, had found 15% of second ACL reinjury rate, with 7% for the ipsilateral ACL and 8% for the contralateral reinjury rate. Moreover, in the subgroup of younger patient who wanted to return to sport, the secondary ACL injury rate was 23%. A new injury after an ACLR could nonetheless be another musculoskeletal injury, as well it could affect the joint (rupture of the graft or contralateral ACL, chondral and/or meniscal lesion). Indeed, a history of an ACLR is a risk factor for developing a repeat hamstring strain, hindering RTS and the future practice of sport. Thus, the decision of when RTS is a challenging decision, in order to optimize the chance to return to sport at the pre-injury level, and in a health protection perspective to minimize the risk of reinjury.

Many factors have been implicated in reinjury risk, including sex, age, activity level, graft placement, graft type, time from surgery, and deficits in neuromuscular and biomechanical control of the lower limb. Considering those risk-factors, clinical studies used many techniques and criteria to determine the optimal moment for a return to sport after ACLR. The most used is the post-operative timeline, either alone or with: muscle strength, knee laxity, knee assessment form, or functional tests. However, to the best of our knowledge, there are no clearly validated criteria for determining a safe return
to sport after ACLR. This decision is currently based on multiple criteria mostly using the post-operative time frame needed for the biological integration of the graft. It seems, according to a recent publication that a delayed RTS from 6 months after surgery to 9 months after surgery decreased the risk of reinjury by 51% each month RTS is delayed. However time criteria alone was not sufficient to determining readiness for a safe RTS; Grindern et al. thus recommended to uses of both time-based and functional RTS criteria. Barber-Westin and Noyes, in a systematic review, described how this decision is associated with subjective parameters ("satisfactory clinical examination", "stable knee", "normal joint function", self-reported knee function (subjective IKDC (The International Knee Documentation Committee) and that only 10% of the included studies used objective criteria such as: muscular strength, knee laxity, the limb symmetry index (LSI) or functional tests (Hop Tests, Star Excursion Balance Tests). Kyritsis et al. had also evaluated a set of objective criteria (muscle strength and functional tests) with 158 male professional athletes. Those who did not meet criteria (quadriceps deficit < 10% at 60°/s, LSI for each Hop Tests > 90%, running T test <11s) had four times greater risk of graft reinjury, and hamstring to quadriceps ratio deficits were associated with an increased risk of ACL re-rupture. Among the objective criteria, testing isokinetic muscular strength is a clear measure of strength recovery and seems to be central in objective assessment of a readiness to return to sport. Moreover, contextual factors such as a positive attitude and fear of injury have not been assessed either in these studies or in the literature as predictors of reinjury although it is well known that these factors influence the capacity to return to sport, especially at the same level of participation.
In addition, evaluation of lower limb function, in close to sport tasks, could also give important information to allow RTS. Kyritsis et al. have recently associated classical functional tests and “running t test” to evaluate agility and performance, but analysis of running or sprinting pattern has not been performed. Mazet et al. have analysed running patterns in patients with ACLR, and reported that biomechanical stiffness, calculated using time of flight and contact time, was significantly greater on the operated limb than on the healthy limb or in healthy patients. Using a non-motorized treadmill fitted with force sensors, Brown and Brughelli evaluated the sprint of a rugby player after ACLR during the period of return to sport (between the return to training and competition). An asymmetry of the Ground Reaction Force (GRF) persisted (horizontal force: 13%, vertical force: 7%) while the isokinetic muscular strength testing appeared normal. They concluded that an evaluation of sprint mechanics complemented the usual functional assessments. This analysis, in line with sports reality, could detect an asymmetry during the return to sport phase (6-12 months). This sport-specific assessment seems very relevant to the decision to return to sport; indeed, a good gait with efficient biomechanical performance in the sagittal plan is an essential step for a return to pivoting/cutting sports.

In this context, the determination of an association of criteria to help in the decision-making process regarding RTS with the lowest risk of reinjury or associated lesions (muscles or ligaments of the lower limbs) is of major interest in the management of patients with ACLR who want to return to a competitive pivoting sport. Thus, the aim of the present study is therefore to determine which criteria or combination of criteria could allow to return to sport with the lowest possible risk of reinjury.
METHODS

The present study is a prospective cohort single-center study, with repeated measures at 6, 9 and 12 months post-operatively after an ACLR and follow-up of the return to sport and reinjury for 3 years after the ACLR. The research started in January 2015, and is due to be completed in December 2020. The study design is shown in Fig 1.

Please insert Fig 1.

Study patients

Potential patients will be drawn consecutively from along the patients of the Sports Medicine Unit or the Orthopedic Surgery and Traumatology department of the local University Hospital. Patients included in the study must meet the criteria for inclusion/exclusion shown in Table 1. All study patients will undergo post-surgical rehabilitation in the same Physiotherapy Clinic using the protocol recommended in the literature 8 9 51 (for more information about the protocol please see S1 Appendix. ACL Reconstruction Rehabilitation Protocol).
Table 1 Inclusion and exclusion criteria for patients

<table>
<thead>
<tr>
<th>Inclusion criteria</th>
<th>Exclusion criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>➢ Participation in pivot and/or contact sports and with intensive sporting activity before the ACL tear:</td>
<td>➢ Bilateral lower limb pathologies</td>
</tr>
<tr>
<td>- with a Marx scale score above 11 before the injury</td>
<td>➢ Recurrence of ACL rupture (with a MRI diagnostic)</td>
</tr>
<tr>
<td>- with a Tegner score above 6 before the injury (competition training with more than 3 training sessions per week before the injury)</td>
<td>➢ Contraindications for carrying out a test, i.e.:</td>
</tr>
<tr>
<td>➢ Unilateral tear</td>
<td>➢ Postoperative time less than 6 months</td>
</tr>
<tr>
<td></td>
<td>➢ Persistence of knee pain (score &gt;3 at Numeric Pain Rating Scales)</td>
</tr>
<tr>
<td></td>
<td>➢ Persistence of a joint effusion (positive patellar tap test)</td>
</tr>
<tr>
<td></td>
<td>➢ Incomplete range of motion (Range of motion &lt; 90% on contralateral side)</td>
</tr>
<tr>
<td></td>
<td>➢ Abnormal walk (observable gait deviations during the walk)</td>
</tr>
<tr>
<td></td>
<td>➢ Allografts</td>
</tr>
<tr>
<td></td>
<td>➢ Skeletal immaturity</td>
</tr>
<tr>
<td></td>
<td>➢ Older than 35 years</td>
</tr>
</tbody>
</table>

**Assessment procedure**

All tests will be performed in the same place and all patients will be tested at the same time of day between 2 pm and 6 pm. Forty-eight hours before each evaluation session, patients will receive an email reminding them of the test procedure and asking them to complete a subjective questionnaire online (IKDC, TSK11, ACL-RSI and SANE).

Informed consent will be obtained from all patients before testing begins and a standardized explanation of the assessment procedure given to the patients. Each test session will include, in the same order, a medical check-up, postural control analysis, knee laxity measurements, a modified Star Excursion Balance Test, biomechanical running and sprint analysis, Hop Tests and isokinetic tests, with a 5-minute rest between each test. Before the biomechanical analysis begins, patients will warm-up with 10 minutes of cycling to raise muscle temperature. A
specific warm up activity will be included before each new activity. The isokinetic evaluation is at the end of the battery to avoid tiredness affecting the results of the other tests.

**Evaluation of subjective parameters by questionnaires**

The first questionnaire is the IKDC, an algo-functional questionnaire commonly used for ACLR follow-up.\(^\text{52, 53}\) An IKDC within the 15th percentile of healthy patients is considered as criteria for a return to sport.\(^\text{42, 54, 55}\) The patient will then complete the Tampa Scale of Kinesiophobia-11 (TSK11). This questionnaire, containing 11 questions (choice between 5 answers), is used to estimate a patient’s fear of movement and reinjury giving a score from 11 to 55.\(^\text{56-58}\) A score below 20 indicates low pain avoidance and could also allow a return to sport.\(^\text{59}\) The last questionnaire the patient is asked to complete is the ACL-Return to Sport after reinjury (ACL-RSI). This 12-item scale measures three specific psychological constructs – emotions, confidence in performance, and risk appraisal – on a scale from 0 to 100. This scale is a predictive parameter for a successful return to sport after ACLR.\(^\text{55}\)

The patient will also be asked to estimate his knee recovery on a scale (from 0 to 100) with a single assessment numeric evaluation (SANE).\(^\text{53, 60}\)

**Medical check-up**

Firstly, we will check if the online questionnaires have been done, and the presence of inclusion criteria and absence of exclusion criteria. The assessor will fill out the demographic information in the observation book (sex, age, weight, height, sport, training frequency and
Marx’s score before the ACL tear), a timeline for a return to running, sport-specific training and competitive play where possible, and finally the ACLR surgeon and technique used. The clinical examination will follow the IKDC-2000 grid\textsuperscript{52}.

**Postural control analysis**

A WinPosturo\textsuperscript{®} (Medicapteurs, Balma, France) stabilometry platform will be used with the WinPosture\textsuperscript{®} software (Medicapteur, Balma, France) to determine variations in the center of pressure (CoP). The force plate, which measures $530 \times 460 \times 35$ mm has three pressure gauges (hysteresis $< 0.2\%$), with a sensitivity of 90 points per Newton. The sampling frequency will be fixed at 40 Hz with the platform recalibrated before each session. The assessment will be conducted in an isolated room, in a noise-free environment, with a hard, flat floor, following the recommendations of the American Academy of Neurology (AAN)\textsuperscript{61} and the study of Ruhe et al.\textsuperscript{62}. The standardized position of the feet will be: oriented $15^\circ$ laterally to the sagittal plane. The patient will have to breathe normally and stare at a point 1.5 m in front him, at eye level, the arms relaxed along the body. The patient will be in sportswear and socks.

Four measurements, knees in extension, separated by 30 seconds of recovery in a sitting position, will be performed:

- bipedal position, eyes open (60s)
- bipedal position, eyes closed (60s)
- Single-leg squat following by balancing on the healthy leg (30s), eyes open\textsuperscript{17}
- Single-leg squat following by balancing on the operated leg, eyes open (30s)\textsuperscript{17}
The values of total CoP path (CoP in mm), CoP velocity (in mm.s\(^{-1}\)), standard derivations of CoP (SDx and SDY), and CoP sway area (in mm\(^2\)) will be recorded. Kouvelioti et al. showed good or excellent reproducibility of all these variables using a similar assessment protocol (Intraclass Correlation Coefficient (ICC) range from 0.68 to 0.91)\(^{63}\).

Knee laxity measurements
The GNRB® system (Genourob, Laval, France) is a non-invasive arthrometer that provides comparative bilateral measurements of knee laxity. This system is reliable and reproducible (ICC range from 0.77 to 0.91)\(^{64,66}\). The patient will lie on a standard examination table in the supine position, with the knee at 20° flexion and 0° of rotation (Fig 2). The lower limb is immobilized in a thermoformed shell, adaptable for different leg lengths, at the patella and the foot with a force of about 65±5N controlled by a force sensor with a precision of 0.1 mm. The analysis will begin with the healthy leg, with a push to 134N and 3 pushes to 250N. The same procedure is then repeated on the operated limb. The displacement of the anterior tibial tubercle relative to the femur is measured. The drawer shift/pressure curve is determined by the displacement (with 0.1 mm precision) and the slope of the curve (Slp in degree) which defines ligamentous laxity. The push to 250 N with the largest displacement (\(D_{op}\) in mm) and Slp will be retained. The difference between the operated and healthy limb will be calculated for \(D_{op}\) and Slp.

Please insert Fig 2.
Modified Star Excursion Balance Test

The patient, shoeless, will be asked to stand on one leg, starting with the healthy limb, without lifting the heel and with hands on hips and perform the following exercise as described in the literature: \(^{67-69}\); to reach maximally to touch a point as far as possible in 3 directions, along i) an antero-posterior axis ii) the postero-lateral axis and finally iii) the postero-medial axis, returning to the initial position between each movement. Two attempts and 2 measurements will be made for each direction. The longest distance (in cm) will be noted for each direction. The reliability is high with ICC from 0.83 to 0.96 \(^{70}\).

Running and sprinting mechanics

Patients will choose either a cycle ergometer and/or jogging for a 10-15 general warm-up, followed by a specific sprint warm-up included sprint drills and short sprints. On a motorized instrumented treadmill (ADAL3D-WR; Medical Development, HEF Tecmachine, Andrezieux-Boutheon, France), with four piezoelectric force transducers (KI 9077b, Kistler, Winterthur, Switzerland), on a hard, flat surface in a quiet room, the patient will be then undergo the biomechanical evaluations first for running and then sprinting with a one minute rest between them (Fig 3). The reliability is high with ICC from 0.85 to 0.90 \(^{71}\).

For the running biomechanical evaluation, each patient will run for three minutes at 3.33 m.s\(^{-1}\) (12 km.h\(^{-1}\)) and, without the patient being informed of the exact moment of data recording, 20 sec of biomechanical parameters will be recorded. Mechanical data will be sampled at 1000 Hz. After appropriate filtering (Butterworth-type 30 Hz low-pass filter, 2\(^{nd}\) order),
instantaneous data of vertical force will be averaged for each support phase (vertical force above 30 N) over the 20-s ($F_{VR}$), and expressed in N and body weight (BW). For each step, contact ($t_c$) and aerial ($t_a$) times will be calculated. Spring–mass parameters, like vertical stiffness ($k_{vert}$ in kN m$^{-1}$) and leg stiffness ($k_{leg}$ in kN m$^{-1}$), will be calculated using the computation method proposed by Morin et al.[59] The lower limb leg length will be the distance behind the great trochanter to ground distance in a standing position. The stride length ($l_{stride}$ in m) will be calculated as: $l_{stride} = (t_c+t_a)\cdot v$.

For the sprint running biomechanical evaluation, each patient will first be familiarized with sprinting on a treadmill by three 6-sec sprints separated by 1 minute of rest. The patient is fitted with a leather weightlifting belt attached via a rigid tether (0.6 cm in diameter) to the wall (Figure 3), as described by Morin et al. The constant motor torque will be set to 160% of the default torque, i.e. the motor torque necessary to overcome the friction on the treadmill belt due to the participant’s body weight. The default torque will be measured by making the participants stand still and by increasing the driving torque until a movement of the treadmill belt greater than 2 cm is observed over 5 s. Motor torque of 160% of the default value will be selected after several preliminary measurements comparing various torques, as this will allow participants to sprint in a comfortable manner and produce maximal effort without risking a loss of balance. Once the patient is correctly attached, he will be required to lean forward in a typical crouched sprint-start position with their preferred foot forward. This starting position will be used and standardized throughout the sprint series. After a 3-s countdown, the treadmill will be released, and the treadmill belt will begin to accelerate as participants apply a positive horizontal force. With patients strongly encouraged to produce their maximum intensity, two sprints will be recorded separated by a 1-minute rest period. The data used for
analysis will be: instantaneous data of vertical, net horizontal and total GRF averaged for each support phase (vertical force above 30 N) over 6-s sprints ($F_{V_{sprint}}$, $F_{H_{sprint}}$, $F_{tot_{sprint}}$ respectively), and expressed in N and BW. For each step, the ratio of forces applied on the ground (RF) will be calculated as the ratio of $F_{H_{sprint}}$ to $F_{tot_{sprint}}$ for one contact as follows: 

$$RF = \frac{F_{H_{sprint}}}{F_{tot_{sprint}}} - 1$$

(expressed in %). Then, mean and maximal values of ratio forces for the 6-s sprint will be computed (RF-mean and RF-max, respectively). The index of force application technique ($D_{RF}$) representing the decrement in RF with increasing speed (S) will be computed as the slope of the linear RF-speed relationship calculated from the step-averaged values between the second step and the step at top speed. Therefore, the higher the DRF (i.e. a flat RF-speed relationship), the more RF will be maintained despite increasing velocity, and vice versa. Lastly, for each 6-s sprint, performance will be described through mean and maximal running speeds (S and S-max, respectively).

Please insert Fig 3.

Hop Tests:

The patient will be asked to perform the following exercises, as described by Noyes and al. (Fig 4.):

- **Single One-Leg Hop Test** on the healthy limb and then the operated limb, with the arms crossed, hands on shoulders. The patient will perform one hop, as far as possible, with a controlled, balanced landing (minimum 3 seconds). If the patient cannot maintain the landing position, makes extra hops, or does not keep his hands on his shoulders, then the Hop Test will be considered a failure.
- **Triple One-Leg Hop Test** on the healthy limb and then the operated limb with the arms in any position. The patient will perform 3 consecutive hops as far as possible. The last hop position must be maintained for a minimum of 3 seconds as with the **Single One-Leg Hop Test**.

- **Cross-over One-Leg Hop Test** on the healthy limb and then the operated limb with the arms in any position. The test is carried out on a 6.5 m strip of carpet with a central line 15 cm in width. The patient is asked to make three hops, the first laterally, crossing the line on each hop. Landing after the final hop must be as with the **Single One-Leg Hop Test**. The **Cross-over One-Leg Hop Test** allows assessment of the cutting movement capabilities of the patient. It imposes both predominant sagittal plane and rotation forces on the frontal plane of the knee. In addition, the test highlights any instability in the knee, but also tests muscle extensibility, muscle strength and power, proprioception, neuromuscular control, dynamic balance, and agility.  

Patients start from single limb stance. Every attempt will include at least 3 jumps and will continue until the patient progresses. The best distance for each leg and each Hop Test will be recorded for analysis (in cm). In case of failure, the patient will have the opportunity to do the Hop-Test again until it will be considered valid. The reliability is high with ICC from 0.84 to 0.92.  

Please insert Fig 4.

**Isokinetic assessment**
As the resulting tiredness could affect the other tests if done earlier in the battery, the isokinetic quadriceps and hamstring muscle strength assessment will be performed last. They will be done on a Con-Trex® Multi-Joint dynamometer (CMV AG, Dübendorf, Switzerland) and controlled by Con-Trex Software. The installation is described elsewhere in the literature.

The participants will be seated with the hip joint at about 85° and strapped in place at the chest, pelvis and mid-thigh to avoid postural compensation during the assessment. The contralateral limb will be fixed to a support at the ankle. The axis of the dynamometer will be perfectly aligned with the rotation axis (lateral femoral epicondyle) of the knee joint. Resistive support will be strapped to the leg, at 2-3 cm proximal to the ankle joint line. The range of knee motion will be set from 80° for a safe, comfortable, comparative assessment of quadriceps (extensor) and hamstrings (flexors) muscles. The gravity correction will be used. Assessment will begin with the healthy knee, and then the operated knee, and each series of repetitions will be followed by one minute of rest. The assessment is summarized in Table 2.

Table 2 Isokinetic assessment design

<table>
<thead>
<tr>
<th>Timepoint</th>
<th>Repetitions</th>
<th>Angular velocity and mode of contraction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First specific warm-up</strong></td>
<td>↓ 6 sub-maximal</td>
<td>120 °/s in concentric</td>
</tr>
<tr>
<td><strong>Second specific warm-up</strong></td>
<td>↓ 6 sub-maximal</td>
<td>120 °/s in concentric</td>
</tr>
<tr>
<td><strong>Habituation session</strong></td>
<td>↓ 3 sub-maximal</td>
<td>60 °/s in concentric</td>
</tr>
<tr>
<td><strong>Maximal test session with encouragement</strong></td>
<td>↓ 3 maximal</td>
<td>60 °/s in concentric</td>
</tr>
<tr>
<td><strong>Maximal test session with encouragement</strong></td>
<td>↓ 3 maximal</td>
<td>120 °/s in concentric</td>
</tr>
<tr>
<td><strong>Habituation session</strong></td>
<td>↓ 3 sub-maximal</td>
<td>30°/s in eccentric</td>
</tr>
<tr>
<td><strong>Maximal test session with encouragement</strong></td>
<td>↓ 3 maximal</td>
<td>30°/s in eccentric</td>
</tr>
</tbody>
</table>
The isokinetic assessment will be performed in this order, using gravity corrections, at a range of motion of 5°-85°, and measuring peak torque for each test session. A 1-minute rest will be allowed between each session.

Torque, position and angular velocity data will be recorded from the isokinetic dynamometer with a sampling rate of 100 Hz. After appropriate filtering, for concentric and eccentric strength trials, the software will calculate a large number of parameters, but we will retain only the absolute peak torque, the most reproducible parameter (ICC > 0.96)\(^78\).

The peak torque value normalized to the body weight (Nm/kg) will be recorded for each mode and speed of contraction for the Quadriceps (Q) and Hamstring (H). The Q/H ratio will be calculated for each mode and speed of contraction on the operated side, with a ratio ≥ 60% considered to be physiologically sufficient to obtain joint control. A mixed functional ratio, associating the eccentric performance of the flexor (at 30°/s) and the concentric performance of the extensor (at 240°/s) will also be calculated, as reported by Croisier and al.\(^79\).

**Follow-up after ACL surgical reconstruction**

Patient follow-up will continue until 36 months post-operatively. After the evaluation at 12-months post-surgery patient follow-up will continue for a further 2 years. The researchers will attempt to follow-up all patients by phone interview every 6 months to determine the date of return to running, to pivoting sport-specific training, and to pivoting sport competition, as well as the date and the nature of any reinjury that may occur. The reinjury is defined as: rupture of the transplant, or the contralateral ACL, or any injury requiring the sporting activity
to cease and necessitating a consultation and/or medical care. We will also collect the Tegner score at 3-years post-ACLR.

The decision for clearance to a return to sport will be made by a sport-physician, blinded to all the tests results except the isokinetics results. This decision will be taken after considering the time from surgery, clinical experience and the isokinetics results.

**Primary outcome**

The main criterion for assessment is the occurrence of reinjury during the 3-year follow-up. A reinjury is defined as a rupture of the transplant or the contralateral ACL, or any injury requiring the sporting activity to cease and necessitating a consultation and/or medical care.

**Method of accounting for missing, unused or invalid data**

A patient’s participation in the study will cease if significant complications appear when performing the tests and all data collected before that point will be analyzed.

**Power and sample size considerations**

Based on the rate of ACL reinjury (rupture of the transplant or the contralateral ACL\(^\text{18}\)) described in the literature for the subgroup of younger athletes who return to sport, and considering the unknown rate of other possible injuries (any injury requiring the sporting activity to cease and necessitating a consultation and/or medical care) after an ACLR, a global rate of reinjury after ACLR could be assumed at 20%. Considering a 10% dropout rate, and that 10 cases (reinjury) are needed to test one explanatory variable, it is necessary to include...
50 patients to test one explanatory variable for 95% power and a Type-I error rate (alpha) of 0.05. Depending on the results of the Data Mining procedures (Principal components analysis and Hierarchical Clustering on Principal Components) on the variables presented in table 3, we will choose a maximum of 5 variables to construct the model. We will therefore need to include 275 patients.

**Statistical analyses**

Exploratory data analysis will be performed, following five steps adapted from Data Mining processes: 1) Identification of study objectives, 2) Data acquisition, 3) Data evaluation and preparation, 4) Data analysis and modeling, 5) Results, interpretation and validation. In step 3, we will analyze the data quality checking that there are no inconsistencies, errors, duplicates or "aberrant" data. We will also verify the overall consistency of the data.

In step 4, classification and selection of variables reported in Table 3 will define the explanatory variables required to build the models (with Principal components analysis then Hierarchical Clustering on Principal Components). We will choose the best data analysis taking into account the characteristic of the model variables.

Lastly, in step 5, the model (s) will be analyzed and compared in order to define as precisely as possible the explanatory variables and the most suitable model. The p-value will be adjusted if necessary and other methods could be used (Akaike information criterion (AIC) or Bayesian information criterion (BIC)). The parameters of the model will then be analyzed in order to define their clinical relevance.
The use of this exploratory data analysis will be based on by some of the work in medical research to use Data Mining. However, this method does not exclude the classical statistical analyses for the creation of a model. Lasting, depending on our variables, we will use the appropriate statistical tests. After performing a correlation matrix and calculating colinearity using linear regression, we will calculate several Generalized Linear Models if possible: Linear Regression, Generalized Estimating Equations, Generalized Linear Mixed Model, depending on the characteristics of our variables.

Statistical analyses will be performed using R (http://www.R-project.org).

Table 3. Explanatory variables

<table>
<thead>
<tr>
<th>Categories of criteria</th>
<th>Explanatory variables</th>
<th>unit or range</th>
<th>Calculated data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Marx pre injury</td>
<td>0-16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tegner pre injury</td>
<td>0-10</td>
<td></td>
</tr>
<tr>
<td>self-reported measures</td>
<td>IKDC</td>
<td>0-100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TSK-11</td>
<td>11-55</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SANE</td>
<td>0-100</td>
<td></td>
</tr>
<tr>
<td>Postural control</td>
<td>Center of pressure (CoP)</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>analysis</td>
<td>Center of pressure (CoV)</td>
<td>mm.s-1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Center of pressure (CoP)</td>
<td>mm²</td>
<td></td>
</tr>
<tr>
<td>Knee laxity</td>
<td>GnRB slope</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>measurements</td>
<td>GnRB anteroposterior displacement</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>SEBT</td>
<td>Anterior distance</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Postero-lateral distance</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Postero-lateral distance</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>composite SEBT score</td>
<td>%</td>
<td>X</td>
</tr>
<tr>
<td>Running and Sprinting</td>
<td>LSI Leg stiffness</td>
<td>%</td>
<td>X</td>
</tr>
<tr>
<td>mechanics</td>
<td>LSI stride length</td>
<td>%</td>
<td>X</td>
</tr>
<tr>
<td>LSI Sprint vertical force</td>
<td>%</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>--------------------------</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>LSI Sprint horizontal force</td>
<td>%</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>LSI Sprint total Force</td>
<td>%</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>LSI Sprint ratio of forces</td>
<td>%</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>LSI Sprint DRF</td>
<td>%</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

### Hop Tests

| | LSI Single One-Leg Hop Test | % | X |
|--------------------------|---|---|
| LSI Triple One-Leg Hop Test | % | X |
| LSI Cross-over One-Leg Hop Test | % | X |

### Isokinetic assessment

<table>
<thead>
<tr>
<th>Quadriceps peak tork at 60°/s BW</th>
<th>N/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadriceps peak tork at 240°/s BW</td>
<td>N/kg</td>
</tr>
<tr>
<td>Quadriceps peak tork at 30°/s BW</td>
<td>N/kg</td>
</tr>
<tr>
<td>Hamstring peak tork at 60°/s BW</td>
<td>N/kg</td>
</tr>
<tr>
<td>Hamstring peak tork at 240°/s BW</td>
<td>N/kg</td>
</tr>
<tr>
<td>Hamstring peak tork at 30°/s BW</td>
<td>N/kg</td>
</tr>
<tr>
<td>Mixed Functional Ratio</td>
<td>%</td>
</tr>
</tbody>
</table>

### Follow-up

<table>
<thead>
<tr>
<th></th>
<th>Marx 3 years postop</th>
<th>0-16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tegner 3 years postop</td>
<td>0-10</td>
<td></td>
</tr>
<tr>
<td>SANE 3 years postop</td>
<td>0-100</td>
<td></td>
</tr>
</tbody>
</table>

LSI = operated leg/ healthy leg, Mixed Functional Ratio = IJ30 / Q 240

## ETHICS AND DISSEMINATION

The present study has been approved by the local Ethical Committee (IRBN522015/CHUSTE) and will be recorded on ClinicalTrials.gov. Prior to enrolment in the study, all patients will be asked to give their informed consent. The patient can decide at any time to be released from the study and they will be informed of this in the information leaflet. His/her data will then be deleted from the data collection file. Leaving the study will have no incidence on the normal monitoring protocol of patients post-surgery. The results of this study
will be disseminated via presentation at local, national and international conferences and peer-reviewed journals.

CONCLUSION

After ACLR, long-term problems like reinjuries or osteoarthritis highlight the importance of secondary and tertiary prevention. The management of return to sport is a public health challenge because these decisions are made during a period with a high risk of reinjury. Many criteria to allow a return to sport are proposed in clinical studies and used in clinical practice but no evidence-based criteria exist. In this study, we have chosen to use many criteria described in the literature, to use a new exploratory data analysis allowing creation of new explanatory variables explaining the return to sport without injury, and to continue monitoring all these variables during the return to sport phase. Repeating these assessments will enable us to observe the recovery kinetics of many of these criteria, linking them to the biomechanical assessments.

However, the main limitation of this study is the utilization of one of these criteria (isokinetics) to clear the patient to return to sport participation. This selection bias will be taken into account when the rate of reinjury has been evaluated, and will be considered when interpreting our results.

This study is the first clinical study aiming to analyze the criteria used for a return to sport, and adds biomechanical evaluation using force sensors when running. This analysis, mimicking sporting reality\textsuperscript{50} will detect any asymmetry during the return to sport phase (6 - 12 months), a point that standard evaluation procedures do not address. This evaluation is highly specific for the analysis of patients in the return to sport phase and consequently,
useful to the decision of when this phase can safely start. These assessments will provide a
great deal of specific data.

Moreover, data mining will be used to build a predictive model if possible. Data mining will
allow us to find models and patterns from the available data. It includes descriptive data
mining algorithms for finding interesting patterns in the data, like associations, clusters and
subgroups.

The aim of our model, if possible, is Predictive modeling to build a predictive model for a
target variable, based on explanatory variables. But data Mining also includes Attribute
selection and most machine learning algorithms allow us to learn which are the most
appropriate attributes (predictor variables) to use for making decisions. Most methods for
Attribute selection involve the space of attributes for the subset which is most likely to predict
the best class.

The use of this exploratory data analysis will be inspired by some of the work done by
Combes & Azema. and Esfandiari et al. On the other hand, this method does not
exclude the classical statistical analyses for the creation of a model.

These new criteria will allow an individualization of the return to sport decision accordingly
to a global patient condition assessment. This optimization could limit the risk of reinjury, and
so minimized associated long-term knee-problems.
Acknowledgements

The authors are grateful to the study participants, hospital staff and study staff, and especially Léa Feuillassier, Alex Pavoine, Antoine Dany and Stephane Moret.

Contributors

AJMR, BS and PE designed the CRSTAL study and contributed to development of the study protocol. AJMR and BS drafted the manuscript. BS submitted to ethic committee. AJMR, BS, RT, PS, JBM, RP and PE assisted in drafting the manuscript. All authors read and approved the final manuscript.

Conflict of interest

None declared.

Ethics approval

Ethical approval was obtained through the University Hospital of Saint-Etienne Ethics Committee (Reference number IRBN522015/CHUSTE).

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.
References


Figure 1. The study design:

Figure 2. Knee laxity measurement position and the GNRB® system.

Figure 3. A runner fitted with a leather weightlifting belt (D) attached with a rigid tether (C) to the wall mounting bracket (A and B) sprinting on a motorized treadmill.

Figure 4. Hop Tests: A: Single One-Leg Hop Test, B: Triple One-Leg Hop Test, and C: Cross-over One-Leg Hop Test.
Fig 1. The study design

71x40mm (300 x 300 DPI)
Fig 2. Knee laxity measurement position and the GNRB® system.

395x559mm (300 x 300 DPI)
A runner fitted with a leather weightlifting belt (D) attached with a rigid tether (C) to the wall mounting bracket (A and B) sprinting on a motorized treadmill.

51x26mm (300 x 300 DPI)
Fig 4. Hop Tests: A: Single One-Leg Hop Test, B: Triple One-Leg Hop Test, and C: Cross-over One-Leg Hop Test

68x61mm (300 x 300 DPI)
Postoperative rehabilitation [1-3]

Phase 1

Acute Management/Early Motion and Basic Movement Retraining

Goals
1. Achieve full active knee extension equal to the uninvolved side with active Vaste Medialis recruitment.
2. Eliminate swelling.
3. Restore the ability to control the leg while weight bearing.
4. Achieve at least 90° of knee flexion.
5. Be able to straight leg raise.
6. Normalize walking patterns with the assistance of crutches and/or a brace.

If hamstring graft, no active hamstring exercises until 2 weeks and no open chain resisted hamstring curls until 4 weeks post-op.

Type of exercises:
—Range of Motion (ROM) Exercises (Heel-slides to improve knee flexion.)
—Soft tissue treatments to patella, patella tendon, incisions, and posterior musculature to improve range of motion and decrease fibrosis.
—Muscle Activation with quad sets, straight leg raises and double leg mini squats (ROM 0–60°). Use manual facilitation techniques or electrostimulation when voluntary contraction of the quadriceps is not possible.
—Core Body Training and Neuromuscular Training. Encourage a correct quality of performance (e.g. trunk lateroflexion, hip- and knee flexion, dynamic knee valgus and
knee-over-toe) during strength training and walking. Use implicit learning techniques instead of explicit learning techniques.

—Ambulation like diagonal weight shifting, backward stepping and step-overs

Criteria to start phase 2:

—Closed wound
—No knee pain with phase 1 exercises (VAS)
—Minimal synovitis or effusion
—Normal mobility (left=right) of the patellofemoral joint
—Knee extension of at least 0° and a 120–130° flexion
—Voluntary control of the quadriceps
—Active dynamic gait pattern without crutches
—Correct qualitative performance of phase 1 exercises.

Phase 2

Basic Strength and Proprioception

Goals

1. Restore proper body alignment and control with basic movements, such as walking without assistance, squats, stationary lunges and single-leg balance.
2. Build lower extremities and core body strength
3. Develop increased proprioception, starting with stationary postures and then progressing to movements.
4. Achieve active range of motion equal to the uninvolved Knee.

Type of exercises:

—Range of Motion (ROM) and stationary bike
—Soft tissue treatments
—Gait Drills
—Functional Strengthening (add weight or resistance with exercises), Single-leg/unilateral workouts (i.e. on weight machines, squats, side and forward step-downs).
—increase depth of balance exercises
—Neuromuscular training: Increase difficulty of neuromuscular and perturbation training
—Core Body and increase intensity with aerobic machines.

Carefully monitor exercises for signs of diminished eccentric control, weakness, or poor ability to stabilize against varus/valgus moment with loading exercises.

Criteria to start phase 3:
—Correct qualitative performance of phase 2 exercises
—Limb Symmetry Index (LSI) >80% for quadriceps and hamstring strength
—LSI >80% for a hop test battery, preferably using the hop test battery of Gustavsson

Phase 3

Dynamic Neuromotor Strength, Endurance and Coordination

Goals
1. Increase the strength of the involved leg.
2. Develop eccentric neuromuscular control to allow acceptance of impact activities without increasing symptoms.
3. Develop dynamic flexibility to allow for proper alignment during activities of increasing speed.
4. Full range of motion is expected.

Type of exercises:
—Range of Motion
Dynamic Agility Drills: begin with small strides at low velocity, gradually increasing the velocity.

Functional Strengthening. The recommended strengthening exercises are closed chain: squat, lunge.

Landing and Takeoff Drills: before initiating impact activities the patient should not have any swelling, have full knee extension, be able to balance on one leg for 10 seconds and be able to perform a single leg squat to approximately 45–60° of knee flexion with good posture and control.

Balance exercises with challenge postural control and duration: balance board activities, swim strokes, single leg balance with eyes closed

- Core Body and cardiovascular conditioning

**Phase 4**

**Athletic Enhancement and Return to Activity**

This phase can be initiated when the goals of Phase 3 are met. This phase will usually begin 12–16 weeks after surgery.

**Goals**

1. Progress from double leg impact control to single leg impact control.
2. Develop proper technique and appropriate neuromuscular control with start and stop movements and change of direction movements.
3. Eliminate apprehension that may exist with complex movements related to sports.

**Type of exercises:**

- Dynamic Warm Up: will help with increasing core body temperature, mental alertness, elasticity of the muscular system and activation of the neuromuscular system.
- Multi-planar Landing Control and Neuromuscular Reaction: Jump rotations, fast feet and lunge, multi-planar leap and land, stop and go, hopping.
—Functional movements and strengthening: one-legged squat, single leg dead lift, lateral lunge walk, power step up.

—Advanced Core Training and begin for jogging.

Reference


Criteria for Return to Sport after Anterior Cruciate Ligament reconstruction with lower reinjury risk (CR’STAL study): protocol for a prospective observational study in France

<table>
<thead>
<tr>
<th>Journal:</th>
<th>BMJ Open</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuscript ID</td>
<td>bmjopen-2016-015087.R3</td>
</tr>
<tr>
<td>Article Type:</td>
<td>Protocol</td>
</tr>
<tr>
<td>Date Submitted by the Author:</td>
<td>12-Apr-2017</td>
</tr>
<tr>
<td>Complete List of Authors:</td>
<td>Rambaud, Alexandre; Universite Jean Monnet Saint-Etienne, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424); Centre de kinésithérapie du Pôle Sportif, SEMAY, Bertrand ; Universite Jean Monnet Saint-Etienne Faculte de Medecine Jacques Lisfranc, Department of Orthopaedic and Trauma Surgery ; Universite Jean Monnet Saint-Etienne, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424) Samozino, Pierre; Universite Savoie Mont-Blanc, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424) Morin, Jean-Benoît; Universite Cote d'Azur, LAMHESSTesta, Rodolphe; Universite Jean Monnet Saint-Etienne, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424) Philippot, Rémi; Centre Hospitalier Universitaire de Saint-Etienne, Department of Orthopaedic and Trauma Surgery; Universite Jean Monnet Saint-Etienne, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424) Rossi, Jérémy; Universite Jean Monnet Saint-Etienne, Inter-university Laboratory of Human Movement Biology (LIBM EA 7424) Edouard, Pascal; Centre Hospitalier Universitaire de Saint-Etienne, Department of Clinical and Exercise Physiology, Sports Medicine Unit; Universite Jean Monnet Saint-Etienne, Laboratory of Human Motricity, Education Sport and Health (EA 6312)</td>
</tr>
<tr>
<td>Primary Subject Heading:</td>
<td>Sports and exercise medicine</td>
</tr>
<tr>
<td>Secondary Subject Heading:</td>
<td>Rehabilitation medicine</td>
</tr>
<tr>
<td>Keywords:</td>
<td>Anterior Cruciate Ligament Reconstruction, injury prevention, Risk factors, Biomechanics, Return to Sport</td>
</tr>
</tbody>
</table>
Criteria for Return to Sport after Anterior Cruciate Ligament reconstruction with lower reinjury risk (CR'STAL study): protocol for a prospective observational study in France

Alexandre JM RAMBAUD¹ ², Bertrand SEMAY¹ ³*, Pierre SAMOZINO⁴, Jean-Benoît MORIN⁵, Rodolphe TESTA¹, Rémi PHILIPPOT¹ ³, Jérémy ROSSI¹, Pascal EDOUARD¹ ⁶

¹ Inter-university Laboratory of Human Movement Biology (LIBM EA 7424), University of Lyon, University Jean Monnet, Saint Etienne, France
² Physiotherapy Clinic of the Sport Center, La Talaudière, France
³ Department of Orthopaedic and Trauma Surgery, University Hospital Center of Saint-Etienne, Hôpital Nord, Saint-Etienne, France
⁴ Inter-university Laboratory of Human Movement Biology (LIBM EA 7424), University Savoie Mont Blanc, Le Bourget-du-Lac, France
⁵ Université Côte d’Azur, LAMHESS,, Nice, France
⁶ Department of Clinical and Exercise Physiology, Sports Medicine Unit, University Hospital of Saint-Etienne, Faculty of Medicine, Saint-Etienne. France

Corresponding Author:
Alexandre JM RAMBAUD, LIBM, University of Lyon, Campus Santé Innovations IRMIS, 10 rue de la Marandière, 42270 Saint-Priest en Jarez, France.
Email: alexandre.rambaud.kine@gmail.com +33 (0)4 77 30 76 55
*These authors contributed equally to this work.

Keywords:
Anterior Cruciate Ligament Reconstruction, Return to Sport, Biomechanics, risk factors; injury prevention
ABSTRACT

Introduction:

The decision regarding when to return to sport after an Anterior Cruciate Ligament Reconstruction (ACLR) is an important one. Using a variety of subjective and objective parameters, various attempts have been made to determine an optimal timeline for a return to sport after ACLR, but none have been validated.

The aim of the present study is therefore to determine which criteria or combination of criteria could allow to return to sport with the lowest possible risk of reinjury.

Methods and analysis

This study is a prospective cohort, single-center study, with repeated assessments at 6, 9 and 12 months post-ACLR surgical reconstruction and including a 3-year follow-up of patients’ sporting activity and reinjuries. 275 patients will be included to test explanatory variables.

Postural control analysis, knee laxity, questionnaires (IKDC, TSK11, ACLR-RSI, SANE), modified Star Excursion Balance Tests, running and sprinting biomechanics, Hop Tests and isokinetic tests will all be used. The primary outcome will be any reinjury during the follow-up period, defined as a graft rupture, a contralateral ACL rupture, or any injury necessitating an interruption of training and requiring a medical consultation. Two groups will be constituted during the follow-up, separating reinjured from non-reinjured patients. In addition, classic analysis and Data Mining approaches will be used to build predictive models.
Ethics and dissemination

The results of this study will be disseminated through peer-reviewed publications and scientific presentations. Ethical approval was obtained through the University Hospital of Saint-Etienne Ethics Committee (Reference number IRBN522015/CHUSTE).
STRENGTHS AND LIMITATIONS OF THIS STUDY:

- This is the first study to associate the analysis of several parameters (both habitual and innovative, considered both singly and in combination) with an exploratory data analysis (Data Mining), to formulate the best decision-making model for determining the optimal time for a return to sport after ACLR.

- This study has been designed to include evaluations at 6, 9 and 12 months post-ACLR in order to include and analyze data from the usual time when athletes return to pivot-sport training (6-9 months) and the time when they can return to competition (generally 9-12 months).

  - The study includes only young competitive athletes, which is the population with the highest risk of reinjury, but also with the highest chance to return to sport at the pre-injury level. These findings would not necessarily be applicable to the general population.

- This screening protocol seeks to assess elements involved in the return to sport after ACLR with knee-specific and task-specific objective measurements associated with subjective assessment of knee function and psychometric capabilities.

- The design and objectives of this study will require a significant number of patients, but since this population is highly motivated to return to sport, we are convinced that this choice will limit dropouts.
INTRODUCTION

Anterior cruciate ligament (ACL) tears represent a public health challenge with an incidence reported as 60-71 per 100,000 subjects. ACL tears often give rise to problems like post-traumatic osteoarthritis; that could lead to middle- and long-term problems for the patient, a potential increase in knee surgery in the future and consequently a significant cost to society.

In this context, appropriate treatment of ACL tears and secondary and tertiary prevention among young pivot-shift athletes represent very relevant challenges and a major orientation for orthopedics and sports medicine research.

After an injury, and especially ACL tear, one of the most frequent question asked by the patient is: “when can I get back to my sport?”. ACL Reconstruction (ACLR) is the current clinical standard for patients with an ACL tear and considered to be at a high risk of knee instability (young, high-level athletes in a pivoting and/or contact sport). After surgical reconstruction, a rehabilitation program is set up to allow patients to return to a painless and fully functional daily life.

In patients aiming to return to sport, the rehabilitation program must continue until this is possible.

To consider an ACLR successful, the patient should be able to return to the same level of sporting activity as before the injury. Moreover a recent patient satisfaction survey confirms that a patient who can resume his sporting activity is more likely to be satisfied with the outcome of the ACLR. However, in their updated review, Ardern and al. had shown that on average 80% of patients returned to sport, while only 55% returned to competitive levels after ACLR. Theses mitigated results highlight the fact that the return to sport (RTS) represents an important challenge after ACLR, and that current practices should be improved in this aim.
After ACLR, rehabilitation should be optimal to allow athletes’ RTS, and the decision of when RTS is an important one for patient satisfaction and challenging in the context of secondary and tertiary prevention. Indeed, more the time to RTS is delayed, more the patient motivation and his psychological readiness could be poorer, decreasing as well his chance to return to sport at the same level, but on the other hand an early return to sport exposes the patient to a high risk of reinjury. RTS, especially with pivoting or contact sports, exposes the athlete to a risk of reinjury: Wiggins et al., in a systematic review and meta-analysis, had found 15% of second ACL reinjury rate, with 7% for the ipsilateral ACL and 8% for the contralateral reinjury rate. Moreover, in the subgroup of younger patient who wanted to return to sport, the secondary ACL injury rate was 23%. A new injury after an ACLR could nonetheless be another musculoskeletal injury, as well it could affect the joint (rupture of the graft or contralateral ACL, chondral and/or meniscal lesion). Indeed, a history of an ACLR is a risk factor for developing a repeat hamstring strain, hindering RTS and the future practice of sport. Thus, the decision of when RTS is a challenging decision, in order to optimize the chance to return to sport at the pre-injury level, and in a health protection perspective to minimize the risk of reinjury.

Many factors have been implicated in reinjury risk, including sex, age, activity level, graft placement, graft type, time from surgery, and deficits in neuromuscular and biomechanical control of the lower limb. Considering those risk-factors, clinical studies used many techniques and criteria to determine the optimal moment for a return to sport after ACLR. The most used is the post-operative timeline, either alone or with: muscle strength, knee laxity, knee assessment form, or functional tests. However, to the best of our knowledge, there are no clearly validated criteria for determining a safe return
to sport after ACLR. This decision is currently based on multiple criteria mostly using the post-operative time frame needed for the biological integration of the graft. It seems, according to a recent publication that a delayed RTS from 6 months after surgery to 9 months after surgery decreased the risk of reinjury by 51% each month RTS is delayed. However time criteria alone was not sufficient to determining readiness for a safe RTS; Grindern et al. thus recommended to uses of both time-based and functional RTS criteria. Barber-Westin and Noyes, in a systematic review, described how this decision is associated with subjective parameters ("satisfactory clinical examination", "stable knee", "normal joint function", self-reported knee function (subjective IKDC (The International Knee Documentation Committee) and that only 10% of the included studies used objective criteria such as: muscular strength, knee laxity, the limb symmetry index (LSI) or functional tests (Hop Tests, Star Excursion Balance Tests). Kyritsis et al. had also evaluated a set of objective criteria (muscle strength and functional tests) with 158 male professional athletes. Those who did not meet criteria (quadriceps deficit < 10% at 60°/s, LSI for each Hop Tests > 90%, running T test <11s) had four times greater risk of graft reinjury, and hamstring to quadriceps ratio deficits were associated with an increased risk of ACL re-rupture. Among the objective criteria, testing isokinetic muscular strength is a clear measure of strength recovery and seems to be central in objective assessment of a readiness to return to sport. Moreover, contextual factors such as a positive attitude and fear of injury have not been assessed either in these studies or in the literature as predictors of reinjury although it is well known that these factors influence the capacity to return to sport, especially at the same level of participation.
In addition, evaluation of lower limb function, in close to sport tasks, could also give important information to allow RTS. 47 Kyritsis et al. 39 have recently associated classical functional tests and “running t test” to evaluate agility and performance, but analysis of running or sprinting pattern has not been performed. Mazet et al. 48 have analysed running patterns in patients with ACLR, and reported that biomechanical stiffness, calculated using time of flight and contact time, was significantly greater on the operated limb than on the healthy limb or in healthy patients. Using a non-motorized treadmill fitted with force sensors, Brown and Brughelli 49 evaluated the sprint of a rugby player after ACLR during the period of return to sport (between the return to training and competition). An asymmetry of the Ground Reaction Force (GRF) persisted (horizontal force: 13%, vertical force: 7%) while the isokinetic muscular strength testing appeared normal. They concluded that an evaluation of sprint mechanics complemented the usual functional assessments. This analysis, in line with sports reality, 50 could detect an asymmetry during the return to sport phase (6-12 months). This sport-specific assessment seems very relevant to the decision to return to sport; indeed, a good gait with efficient biomechanical performance in the sagittal plan is an essential step for a return to pivoting/cutting sports.

In this context, the determination of an association of criteria to help in the decision-making process regarding RTS with the lowest risk of reinjury or associated lesions (muscles or ligaments of the lower limbs) is of major interest in the management of patients with ACLR who want to return to a competitive pivoting sport. Thus, the aim of the present study is therefore to determine which criteria or combination of criteria could allow to return to sport with the lowest possible risk of reinjury.
METHODS

The present study is a prospective cohort single-center study, with repeated measures at 6, 9 and 12 months post-operatively after an ACLR and follow-up of the return to sport and reinjury for 3 years after the ACLR. The research started in January 2015, and is due to be completed in December 2020. The study design is shown in Fig 1.

Please insert Fig 1.

Study patients

Potential patients will be drawn consecutively from among the patients of the Sports Medicine Unit or the Orthopedic Surgery and Traumatology department of the local University Hospital. Patients included in the study must meet the criteria for inclusion/exclusion shown in Table 1. All study patients will undergo post-surgical rehabilitation in the same Physiotherapy Clinic using the protocol recommended in the literature 8 9 51 (for more information about the protocol please see S1 Appendix. ACL Reconstruction Rehabilitation Protocol).
Table 1 Inclusion and exclusion criteria for patients

<table>
<thead>
<tr>
<th>Inclusion criteria</th>
<th>Exclusion criteria</th>
</tr>
</thead>
</table>
| ➢ Participation in pivot and/or contact sports and with intensive sporting activity before the ACL tear:  
  - with a Marx scale score above 11 before the injury  
  - with a Tegner score above 6 before the injury  
  (competition training with more than 3 training sessions per week before the injury)  
| ➢ Unilateral tear | ➢ Bilateral lower limb pathologies |
| | ➢ Recurrence of ACL rupture (with a MRI diagnostic) |
| | ➢ Contraindications for carrying out a test, i.e.:  
  ➢ Postoperative time less than 6 months  
  ➢ Persistence of knee pain (score >3 at Numeric Pain Rating Scales)  
  ➢ Persistence of a joint effusion (positive patellar tap test)  
  ➢ Incomplete range of motion (Range of motion < 90% on contralateral side)  
  ➢ Abnormal walk (observable gait deviations during the walk)  
  ➢ Allografts  
  ➢ Skeletal immaturity  
  ➢ Older than 35 years |

Assessment procedure

All tests will be performed in the same place and all patients will be tested at the same time of day between 2 pm and 6 pm. Forty-eight hours before each evaluation session, patients will receive an email reminding them of the test procedure and asking them to complete a subjective questionnaire online (IKDC, TSK11, ACL-RSI and SANE).

Informed consent will be obtained from all patients before testing begins and a standardized explanation of the assessment procedure given to the patients. Each test session will include, in the same order, a medical check-up, postural control analysis, knee laxity measurements, a modified Star Excursion Balance Test, biomechanical running and sprint analysis, Hop Tests and isokinetic tests, with a 5-minute rest between each test. Before the biomechanical analysis begins, patients will warm-up with 10 minutes of cycling to raise muscle temperature. A
specific warm up activity will be included before each new activity. The isokinetic evaluation is at the end of the battery to avoid tiredness affecting the results of the other tests.

**Evaluation of subjective parameters by questionnaires**

The first questionnaire is the IKDC, an algo-functional questionnaire commonly used for ACLR follow-up. An IKDC within the 15th percentile of healthy patients is considered as criteria for a return to sport. The patient will then complete the Tampa Scale of Kinesiophobia-11 (TSK11). This questionnaire, containing 11 questions (choice between 5 answers), is used to estimate a patient’s fear of movement and reinjury giving a score from 11 to 55. A score below 20 indicates low pain avoidance and could also allow a return to sport. The last questionnaire the patient is asked to complete is the ACL-Return to Sport after reinjury (ACL-RSI). This 12-item scale measures three specific psychological constructs – emotions, confidence in performance, and risk appraisal – on a scale from 0 to 100. This scale is a predictive parameter for a successful return to sport after ACLR.

The patient will also be asked to estimate his knee recovery on a scale (from 0 to 100) with a single assessment numeric evaluation (SANE).

**Medical check-up**

Firstly, we will check if the online questionnaires have been done, and the presence of inclusion criteria and absence of exclusion criteria. The assessor will fill out the demographic information in the observation book (sex, age, weight, height, sport, training frequency and
Marx's score before the ACL tear), a timeline for a return to running, sport-specific training and competitive play where possible, and finally the ACLR surgeon and technique used. The clinical examination will follow the IKDC-2000 grid\textsuperscript{52}.

Postural control analysis

A WinPosturo\textsuperscript{®} (Medicapteurs, Balma, France) stabilometry platform will be used with the WinPosture\textsuperscript{®} software (Medicapteur, Balma, France) to determine variations in the center of pressure (CoP). The force plate, which measures $530 \times 460 \times 35$ mm has three pressure gauges (hysteresis < 0.2\%), with a sensitivity of 90 points per Newton. The sampling frequency will be fixed at 40 Hz with the platform recalibrated before each session. The assessment will be conducted in an isolated room, in a noise-free environment, with a hard, flat floor, following the recommendations of the American Academy of Neurology (AAN)\textsuperscript{61} and the study of Ruhe et al.\textsuperscript{62}. The standardized position of the feet will be: oriented 15\textdegree{} laterally to the sagittal plane. The patient will have to breathe normally and stare at a point 1.5 m in front him, at eye level, the arms relaxed along the body. The patient will be in sportswear and socks.

Four measurements, knees in extension, separated by 30 seconds of recovery in a sitting position, will be performed:

- bipedal position, eyes open (60s)
- bipedal position, eyes closed (60s)
- Single-leg squat following by balancing on the healthy leg (30s), eyes open\textsuperscript{17}
- Single-leg squat following by balancing on the operated leg, eyes open (30s)\textsuperscript{17}
The values of total CoP path (CoP in mm), CoP velocity (in mm.s\(^{-1}\)), standard derivations of CoP (SDx and SDY), and CoP sway area (in mm\(^2\)) will be recorded. Kouvelioti et al. showed good or excellent reproducibility of all these variables using a similar assessment protocol (Intraclass Correlation Coefficient (ICC) range from 0.68 to 0.91).

**Knee laxity measurements**

The GNRB® system (Genourob, Laval, France) is a non-invasive arthrometer that provides comparative bilateral measurements of knee laxity. This system is reliable and reproducible (ICC range from 0.77 to 0.91\(^{64,66}\)). The patient will lie on a standard examination table in the supine position, with the knee at 20° flexion and 0° of rotation (Fig 2). The lower limb is immobilized in a thermoformed shell, adaptable for different leg lengths, at the patella and the foot with a force of about 65±5N controlled by a force sensor with a precision of 0.1 mm. The analysis will begin with the healthy leg, with a push to 134N and 3 pushes to 250N. The same procedure is then repeated on the operated limb. The displacement of the anterior tibial tubercle relative to the femur is measured. The drawer shift/pressure curve is determined by the displacement (with 0.1 mm precision) and the slope of the curve (Slp in degree) which defines ligamentous laxity. The push to 250 N with the largest displacement (\(D_{ap}\) in mm) and \(Slp\) will be retained. The difference between the operated and healthy limb will be calculated for \(D_{ap}\) and \(Slp\).

Please insert Fig 2.
Modified Star Excursion Balance Test

The patient, shoeless, will be asked to stand on one leg, starting with the healthy limb, without lifting the heel and with hands on hips and perform the following exercise as described in the literature: 67-69; to reach maximally to touch a point as far as possible in 3 directions, along i) an antero-posterior axis ii) the postero-lateral axis and finally iii) the postero-medial axis, returning to the initial position between each movement. Two attempts and 2 measurements will be made for each direction. The longest distance (in cm) will be noted for each direction. The reliability is high with ICC from 0.83 to 0.96 70.

Running and sprinting mechanics

Patients will choose either a cycle ergometer and/or jogging for a 10-15 general warm-up, followed by a specific sprint warm-up included sprint drills and short sprints. On a motorized instrumented treadmill (ADAL3D-WR; Medical Development, HEF Tecmachine, Andrezieux-Boutheon, France), with four piezoelectric force transducers (KI 9077b, Kistler, Winterthur, Switzerland), on a hard, flat surface in a quiet room, the patient will be then undergo the biomechanical evaluations first for running and then sprinting with a one minute rest between them (Fig 3). The reliability is high with ICC from 0.85 to 0.90 71.

For the running biomechanical evaluation, each patient will run for three minutes at 3.33 m.s⁻¹ (12 km.h⁻¹) and, without the patient being informed of the exact moment of data recording, 20 sec of biomechanical parameters will be recorded. Mechanical data will be sampled at 1000 Hz. After appropriate filtering (Butterworth-type 30 Hz low-pass filter, 2nd order),
instantaneous data of vertical force will be averaged for each support phase (vertical force above 30 N) over the 20-s ($F_{V,R}$), and expressed in N and body weight (BW). For each step, contact ($t_c$) and aerial ($t_a$) times will be calculated. Spring–mass parameters, like vertical stiffness ($k_{vert}$ in kN m$^{-1}$) and leg stiffness ($k_{leg}$ in kN m$^{-1}$), will be calculated using the computation method proposed by Morin et al.[59] The lower limb leg length will be the distance behind the great trochanter to ground distance in a standing position. The stride length ($l_{stride}$ in m) will be calculated as:

$$l_{stride} = (t_c + t_a) \cdot v.$$

For the sprint running biomechanical evaluation, each patient will first be familiarized with sprinting on a treadmill by three 6-sec sprints separated by 1 minute of rest. The patient is fitted with a leather weightlifting belt attached via a rigid tether (0.6 cm in diameter) to the wall (Figure 3), as described by Morin et al. [72] The constant motor torque will be set to 160% of the default torque, i.e. the motor torque necessary to overcome the friction on the treadmill belt due to the participant’s body weight. The default torque will be measured by making the participants stand still and by increasing the driving torque until a movement of the treadmill belt greater than 2 cm is observed over 5 s. Motor torque of 160% of the default value will be selected after several preliminary measurements comparing various torques, as this will allow participants to sprint in a comfortable manner and produce maximal effort without risking a loss of balance. Once the patient is correctly attached, he will be required to lean forward in a typical crouched sprint-start position with their preferred foot forward. This starting position will be used and standardized throughout the sprint series. After a 3-s countdown, the treadmill will be released, and the treadmill belt will begin to accelerate as participants apply a positive horizontal force. With patients strongly encouraged to produce their maximum intensity, two sprints will be recorded separated by a 1-minute rest period. The data used for
analysis will be: instantaneous data of vertical, net horizontal and total GRF averaged for each support phase (vertical force above 30 N) over 6-s sprints (\(F_{V\text{sprint}}\), \(F_{H\text{sprint}}\), \(F_{t\text{ot}\text{sprint}}\) respectively), and expressed in N and BW. For each step, the ratio of forces applied on the ground (RF) will be calculated as the ratio of \(F_{H\text{sprint}}\) to \(F_{t\text{ot}\text{sprint}}\) for one contact as follows: \(RF = F_{H\text{sprint}} \cdot F_{t\text{ot}\text{sprint}}^{-1}\) (expressed in %).\(^{73}\) Then, mean and maximal values of ratio forces for the 6-s sprint will be computed (RF-mean and RF-max, respectively). The index of force application technique (\(D_{RF}\)) representing the decrement in RF with increasing speed (S) will be computed as the slope of the linear RF-speed relationship calculated from the step-averaged values between the second step and the step at top speed.\(^{50}\) Therefore, the higher the DRF (i.e. a flat RF-speed relationship), the more RF will be maintained despite increasing velocity, and vice versa.\(^{74}\) Lastly, for each 6-s sprint, performance will be described through mean and maximal running speeds (S and S-max, respectively).

Please insert Fig 3.

Hop Tests:

The patient will be asked to perform the following exercises, as described by Noyes and al.\(^ {75}\) (Fig 4.):

- **Single One-Leg Hop Test** on the healthy limb and then the operated limb, with the arms crossed, hands on shoulders. The patient will perform one hop, as far as possible, with a controlled, balanced landing (minimum 3 seconds). If the patient cannot maintain the landing position, makes extra hops, or does not keep his hands on his shoulders, then the Hop Test will be considered a failure.
- **Triple One-Leg Hop Test** on the healthy limb and then the operated limb with the arms in any position. The patient will perform 3 consecutive hops as far as possible. The last hop position must be maintained for a minimum of 3 seconds as with the **Single One-Leg Hop Test**.

- **Cross-over One-Leg Hop Test** on the healthy limb and then the operated limb with the arms in any position. The test is carried out on a 6.5 m strip of carpet with a central line 15 cm in width. The patient is asked to make three hops, the first laterally, crossing the line on each hop. Landing after the final hop must be as with the **Single One-Leg Hop Test**. The **Cross-over One-Leg Hop Test** allows assessment of the cutting movement capabilities of the patient. It imposes both predominant sagittal plane and rotation forces on the frontal plane of the knee. In addition, the test highlights any instability in the knee, but also tests muscle extensibility, muscle strength and power, proprioception, neuromuscular control, dynamic balance, and agility.

Patients start from single limb stance. Every attempt will include at least 3 jumps and will continue until the patient progresses. The best distance for each leg and each Hop Test will be recorded for analysis (in cm). In case of failure, the patient will have the opportunity to do the Hop-Test again until it will be considered valid. The reliability is high with ICC from 0.84 to 0.92.

Please insert Fig 4.

**Isokinetic assessment**
As the resulting tiredness could affect the other tests if done earlier in the battery, the isokinetic quadriceps and hamstring muscle strength assessment will be performed last. They will be done on a Con-Trex® Multi-Joint dynamometer (CMV AG, Dübendorf, Switzerland) and controlled by Con-Trex Software. The installation is described elsewhere in the literature. The participants will be seated with the hip joint at about 85° and strapped in place at the chest, pelvis and mid-thigh to avoid postural compensation during the assessment. The contralateral limb will be fixed to a support at the ankle. The axis of the dynamometer will be perfectly aligned with the rotation axis (lateral femoral epicondyle) of the knee joint. Resistive support will be strapped to the leg, at 2-3 cm proximal to the ankle joint line. The range of knee motion will be set from 80° for a safe, comfortable, comparative assessment of quadriceps (extensor) and hamstrings (flexors) muscles. The gravity correction will be used. Assessment will begin with the healthy knee, and then the operated knee, and each series of repetitions will be followed by one minute of rest. The assessment is summarized in Table 2.

Table 2 Isokinetic assessment design

<table>
<thead>
<tr>
<th>Repetitions</th>
<th>Angular velocity and mode of contraction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First specific warm-up</strong></td>
<td>↓ 6 sub-maximal</td>
</tr>
<tr>
<td></td>
<td>120 °/s in concentric</td>
</tr>
<tr>
<td><strong>Second specific warm-up</strong></td>
<td>↓ 6 sub-maximal</td>
</tr>
<tr>
<td></td>
<td>120 °/s in concentric</td>
</tr>
<tr>
<td><strong>Habituation session</strong></td>
<td>↓ 3 sub-maximal</td>
</tr>
<tr>
<td></td>
<td>60 °/s in concentric</td>
</tr>
<tr>
<td><strong>Maximal test session with encouragement</strong></td>
<td>↓ 3 maximal</td>
</tr>
<tr>
<td></td>
<td>60 °/s in concentric</td>
</tr>
<tr>
<td><strong>Maximal test session with encouragement</strong></td>
<td>↓ 3 maximal</td>
</tr>
<tr>
<td></td>
<td>120 °/s in concentric</td>
</tr>
<tr>
<td><strong>Habituation session</strong></td>
<td>↓ 3 sub-maximal</td>
</tr>
<tr>
<td></td>
<td>30 °/s in eccentric</td>
</tr>
<tr>
<td><strong>Maximal test session with encouragement</strong></td>
<td>↓ 3 maximal</td>
</tr>
<tr>
<td></td>
<td>30 °/s in eccentric</td>
</tr>
</tbody>
</table>
The isokinetic assessment will be performed in this order, using gravity corrections, at a range of motion of 5°-85°, and measuring peak torque for each test session. A 1-minute rest will be allowed between each session.

Torque, position and angular velocity data will be recorded from the isokinetic dynamometer with a sampling rate of 100 Hz. After appropriate filtering, for concentric and eccentric strength trials, the software will calculate a large number of parameters, but we will retain only the absolute peak torque, the most reproducible parameter (ICC > 0.96)\textsuperscript{78}. The peak torque value normalized to the body weight (Nm/kg) will be recorded for each mode and speed of contraction for the Quadriceps (Q) and Hamstring (H). The Q/H ratio will be calculated for each mode and speed of contraction on the operated side, with a ratio ≥ 60% considered to be physiologically sufficient to obtain joint control. A mixed functional ratio, associating the eccentric performance of the flexor (at 30°/s) and the concentric performance of the extensor (at 240°/s) will also be calculated, as reported by Croisier and al.\textsuperscript{79}.

**Follow-up after ACL surgical reconstruction**

Patient follow-up will continue until 36 months post-operatively. After the evaluation at 12-months post-surgery patient follow-up will continue for a further 2 years. The researchers will attempt to follow-up all patients by phone interview every 6 months to determine the date of return to running, to pivoting sport-specific training, and to pivoting sport competition, as well as the date and the nature of any reinjury that may occur. The reinjury is defined as: rupture of the transplant, or the contralateral ACL, or any injury requiring the sporting activity
to cease and necessitating a consultation and/or medical care. We will also collect the Tegner score at 3-years post-ACLR.

The decision for clearance to a return to sport will be made by a sport-physician, blinded to all the tests results except the isokinetics results. This decision will be taken after considering the time from surgery, clinical experience and the isokinetics results.

**Primary outcome**

The main criterion for assessment is the occurrence of reinjury during the 3-year follow-up. A reinjury is defined as a rupture of the transplant or the contralateral ACL, or any injury requiring the sporting activity to cease and necessitating a consultation and/or medical care.

**Method of accounting for missing, unused or invalid data**

A patient’s participation in the study will cease if significant complications appear when performing the tests and all data collected before that point will be analyzed.

**Power and sample size considerations**

Based on the rate of ACL reinjury (rupture of the transplant or the contralateral ACL) described in the literature for the subgroup of younger athletes who return to sport, and considering the unknown rate of other possible injuries (any injury requiring the sporting activity to cease and necessitating a consultation and/or medical care) after an ACLR, a global rate of reinjury after ACLR could be assumed at 20%. Considering a 10% dropout rate, and that 10 cases (reinjury) are needed to test one explanatory variable, it is necessary to include
50 patients to test one explanatory variable for 95% power and a Type-I error rate (alpha) of 0.05. Depending on the results of the Data Mining procedures (Principal components analysis and Hierarchical Clustering on Principal Components) on the variables presented in table 3, we will choose a maximum of 5 variables to construct the model. We will therefore need to include 275 patients.

**Statistical analyses**

Exploratory data analysis will be performed, following five steps adapted from Data Mining processes: 1) Identification of study objectives, 2) Data acquisition, 3) Data evaluation and preparation, 4) Data analysis and modeling, 5) Results, interpretation and validation.

In step 3, we will analyze the data quality checking that there are no inconsistencies, errors, duplicates or "aberrant" data. We will also verify the overall consistency of the data.

In step 4, classification and selection of variables reported in Table 3 will define the explanatory variables required to build the models (with Principal components analysis then Hierarchical Clustering on Principal Components). We will choose the best data analysis taking into account the characteristic of the model variables.

Lastly, in step 5, the model (s) will be analyzed and compared in order to define as precisely as possible the explanatory variables and the most suitable model. The p-value will be adjusted if necessary and other methods could be used (Akaike information criterion (AIC) or Bayesian information criterion (BIC)). The parameters of the model will then be analyzed in order to define their clinical relevance.
The use of this exploratory data analysis will be based on by some of the work in medical research to use Data Mining\(^80\)\(^82\). However, this method does not exclude the classical statistical analyses for the creation of a model. Lasting, depending on our variables, we will use the appropriate statistical tests. After performing a correlation matrix and calculating colinearity using linear regression, we will calculate several Generalized Linear Models if possible: Linear Regression, Generalized Estimating Equations, Generalized Linear Mixed Model, depending on the characteristics of our variables.

Statistical analyses will be performed using R (http://www.R-project.org).

Table 3. Explanatory variables

<table>
<thead>
<tr>
<th>Categories of criteria</th>
<th>Explanatory variables</th>
<th>unit or range</th>
<th>Calculated data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Marx pre injury</td>
<td>0-16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tegner pre injury</td>
<td>0-10</td>
<td></td>
</tr>
<tr>
<td>self-reported measures</td>
<td>IKDC</td>
<td>0-100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TSK-11</td>
<td>11-55</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SANE</td>
<td>0-100</td>
<td></td>
</tr>
<tr>
<td>Postural control analysis</td>
<td>Center of pressure (CoP)</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Center of pressure (CoV)</td>
<td>mm.s⁻¹</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Center of pressure (CoP)</td>
<td>mm²</td>
<td></td>
</tr>
<tr>
<td>Knee laxity measurements</td>
<td>GnRB slope</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GnRB anteroposterior displacement</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>SEBT</td>
<td>Anterior distance</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Postero-lateral distance</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Postero-lateral distance</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>composite SEBT score</td>
<td>%</td>
<td>X</td>
</tr>
<tr>
<td>Running and Sprinting mechanics</td>
<td>LSI Leg stiffness</td>
<td>%</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>LSI stride length</td>
<td>%</td>
<td>X</td>
</tr>
<tr>
<td>LSI Sprint vertical force</td>
<td>%</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>--------------------------</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>LSI Sprint horizontal force</td>
<td>%</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>LSI Sprint total Force</td>
<td>%</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>LSI Sprint ratio of forces</td>
<td>%</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>LSI Sprint DRF</td>
<td>%</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hop Tests</th>
<th>LSI Single One-Leg Hop Test</th>
<th>%</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSI Triple One-Leg Hop Test</td>
<td>%</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>LSI Cross-over One-Leg Hop Test</td>
<td>%</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Isokinetic assessment</th>
<th>Quadriceps peak torque at 60°/s BW</th>
<th>N/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadriceps peak torque at 240°/s BW</td>
<td>N/kg</td>
<td></td>
</tr>
<tr>
<td>Quadriceps peak torque at 30°/s BW</td>
<td>N/kg</td>
<td></td>
</tr>
<tr>
<td>Hamstring peak torque at 60°/s BW</td>
<td>N/kg</td>
<td></td>
</tr>
<tr>
<td>Hamstring peak torque at 240°/s BW</td>
<td>N/kg</td>
<td></td>
</tr>
<tr>
<td>Hamstring peak torque at 30°/s BW</td>
<td>N/kg</td>
<td></td>
</tr>
<tr>
<td>Mixed Functional Ratio</td>
<td>%</td>
<td>X</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Follow-up</th>
<th>Marx 3 years postop</th>
<th>0-16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tegner 3 years postop</td>
<td>0-10</td>
<td></td>
</tr>
<tr>
<td>SANE 3 years postop</td>
<td>0-100</td>
<td></td>
</tr>
</tbody>
</table>

LSI = operated leg/ healthy leg, Mixed Functional Ratio = IJ30 / Q 240

ETHICS AND DISSEMINATION

The present study has been approved by the local Ethical Committee (IRBN522015/CHUSTE) and will be recorded on ClinicalTrials.gov. Prior to enrolment in the study, all patients will be asked to give their informed consent. The patient can decide at any time to be released from the study and they will be informed of this in the information leaflet. His/her data will then be deleted from the data collection file. Leaving the study will have no incidence on the normal monitoring protocol of patients post-surgery. The results of this study
will be disseminated via presentation at local, national and international conferences and peer-reviewed journals.

Acknowledgements

The authors are grateful to the study participants, hospital staff and study staff, and especially Léa Feuillassier, Alex Pavoine, Antoine Dany and Stephane Moret.

Contributors

AJMR, BS and PE designed the CRSTAL study and contributed to development of the study protocol. AJMR and BS drafted the manuscript. BS submitted to ethic committee. AJMR, BS, RT, PS, JBM, RP and PE assisted in drafting the manuscript. All authors read and approved the final manuscript.

Conflict of interest

None declared.

Ethics approval

Ethical approval was obtained through the University Hospital of Saint-Etienne Ethics Committee (Reference number IRBN522015/CHUSTE).

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.
References


Figure 1 The study design:

Figure 2. Knee laxity measurement position and the GNRB® system.

Figure 3. A runner fitted with a leather weightlifting belt (D) attached with a rigid tether (C) to the wall mounting bracket (A and B) sprinting on a motorized treadmill.

Figure 4. Hop Tests: A: Single One-Leg Hop Test, B: Triple One-Leg Hop Test, and C: Cross-over One-Leg Hop Test
Fig 1. The study design

71x40mm (300 x 300 DPI)
Fig 2. Knee laxity measurement position and the GNRB® system.

395x559mm (300 x 300 DPI)
A runner fitted with a leather weightlifting belt (D) attached with a rigid tether (C) to the wall mounting bracket (A and B) sprinting on a motorized treadmill.

51x26mm (300 x 300 DPI)
Fig 4. Hop Tests: A: Single One-Leg Hop Test, B: Triple One-Leg Hop Test, and C: Cross-over One-Leg Hop Test

68x61mm (300 x 300 DPI)
Postoperative rehabilitation [1-3]

Phase 1

Acute Management/Early Motion and Basic Movement Retraining

Goals
1. Achieve full active knee extension equal to the uninvolved side with active Vastus Medialis recruitment.
2. Eliminate swelling.
3. Restore the ability to control the leg while weight bearing.
4. Achieve at least 90° of knee flexion.
5. Be able to straight leg raise.
6. Normalize walking patterns with the assistance of crutches and/or a brace.

If hamstring graft, no active hamstring exercises until 2 weeks and no open chain resisted hamstring curls until 4 weeks post-op.

Type of exercises:
—Range of Motion (ROM) Exercises (Heel-slides to improve knee flexion.)
—Soft tissue treatments to patella, patella tendon, incisions, and posterior musculature to improve range of motion and decrease fibrosis.
—Muscle Activation with quad sets, straight leg raises and double leg mini squats (ROM 0–60°). Use manual facilitation techniques or electrostimulation when voluntary contraction of the quadriceps is not possible.
—Core Body Training and Neuromuscular Training. Encourage a correct quality of performance (e.g. trunk lateroflexion, hip- and knee flexion, dynamic knee valgus and...
knee-over-toe) during strength training and walking. Use implicit learning techniques instead of explicit learning techniques.

—Ambulation like diagonal weight shifting, backward stepping and step-overs

**Criteria to start phase 2:**

—Closed wound
—No knee pain with phase 1 exercises (VAS)
—Minimal synovitis or effusion
—Normal mobility (left=right) of the patellofemoral joint
—Knee extension of at least 0° and a 120–130° flexion
—Voluntary control of the quadriceps
—Active dynamic gait pattern without crutches
—Correct qualitative performance of phase 1 exercises.

**Phase 2**

*Basic Strength and Proprioception*

**Goals**

1. Restore proper body alignment and control with basic movements, such as walking without assistance, squats, stationary lunges and single-leg balance.
2. Build lower extremities and core body strength
3. Develop increased proprioception, starting with stationary postures and then progressing to movements.
4. Achieve active range of motion equal to the uninvolved Knee.

**Type of exercises:**

—Range of Motion (ROM) and stationary bike
—Soft tissue treatments
—Gait Drills
—Functional Strengthening (add weight or resistance with exercises), Single-leg/unilateral workouts (i.e. on weight machines, squats, side and forward step-downs).
—increase depth of balance exercises
—Neuromuscular training: Increase difficulty of neuromuscular and perturbation training
—Core Body and increase intensity with aerobic machines.

Carefully monitor exercises for signs of diminished eccentric control, weakness, or poor ability to stabilize against varus/valgus moment with loading exercises.

Criteria to start phase 3:
—Correct qualitative performance of phase 2 exercises
—Limb Symmetry Index (LSI) >80% for quadriceps and hamstring strength
—LSI >80% for a hop test battery, preferably using the hop test battery of Gustavsson

Phase 3

Dynamic Neuromotor Strength, Endurance and Coordination

Goals
1. Increase the strength of the involved leg.
2. Develop eccentric neuromuscular control to allow acceptance of impact activities without increasing symptoms.
3. Develop dynamic flexibility to allow for proper alignment during activities of increasing speed.
4. Full range of motion is expected.

Type of exercises:
—Range of Motion
Dynamic Agility Drills: begin with small strides at low velocity, gradually increasing the velocity.

Functional Strengthening. The recommended strengthening exercises are closed chain: squat, lunge.

Landing and Takeoff Drills: before initiating impact activities the patient should not have any swelling, have full knee extension, be able to balance on one leg for 10 seconds and be able to perform a single leg squat to approximately 45–60° of knee flexion with good posture and control.

Balance exercises with challenge postural control and duration: balance board activities, swim strokes, single leg balance with eyes closed

- Core Body and cardiovascular conditioning

**Phase 4**

*Athletic Enhancement and Return to Activity*

This phase can be initiated when the goals of Phase 3 are met. This phase will usually begin 12–16 weeks after surgery.

**Goals**

1. Progress from double leg impact control to single leg impact control.
2. Develop proper technique and appropriate neuromuscular control with start and stop movements and change of direction movements.
3. Eliminate apprehension that may exist with complex movements related to sports.

**Type of exercises:**

- Dynamic Warm Up: will help with increasing core body temperature, mental alertness, elasticity of the muscular system and activation of the neuromuscular system.
- Multi-planar Landing Control and Neuromuscular Reaction: Jump rotations, fast feet and lunge, multi-planar leap and land, stop and go, hopping.
—Functional movements and strengthening: one-legged squat, single leg dead lift, lateral lunge walk, power step up.
—Advanced Core Training and begin for jogging.

Reference


Criteria for Return to Sport after Anterior Cruciate Ligament reconstruction with lower reinjury risk (CR’STAL study): protocol for a prospective observational study

Alexandre JM RAMBAUD, Bertrand SEMAY, Pierre SAMOZINO, Jean-Benoît MORIN, Rodolphe TESTA, Rémi PHILIPPO, Jérémy ROSSI, Pascal EDOUARD

1 Inter-university Laboratory of Human Movement Biology (LIBM EA 7424), University of Lyon, University Jean Monnet, Saint-Etienne, France
2 Physiotherapy Clinic of the Sport Center, La Talaudière, France
3 Department of Orthopaedic and Trauma Surgery, University Hospital Center of Saint-Etienne, Hôpital Nord, Saint-Etienne, France
4 Inter-university Laboratory of Human Movement Biology (LIBM EA 7424), University Savoie Mont Blanc, Le Bourget-du-Lac, France
5 Université Côte d’Azur, LAMHESS, Nice, France
6 Department of Clinical and Exercise Physiology, Sports Medicine Unit, University Hospital of Saint-Etienne, Faculty of Medicine, Saint-Etienne. France

Corresponding Author:
Alexandre JM RAMBAUD, LIBM, University of Lyon, Campus Santé Innovations IRMIS, 10 rue de la Marandière, 42270 Saint-Priest en Jarez, France.
Email: alexandre.rambaud.kine@gmail.com +33 (0)4 77 30 76 55
*These authors contributed equally to this work.

Keywords:

Anterior Cruciate Ligament Reconstruction, Return to Sport, Biomechanics, risk factors; injury prevention
ABSTRACT

Introduction:

The decision regarding when to return to sport after an Anterior Cruciate Ligament Reconstruction (ACLR) is an important one. Using a variety of subjective and objective parameters, various attempts have been made to determine an optimal timeline for a return to sport after ACLR, but none have been validated.

The aim of the present study is therefore to determine which criteria or combination of criteria could allow to return to sport with the lowest possible risk of reinjury.

Methods and analysis

This study is a prospective cohort, single-center study, with repeated assessments at 6, 9 and 12 months post-ACLR surgical reconstruction and including a 3-year follow-up of patients’ sporting activity and reinjuries. 275 patients will be included to test explanatory variables. Postural control analysis, knee laxity, questionnaires (IKDC, TSK11, ACLR-RSI, SANE), modified Star Excursion Balance Tests, running and sprinting biomechanics, Hop Tests and isokinetic tests will all be used. The primary outcome will be any reinjury during the follow-up period, defined as a graft rupture, a contralateral ACL rupture, or any injury necessitating an interruption of training and requiring a medical consultation. Two groups will be constituted during the follow-up, separating reinjured from non-reinjured patients. In addition, classic analysis and Data Mining approaches will be used to build predictive models.
Ethics and dissemination

The results of this study will be disseminated through peer-reviewed publications and scientific presentations. Ethical approval was obtained through the University Hospital of Saint-Etienne Ethics Committee (Reference number IRBN522015/CHUSTE).
STRENGTHS AND LIMITATIONS OF THIS STUDY:

- This is the first study to associate the analysis of several parameters (both habitual and innovative, considered both singly and in combination) with an exploratory data analysis (Data Mining), to formulate the best decision-making model for determining the optimal time for a return to sport after ACLR.

- This study has been designed to include evaluations at 6, 9 and 12 months post-ACLR in order to include and analyze data from the usual time when athletes return to pivot-sport training (6-9 months) and the time when they can return to competition (generally 9-12 months).

- The study includes only young competitive athletes, which is the population with the highest risk of reinjury, but also with the highest chance to return to sport at the pre-injury level. These findings would not necessarily be applicable to the general population.

- This screening protocol seeks to assess elements involved in the return to sport after ACLR with knee-specific and task-specific objective measurements associated with subjective assessment of knee function and psychometric capabilities.

- The design and objectives of this study will require a significant number of patients, but since this population is highly motivated to return to sport, we are convinced that this choice will limit dropouts.
INTRODUCTION

Anterior cruciate ligament (ACL) tears represent a public health challenge with an incidence reported as 60-71 per 100,000 subjects. ACL tears often give rise to problems like post-traumatic osteoarthritis; that could lead to middle- and long-term problems for the patient, a potential increase in knee surgery in the future and consequently a significant cost to society. In this context, appropriate treatment of ACL tears and secondary and tertiary prevention among young pivot-shift athletes represent very relevant challenges and a major orientation for orthopedics and sports medicine research.

After an injury, and especially ACL tear, one of the most frequent question asked by the patient is: “when can I get back to my sport?”. ACL Reconstruction (ACLR) is the current clinical standard for patients with an ACL tear and considered to be at a high risk of knee instability (young, high-level athletes in a pivoting and/or contact sport). After surgical reconstruction, a rehabilitation program is set up to allow patients to return to a painless and fully functional daily life. In patients aiming to return to sport, the rehabilitation program must continue until this is possible.

To consider an ACLR successful, the patient should be able to return to the same level of sporting activity as before the injury. Moreover, a recent patient satisfaction survey confirms that a patient who can resume his sporting activity is more likely to be satisfied with the outcome of the ACLR. However, in their updated review, Ardern and al. had shown that on average 80% of patients returned to sport, while only 55% returned to competitive levels after ACLR. These mitigated results highlight the fact that the return to sport (RTS) represents an important challenge after ACLR, and that current practices should be improved in this aim.
After ACLR, rehabilitation should be optimal to allow athletes’ RTS, and the decision of when RTS is an important one for patient satisfaction and challenging in the context of secondary and tertiary prevention. Indeed, more the time to RTS is delayed, more the patient motivation and his psychological readiness could be poorer, decreasing as well his chance to return to sport at the same level, but on the other hand an early return to sport exposes the patient to a high risk of reinjury. 13-17 RTS, especially with pivoting or contact sports, exposes the athlete to a risk of reinjury: Wiggins et al., 18 in a systematic review and meta-analysis, had found 15% of second ACL reinjury rate, with 7% for the ipsilateral ACL and 8% for the contralateral reinjury rate. Moreover, in the subgroup of younger patient who wanted to return to sport, the secondary ACL injury rate was 23%. A new injury after an ACLR could nonetheless be another musculoskeletal injury, 19 as well it could affect the joint (rupture of the graft or contralateral ACL, chondral and/or meniscal lesion). Indeed, a history of an ACLR is a risk factor for developing a repeat hamstring strain, 20 hindering RTS and the future practice of sport. Thus, the decision of when RTS is a challenging decision, in order to optimize the chance to return to sport at the pre-injury level, and in a health protection perspective to minimize the risk of reinjury.

Many factors have been implicated in reinjury risk, including sex, 7, 21-22 age, 7, 23-25 activity level, 26, 27, graft placement, 28-30 graft type, 31-35 time from surgery, 32, 34 and deficits in neuromuscular and biomechanical control of the lower limb. 36 Considering those risk-factors, clinical studies used many techniques and criteria to determine the optimal moment for a return to sport after ACLR. 13, 16, 37-39 The most used is the post-operative timeline, either alone or with: muscle strength, knee laxity, knee assessment form, or functional tests. However, to the best of our knowledge, there are no clearly validated criteria for determining a safe return
to sport after ACLR. This decision is currently based on multiple criteria mostly using the post-operative time frame needed for the biological integration of the graft. It seems, according to a recent publication that a delayed RTS from 6 months after surgery to 9 months after surgery decreased the risk of reinjury by 51% each month RTS is delayed. However time criteria alone was not sufficient to determining readiness for a safe RTS; Grindern et al. thus recommended to uses of both time-based and functional RTS criteria. Barber-Westin and Noyes, in a systematic review, described how this decision is associated with subjective parameters ("satisfactory clinical examination", "stable knee", "normal joint function", self-reported knee function (subjective IKDC (The International Knee Documentation Committee) and that only 10% of the included studies used objective criteria such as: muscular strength, knee laxity, the limb symmetry index (LSI) or functional tests (Hop Tests, Star Excursion Balance Tests). Kyritsis et al. had also evaluated a set of objective criteria (muscle strength and functional tests) with 158 male professional athletes. Those who did not meet criteria (quadriceps deficit < 10% at 60°/s, LSI for each Hop Tests > 90%, running T test <11s) had four times greater risk of graft reinjury, and hamstring to quadriceps ratio deficits were associated with an increased risk of ACL re-rupture. Among the objective criteria, testing isokinetic muscular strength is a clear measure of strength recovery and seems to be central in objective assessment of a readiness to return to sport. Moreover, contextual factors such as a positive attitude and fear of injury have not been assessed either in these studies or in the literature as predictors of reinjury although it is well known that these factors influence the capacity to return to sport, especially at the same level of participation.
In addition, evaluation of lower limb function, in close to sport tasks, could also give important information to allow RTS. Kyritsis et al. have recently associated classical functional tests and “running t test” to evaluate agility and performance, but analysis of running or sprinting pattern has not been performed. Mazet et al. have analysed running patterns in patients with ACLR, and reported that biomechanical stiffness, calculated using time of flight and contact time, was significantly greater on the operated limb than on the healthy limb or in healthy patients. Using a non-motorized treadmill fitted with force sensors, Brown and Brughelli evaluated the sprint of a rugby player after ACLR during the period of return to sport (between the return to training and competition). An asymmetry of the Ground Reaction Force (GRF) persisted (horizontal force: 13%, vertical force: 7%) while the isokinetic muscular strength testing appeared normal. They concluded that an evaluation of sprint mechanics complemented the usual functional assessments. This analysis, in line with sports reality, could detect an asymmetry during the return to sport phase (6-12 months). This sport-specific assessment seems very relevant to the decision to return to sport; indeed, a good gait with efficient biomechanical performance in the sagittal plan is an essential step for a return to pivoting/cutting sports.

In this context, the determination of an association of criteria to help in the decision-making process regarding RTS with the lowest risk of reinjury or associated lesions (muscles or ligaments of the lower limbs) is of major interest in the management of patients with ACLR who want to return to a competitive pivoting sport. Thus, the aim of the present study is therefore to determine which criteria or combination of criteria could allow to return to sport with the lowest possible risk of reinjury.
METHODS

The present study is a prospective cohort single-center study, with repeated measures at 6, 9 and 12 months post-operatively after an ACLR and follow-up of the return to sport and reinjury for 3 years after the ACLR. The research started in January 2015, and is due to be completed in December 2020. The study design is shown in Fig 1.

Please insert Fig 1.

Study patients

Potential patients will be drawn consecutively from along the patients of the Sports Medicine Unit or the Orthopedic Surgery and Traumatology department of the local University Hospital. Patients included in the study must meet the criteria for inclusion/exclusion shown in Table 1. All study patients will undergo post-surgical rehabilitation in the same Physiotherapy Clinic using the protocol recommended in the literature \(^8\) \(^9\) \(^51\) (for more information about the protocol please see S1 Appendix. ACL Reconstruction Rehabilitation Protocol).
Table 1 Inclusion and exclusion criteria for patients

<table>
<thead>
<tr>
<th>Inclusion criteria</th>
<th>Exclusion criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>➢ Participation in pivot and/or contact sports and with intensive sporting activity before the ACL tear:</td>
<td>➢ Bilateral lower limb pathologies</td>
</tr>
<tr>
<td>- with a Marx scale score above 11 before the injury</td>
<td>➢ Recurrence of ACL rupture (with a MRI diagnostic)</td>
</tr>
<tr>
<td>- with a Tegner score above 6 before the injury</td>
<td>➢ Contraindications for carrying out a test, i.e.:</td>
</tr>
<tr>
<td>(competition training with more than 3 training sessions per week before the injury)</td>
<td>➢ Postoperative time less than 6 months</td>
</tr>
<tr>
<td>➢ Unilateral tear</td>
<td>➢ Persistence of knee pain (score &gt;3 at Numeric Pain Rating Scales)</td>
</tr>
<tr>
<td></td>
<td>➢ Persistence of a joint effusion (positive patellar tap test)</td>
</tr>
<tr>
<td></td>
<td>➢ Incomplete range of motion (Range of motion &lt; 90% on contralateral side)</td>
</tr>
<tr>
<td></td>
<td>➢ Abnormal walk (observable gait deviations during the walk)</td>
</tr>
<tr>
<td></td>
<td>➢ Allografts</td>
</tr>
<tr>
<td></td>
<td>➢ Skeletal immaturity</td>
</tr>
<tr>
<td></td>
<td>➢ Older than 35 years</td>
</tr>
</tbody>
</table>

Assessment procedure

All tests will be performed in the same place and all patients will be tested at the same time of day between 2 pm and 6 pm. Forty-eight hours before each evaluation session, patients will receive an email reminding them of the test procedure and asking them to complete a subjective questionnaire online (IKDC, TSK11, ACL-RSI and SANE). Informed consent will be obtained from all patients before testing begins and a standardized explanation of the assessment procedure given to the patients. Each test session will include, in the same order, a medical check-up, postural control analysis, knee laxity measurements, a modified Star Excursion Balance Test, biomechanical running and sprint analysis, Hop Tests and isokinetic tests, with a 5-minute rest between each test. Before the biomechanical analysis begins, patients will warm-up with 10 minutes of cycling to raise muscle temperature.
specific warm up activity will be included before each new activity. The isokinetic evaluation is at the end of the battery to avoid tiredness affecting the results of the other tests.

Evaluation of subjective parameters by questionnaires

The first questionnaire is the IKDC, an algo-functional questionnaire commonly used for ACLR follow-up. An IKDC within the 15th percentile of healthy patients is considered as criteria for a return to sport. The patient will then complete the Tampa Scale of Kinesiophobia-11 (TSK11). This questionnaire, containing 11 questions (choice between 5 answers), is used to estimate a patient’s fear of movement and reinjury giving a score from 11 to 55. A score below 20 indicates low pain avoidance and could also allow a return to sport. The last questionnaire the patient is asked to complete is the ACL-Return to Sport after reinjury (ACL-RSI). This 12-item scale measures three specific psychological constructs – emotions, confidence in performance, and risk appraisal – on a scale from 0 to 100. This scale is a predictive parameter for a successful return to sport after ACLR.

The patient will also be asked to estimate his knee recovery on a scale (from 0 to 100) with a single assessment numeric evaluation (SANE).

Medical check-up

Firstly, we will check if the online questionnaires have been done, and the presence of inclusion criteria and absence of exclusion criteria. The assessor will fill out the demographic information in the observation book (sex, age, weight, height, sport, training frequency and
Marx's score before the ACL tear), a timeline for a return to running, sport-specific training and competitive play where possible, and finally the ACLR surgeon and technique used. The clinical examination will follow the IKDC-2000 grid\(^52\).

Postural control analysis

A WinPosturo\(^\circledR\) (Medicapteurs, Balma, France) stabilometry platform will be used with the WinPosture\(^\circledR\) software (Medicapteur, Balma, France) to determine variations in the center of pressure (CoP). The force plate, which measures 530 × 460 × 35 mm has three pressure gauges (hysteresis < 0.2\%), with a sensitivity of 90 points per Newton. The sampling frequency will be fixed at 40 Hz with the platform recalibrated before each session. The assessment will be conducted in an isolated room, in a noise-free environment, with a hard, flat floor, following the recommendations of the American Academy of Neurology (AAN)\(^61\) and the study of Ruhe et al.\(^62\). The standardized position of the feet will be: oriented 15° laterally to the sagittal plane. The patient will have to breathe normally and stare at a point 1.5 m in front him, at eye level, the arms relaxed along the body. The patient will be in sportswear and socks.

Four measurements, knees in extension, separated by 30 seconds of recovery in a sitting position, will be performed:

- bipedal position, eyes open (60s)
- bipedal position, eyes closed (60s)
- Single-leg squat following by balancing on the healthy leg (30s), eyes open\(^17\)
- Single-leg squat following by balancing on the operated leg, eyes open (30s)\(^17\)
The values of total CoP path (CoP in mm), CoP velocity (in mm.s\(^{-1}\)), standard derivations of CoP (SDx and SDY), and CoP sway area (in mm\(^2\)) will be recorded. Kouvelioti et al. showed good or excellent reproducibility of all these variables using a similar assessment protocol (Intraclass Correlation Coefficient (ICC) range from 0.68 to 0.91). \(^63\)

**Knee laxity measurements**

The GNRB\(^\text{®}\) system (Genourob, Laval, France) is a non-invasive arthrometer that provides comparative bilateral measurements of knee laxity. This system is reliable and reproducible (ICC range from 0.77 to 0.91 \(^64\)-\(^66\)). The patient will lie on a standard examination table in the supine position, with the knee at 20\(^\circ\) flexion and 0\(^\circ\) of rotation (Fig 2). The lower limb is immobilized in a thermoformed shell, adaptable for different leg lengths, at the patella and the foot with a force of about 65±5N controlled by a force sensor with a precision of 0.1 mm. The analysis will begin with the healthy leg, with a push to 134N and 3 pushes to 250N. The same procedure is then repeated on the operated limb. The displacement of the anterior tibial tubercle relative to the femur is measured. The drawer shift/pressure curve is determined by the displacement (with 0.1 mm precision) and the slope of the curve (Slp in degree) which defines ligamentous laxity. The push to 250 N with the largest displacement (\(D_{ap}\) in mm) and Slp will be retained. The difference between the operated and healthy limb will be calculated for \(D_{ap}\) and Slp.

Please insert Fig 2.
Modified Star Excursion Balance Test

The patient, shoeless, will be asked to stand on one leg, starting with the healthy limb, without lifting the heel and with hands on hips and perform the following exercise as described in the literature: 67-69; to reach maximally to touch a point as far as possible in 3 directions, along i) an antero-posterior axis ii) the postero-lateral axis and finally iii) the postero-medial axis, returning to the initial position between each movement. Two attempts and 2 measurements will be made for each direction. The longest distance (in cm) will be noted for each direction. The reliability is high with ICC from 0.83 to 0.96. 70

Running and sprinting mechanics

Patients will choose either a cycle ergometer and/or jogging for a 10-15 general warm-up, followed by a specific sprint warm-up included sprint drills and short sprints. On a motorized instrumented treadmill (ADAL3D-WR; Medical Development, HEF Tecmachine, Andrezieux-Boutheon, France), with four piezoelectric force transducers (KI 9077b, Kistler, Winterthur, Switzerland), on a hard, flat surface in a quiet room, the patient will be then undergo the biomechanical evaluations first for running and then sprinting with a one minute rest between them (Fig 3). The reliability is high with ICC from 0.85 to 0.90. 71

For the running biomechanical evaluation, each patient will run for three minutes at 3.33 m.s\(^{-1}\) (12 km.h\(^{-1}\)) and, without the patient being informed of the exact moment of data recording, 20 sec of biomechanical parameters will be recorded. Mechanical data will be sampled at 1000 Hz. After appropriate filtering (Butterworth-type 30 Hz low-pass filter, 2\(^{nd}\) order),
instantaneous data of vertical force will be averaged for each support phase (vertical force
above 30 N) over the 20-s ($FV_R$), and expressed in N and body weight (BW). For each step,
contact ($t_c$) and aerial ($t_a$) times will be calculated. Spring–mass parameters, like vertical
stiffness ($k_{vert}$ in kN m$^{-1}$) and leg stiffness ($k_{leg}$ in kN m$^{-1}$), will be calculated using the
computation method proposed by Morin et al.[59] The lower limb leg length will be the
distance behind the great trochanter to ground distance in a standing position. The stride
length ($l_{stride}$ in m) will be calculated as: $l_{stride} = (t_c+t_a)v$.

For the sprint running biomechanical evaluation, each patient will first be familiarized with
sprinting on a treadmill by three 6-sec sprints separated by 1 minute of rest. The patient is
fitted with a leather weightlifting belt attached via a rigid tether (0.6 cm in diameter) to the
wall (Figure 3), as described by Morin et al.[59] The constant motor torque will be set to 160% of
the default torque, i.e. the motor torque necessary to overcome the friction on the treadmill
belt due to the participant’s body weight. The default torque will be measured by making the
participants stand still and by increasing the driving torque until a movement of the treadmill
belt greater than 2 cm is observed over 5 s. Motor torque of 160% of the default value will be
selected after several preliminary measurements comparing various torques, as this will allow
participants to sprint in a comfortable manner and produce maximal effort without risking a
loss of balance. Once the patient is correctly attached, he will be required to lean forward in a
typical crouched sprint-start position with their preferred foot forward. This starting position
will be used and standardized throughout the sprint series. After a 3-s countdown, the
treadmill will be released, and the treadmill belt will begin to accelerate as participants apply
a positive horizontal force. With patients strongly encouraged to produce their maximum
intensity, two sprints will be recorded separated by a 1-minute rest period. The data used for
analysis will be: instantaneous data of vertical, net horizontal and total GRF averaged for each support phase (vertical force above 30 N) over 6-s sprints ($F_{V\text{sprint}}$, $F_{H\text{sprint}}$, $F_{\text{tot}sprint}$ respectively), and expressed in N and BW. For each step, the ratio of forces applied on the ground (RF) will be calculated as the ratio of $F_{H\text{sprint}}$ to $F_{\text{tot}sprint}$ for one contact as follows: $RF = F_{H\text{sprint}} \cdot F_{\text{tot}sprint}^{-1}$ (expressed in %). Then, mean and maximal values of ratio forces for the 6-s sprint will be computed (RF-mean and RF-max, respectively). The index of force application technique ($D_{RF}$) representing the decrement in RF with increasing speed (S) will be computed as the slope of the linear RF-speed relationship calculated from the step-averaged values between the second step and the step at top speed. Therefore, the higher the DRF (i.e. a flat RF-speed relationship), the more RF will be maintained despite increasing velocity, and vice versa. Lastly, for each 6-s sprint, performance will be described through mean and maximal running speeds (S and S-max, respectively).

Please insert Fig 3.

Hop Tests:
The patient will be asked to perform the following exercises, as described by Noyes and al. (Fig 4.):

- **Single One-Leg Hop Test** on the healthy limb and then the operated limb, with the arms crossed, hands on shoulders. The patient will perform one hop, as far as possible, with a controlled, balanced landing (minimum 3 seconds). If the patient cannot maintain the landing position, makes extra hops, or does not keep his hands on his shoulders, then the Hop Test will be considered a failure.
- **Triple One-Leg Hop Test** on the healthy limb and then the operated limb with the arms in any position. The patient will perform 3 consecutive hops as far as possible. The last hop position must be maintained for a minimum of 3 seconds as with the **Single One-Leg Hop Test**.

- **Cross-over One-Leg Hop Test** on the healthy limb and then the operated limb with the arms in any position. The test is carried out on a 6.5 m strip of carpet with a central line 15 cm in width. The patient is asked to make three hops, the first laterally, crossing the line on each hop. Landing after the final hop must be as with the **Single One-Leg Hop Test**. The **Cross-over One-Leg Hop Test** allows assessment of the cutting movement capabilities of the patient. It imposes both predominant sagittal plane and rotation forces on the frontal plane of the knee. In addition, the test highlights any instability in the knee, but also tests muscle extensibility, muscle strength and power, proprioception, neuromuscular control, dynamic balance, and agility.

Patients start from single limb stance. Every attempt will include at least 3 jumps and will continue until the patient progresses. The best distance for each leg and each Hop Test will be recorded for analysis (in cm). **In case of failure, the patient will have the opportunity to do the Hop-Test again until it will be considered valid.** The reliability is high with ICC from 0.84 to 0.92.

Please insert Fig 4.
As the resulting tiredness could affect the other tests if done earlier in the battery, the isokinetic quadriceps and hamstring muscle strength assessment will be performed last. They will be done on a Con-Trex® Multi-Joint dynamometer (CMV AG, Dübendorf, Switzerland) and controlled by Con-Trex Software. The installation is described elsewhere in the literature. The participants will be seated with the hip joint at about 85° and strapped in place at the chest, pelvis and mid-thigh to avoid postural compensation during the assessment. The contralateral limb will be fixed to a support at the ankle. The axis of the dynamometer will be perfectly aligned with the rotation axis (lateral femoral epicondyle) of the knee joint. Resistive support will be strapped to the leg, at 2-3 cm proximal to the ankle joint line. The range of knee motion will be set from 80° for a safe, comfortable, comparative assessment of quadriceps (extensor) and hamstrings (flexors) muscles. The gravity correction will be used. Assessment will begin with the healthy knee, and then the operated knee, and each series of repetitions will be followed by one minute of rest. The assessment is summarized in Table 2.

Table 2 Isokinetic assessment design

<table>
<thead>
<tr>
<th>Repetitions</th>
<th>Angular velocity and mode of contraction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First specific warm-up</strong></td>
<td>↓ 6 sub-maximal</td>
</tr>
<tr>
<td></td>
<td>120 °/s in concentric</td>
</tr>
<tr>
<td><strong>Second specific warm-up</strong></td>
<td>↓ 6 sub-maximal</td>
</tr>
<tr>
<td></td>
<td>120 °/s in concentric</td>
</tr>
<tr>
<td><strong>Habituation session</strong></td>
<td>↓ 3 sub-maximal</td>
</tr>
<tr>
<td></td>
<td>60 °/s in concentric</td>
</tr>
<tr>
<td><strong>Maximal test session with encouragement</strong></td>
<td>↓ 3 maximal</td>
</tr>
<tr>
<td></td>
<td>60 °/s in concentric</td>
</tr>
<tr>
<td><strong>Maximal test session with encouragement</strong></td>
<td>↓ 3 maximal</td>
</tr>
<tr>
<td></td>
<td>120 °/s in concentric</td>
</tr>
<tr>
<td><strong>Habituation session</strong></td>
<td>↓ 3 sub-maximal</td>
</tr>
<tr>
<td></td>
<td>30°/s in eccentric</td>
</tr>
<tr>
<td><strong>Maximal test session with encouragement</strong></td>
<td>↓ 3 maximal</td>
</tr>
<tr>
<td></td>
<td>30°/s in eccentric</td>
</tr>
</tbody>
</table>
The isokinetic assessment will be performed in this order, using gravity corrections, at a range of motion of 5°-85°, and measuring peak torque for each test session. A 1-minute rest will be allowed between each session.

Torque, position and angular velocity data will be recorded from the isokinetic dynamometer with a sampling rate of 100 Hz. After appropriate filtering, for concentric and eccentric strength trials, the software will calculate a large number of parameters, but we will retain only the absolute peak torque, the most reproducible parameter (ICC > 0.96). The peak torque value normalized to the body weight (Nm/kg) will be recorded for each mode and speed of contraction for the Quadriceps (Q) and Hamstring (H). The Q/H ratio will be calculated for each mode and speed of contraction on the operated side, with a ratio ≥ 60% considered to be physiologically sufficient to obtain joint control. A mixed functional ratio, associating the eccentric performance of the flexor (at 30°/s) and the concentric performance of the extensor (at 240°/s) will also be calculated, as reported by Croisier and al.

**Follow-up after ACL surgical reconstruction**

Patient follow-up will continue until 36 months post-operatively. After the evaluation at 12-months post-surgery patient follow-up will continue for a further 2 years. The researchers will attempt to follow-up all patients by phone interview every 6 months to determine the date of return to running, to pivoting sport-specific training, and to pivoting sport competition, as well as the date and the nature of any reinjury that may occur. **The reinjury is defined as:**

- rupture of the transplant, or the contralateral ACL, or any injury requiring the sporting activity...
to cease and necessitating a consultation and/or medical care. We will also collect the Tegner score at 3-years post-ACLR.

The decision for clearance to a return to sport will be made by a sport-physician, blinded to all the tests results except the isokinetics results. This decision will be taken after considering the time from surgery, clinical experience and the isokinetics results.

**Primary outcome**

The main criterion for assessment is the occurrence of reinjury during the 3-year follow-up. A reinjury is defined as a rupture of the transplant or the contralateral ACL, or any injury requiring the sporting activity to cease and necessitating a consultation and/or medical care.

**Method of accounting for missing, unused or invalid data**

A patient’s participation in the study will cease if significant complications appear when performing the tests and all data collected before that point will be analyzed.

**Power and sample size considerations**

Based on the rate of ACL reinjury (rupture of the transplant or the contralateral ACL\textsuperscript{18}) described in the literature for the subgroup of younger athletes who return to sport, and considering the unknown rate of other possible injuries (any injury requiring the sporting activity to cease and necessitating a consultation and/or medical care) after an ACLR, a global rate of reinjury after ACLR could be assumed at 20%. Considering a 10% dropout rate, and that 10 cases (reinjury) are needed to test one explanatory variable, it is necessary to include
50 patients to test one explanatory variable for 95% power and a Type-I error rate (alpha) of 0.05. Depending on the results of the Data Mining procedures (Principal components analysis and Hierarchical Clustering on Principal Components) on the variables presented in table 3, we will choose a maximum of 5 variables to construct the model. We will therefore need to include 275 patients.

Statistical analyses

Exploratory data analysis will be performed, following five steps adapted from Data Mining processes: 1) Identification of study objectives, 2) Data acquisition, 3) Data evaluation and preparation, 4) Data analysis and modeling, 5) Results, interpretation and validation.

In step 3, we will analyze the data quality checking that there are no inconsistencies, errors, duplicates or "aberrant" data. We will also verify the overall consistency of the data.

In step 4, classification and selection of variables reported in Table 3 will define the explanatory variables required to build the models (with Principal components analysis then Hierarchical Clustering on Principal Components). We will choose the best data analysis taking into account the characteristic of the model variables.

Lastly, in step 5, the model (s) will be analyzed and compared in order to define as precisely as possible the explanatory variables and the most suitable model. The p-value will be adjusted if necessary and other methods could be used (Akaike information criterion (AIC) or Bayesian information criterion (BIC)). The parameters of the model will then be analyzed in order to define their clinical relevance.
The use of this exploratory data analysis will be based on by some of the work in medical research to use Data Mining. However, this method does not exclude the classical statistical analyses for the creation of a model. Lasting, depending on our variables, we will use the appropriate statistical tests. After performing a correlation matrix and calculating colinearity using linear regression, we will calculate several Generalized Linear Models if possible: Linear Regression, Generalized Estimating Equations, Generalized Linear Mixed Model, depending on the characteristics of our variables. Statistical analyses will be performed using R.

Table 3. Explanatory variables

<table>
<thead>
<tr>
<th>Categories of criteria</th>
<th>Explanatory variables</th>
<th>unit or range</th>
<th>Calculated data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marx pre injury</td>
<td>0-16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tegner pre injury</td>
<td>0-10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>self-reported measures</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IKDC</td>
<td>0-100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TSK-11</td>
<td>11-55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SANE</td>
<td>0-100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Postural control</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>analysis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Center of pressure (CoP)</td>
<td>mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Center of pressure (CoV)</td>
<td>mm.s-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Center of pressure (CoP)</td>
<td>mm²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee laxity measurements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GnRB slope</td>
<td>mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GnRB anteroposterior displacement</td>
<td>mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEBT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior distance</td>
<td>m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Postero-lateral distance</td>
<td>m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Postero-lateral distance</td>
<td>m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>composite SEBT score</td>
<td>%</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Running and Sprinting</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mechanics</td>
<td>LSI Leg stiffness</td>
<td>%</td>
<td>X</td>
</tr>
<tr>
<td>LSI stride length</td>
<td>%</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>
LSI Sprint vertical force | % | X
LSI Sprint horizontal force | % | X
LSI Sprint total Force | % | X
LSI Sprint ratio of forces | % | X
LSI Sprint DRF | % | X

Hop Tests
LSI Single One-Leg Hop Test | % | X
LSI Triple One-Leg Hop Test | % | X
LSI Cross-over One-Leg Hop Test | % | X

Isokinetic assessment
Quadriceps peak torque at 60°/s BW | N/kg |
Quadriceps peak torque at 240°/s BW | N/kg |
Quadriceps peak torque at 30°/s BW | N/kg |
Hamstring peak torque at 60°/s BW | N/kg |
Hamstring peak torque at 240°/s BW | N/kg |
Hamstring peak torque at 30°/s BW | N/kg |
Mixed Functional Ratio | % | X

Follow-up
Marx 3 years postop | 0-16 |
Tegner 3 years postop | 0-10 |
SANE 3 years postop | 0-100 |

LSI = operated leg/ healthy leg, Mixed Functional Ratio = IJ30 / Q 240

ETHICS AND DISSEMINATION

The present study has been approved by the local Ethical Committee (IRBN522015/CHUSTE) and will be recorded on ClinicalTrials.gov. Prior to enrolment in the study, all patients will be asked to give their informed consent. The patient can decide at any time to be released from the study and they will be informed of this in the information leaflet. His/her data will then be deleted from the data collection file. Leaving the study will have no incidence on the normal monitoring protocol of patients post-surgery. The results of this study
will be disseminated via presentation at local, national and international conferences and peer-reviewed journals.
Acknowledgements

The authors are grateful to the study participants, hospital staff and study staff, and especially Léa Feuillassier, Alex Pavoine, Antoine Dany and Stephane Moret.

Contributors

AJMR, BS and PE designed the CRSTAL study and contributed to development of the study protocol. AJMR and BS drafted the manuscript. BS submitted to ethic committee. AJMR, BS, RT, PS, JBM, RP and PE assisted in drafting the manuscript. All authors read and approved the final manuscript.

Conflict of interest

None declared.

Ethics approval

Ethical approval was obtained through the University Hospital of Saint-Etienne Ethics Committee (Reference number IRBN522015/CHUSTE).

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

References


Figure 1 The study design:

Figure 2. Knee laxity measurement position and the GNRB® system.

Figure 3. A runner fitted with a leather weightlifting belt (D) attached with a rigid tether (C) to the wall mounting bracket (A and B) sprinting on a motorized treadmill.

Figure 4. Hop Tests: A: Single One-Leg Hop Test, B: Triple One-Leg Hop Test, and C: Cross-over One-Leg Hop Test
Criteria for Return to Sport after Anterior Cruciate Ligament reconstruction with lower reinjury risk (CR'LAST study): protocol for a prospective observational study in France

Alexandre J M Rambaud, Bertrand Semay, Pierre Samozino, Jean-Benoît Morin, Rodolphe Testa, Rémi Philippot, Jérémie Rossi and Pascal Edouard

BMJ Open 2017 7:
doi: 10.1136/bmjopen-2016-015087

Updated information and services can be found at:
http://bmjopen.bmj.com/content/7/6/e015087

These include:

References
This article cites 79 articles, 15 of which you can access for free at:
http://bmjopen.bmj.com/content/7/6/e015087#BIBL

Open Access
This is an Open Access article distributed in accordance with the Creative Commons Attribution Non Commercial (CC BY-NC 4.0) license, which permits others to distribute, remix, adapt, build upon this work non-commercially, and license their derivative works on different terms, provided the original work is properly cited and the use is non-commercial. See: http://creativecommons.org/licenses/by-nc/4.0/

Email alerting service
Receive free email alerts when new articles cite this article. Sign up in the box at the top right corner of the online article.

Topic Collections
Articles on similar topics can be found in the following collections
Sports and exercise medicine (220)

Notes

To request permissions go to:
http://group.bmj.com/group/rights-licensing/permissions

To order reprints go to:
http://journals.bmj.com/cgi/reprintform

To subscribe to BMJ go to:
http://group.bmj.com/subscribe/