A review of criteria derived from clinical and AI approaches for return to sport after ACL reconstruction

Revue des critères issus des approches cliniques et de l'IA pour la reprise du sport après reconstruction du LCA

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RÉSUMÉ. Le souhait de retrouver un niveau de mobilité ou de performance sportive équivalent, sans appréhension et sans risque de nouvelle blessure après une reconstruction du Ligament Croisé Antérieur (LCA), est légitime mais reste encore rarement atteint. En effet, à ce jour, aucun protocole de retour au sport n'a véritablement été validé. Les critères actuellement utilisés souffrent d'un manque de standardisation et parfois d'objectivité, ce qui limite leur efficacité clinique. Bien que la littérature souligne l'importance d'évaluer la performance, la force musculaire et l'état psychologique, leur validité prédictive demeure incertaine. De plus, le délai de reprise, très variable (de 6 mois à plus d'un an), ne constitue pas en soi un critère fiable mais pourrait être envisagé comme une variable cible dans un modèle prédictif. Cette approche s'inscrit dans la logique du continuum de retour au sport, distinguant le retour à l'activité, le retour au sport et enfin le retour à la performance. Cet article propose ainsi de présenter les critères existants et d'examiner l'apport des modèles d'auto-apprentissage pour affiner la prédiction du retour au sport.

ABSTRACT. The desire to regain a comparable level of mobility or sporting performance, without apprehension and without the risk of re-injury, after Anterior Cruciate Ligament (ACL) reconstruction is legitimate, yet it remains rarely achieved. To date, no Return To Sport (RTS) protocol has been fully validated. The criteria currently employed lack standardization and, at times, objectivity, which limits their clinical applicability. Although the literature emphasizes the importance of evaluating performance, muscle strength, and psychological readiness, the predictive validity of these parameters remains uncertain. Moreover, the time to RTS, which varies widely (from six months to over a year), is not a reliable criterion in itself but could instead be considered a target variable within a predictive model. This perspective aligns with the RTS continuum, which differentiates between return to activity, RTS and return to performance. The present article reviews existing criteria and examines the potential contribution of machine learning models to improving RTS prediction.

MOTS-CLÉS. Ligament Croisé Antérieur (LCA), Retour au sport, Critères d'évaluation après une reconstruction du LCA, Modèle d'auto-apprentissage, Intelligence Artificielle (IA).

KEYWORDS. Anterior Cruciate Ligament (ACL), Return To Sport (RTS), Evaluation criteria after ACL reconstruction, Machine Learning, Artificial Intelligence (AI).

1. Introduction

It is essential to recognize that for anyone who has undergone trauma or surgery, the main objective is to return to a quality of life comparable to that prior to the operation. The patient is therefore expected to be able to resume all activities consistent with his or her expectations and goals. Unfortunately, some patients are unable to achieve this level of recovery. Between the risk of re-injury and psychological apprehension, returning to sport can be challenging, as highlighted by Burland *et al.*, [BUR 18]. Studies have estimated that only around 55% of sports patients return to competitive sport, with a 15-30% higher risk of re-injury ([ARH 23], [BUR 18], [GRI 20], [HON 23], [KOT 22], [PAR 22]). Therefore, there remains considerable scope for developing novel approaches to optimize each individual's return to normal life.

Increasingly in medicine and more specifically in orthopaedics, Artificial Intelligence (AI) represents a genuine asset for identifying individuals at risk of injury (particularly athletes), detecting potentially harmful movements, and establishing personalized criteria. These capabilities make it possible to optimize prevention and rehabilitation strategies.

Applying these principles could lead to significant advances, both socially and economically. Indeed, in the case of an Anterior Cruciate Ligament (ACL) rupture, surgery is almost systematic and requires a rehabilitation and re-education phase before returning to sporting activity. The timing and intensity of the Return To Sport (RTS) are crucial questions for clinicians and physiotherapists. To address these, they use rehabilitation criteria of varying degrees of relevance. However, this decision is of great importance, as it can strongly influence the risk of recurrence and, consequently, accelerate the early deterioration of the knee joint.

Unfortunately, even today there is no consensus or validated framework regarding the parameters to be taken into account when patients RTS after ACL reconstruction [GOK 22], [TED 20]. However, the literature does highlight certain parameters that are clinically accepted. For example, Kaplan and Witvrouw agree that there are five main criteria commonly used. These include psychological factors (e.g. IKDC questionnaires), performance and functional tests (e.g. jump tests), strength assessments (e.g. isokinetic dynamometry), time-related aspects and both non-modifiable (age, sex, etc.) and modifiable (type of sport practised) risk factors [KAP 19].

The aim of this article is to present the main criteria used to assess RTS after ACL reconstruction and to compare them with those selected in studies employing AI models. This initial state-of-the-art review aims to highlight the importance of a multidisciplinary approach that integrates both patient-reported outcomes and objective data.

Firstly, we will review the essential aspects of the ACL, including knee anatomy, possible movements and the main causes of rupture. The second part will describe the criteria already identified in the literature. Finally, the potential contributions of AI models will be presented, followed by a comparison between the criteria commonly used and those adopted in various AI-based studies.

1.1. *Anatomy of the knee*

The knee joint is one of the most complex joints in the human body and is subject to considerable stress in both everyday activities and sports. It plays a crucial role in maintaining body stability and helping to prevent falls. Knee stability relies on three fundamental elements: the shape and congruence of the joint surfaces, the presence and orientation of the ligaments, and the surrounding muscle tone [MAR 19]. If any of these elements is compromised, the overall stability of the knee is reduced, increasing the risk of imbalance or injury.

1.1.1. *Joint*

A joint is defined as the point where two or more bones meet [GAR 17]. In the case of the knee, the femur, tibia and patella articulate within the same joint cavity, forming a tri-compartmental joint composed of the patellofemoral, medial femorotibial and lateral femorotibial compartments. The knee is a synovial joint, primarily permitting flexion and extension through the sliding of the femoral condyles on the tibial articular surfaces, with slight rotation when the knee is flexed. However, as the articular surfaces of these compartments are not highly congruent, knee stability depends heavily on both the passive structures - comprising the capsule, ligaments, and menisci - and the active muscular system, which provides periarticular support. The collateral ligaments restrict lateral and medial rotational movements, while the cruciate ligaments control antero-posterior translations and axial rotations of the tibia relative to the femur. The menisci absorb shocks and contribute actively to stability, preventing the femur from tilting laterally on the tibia [MAR 19].

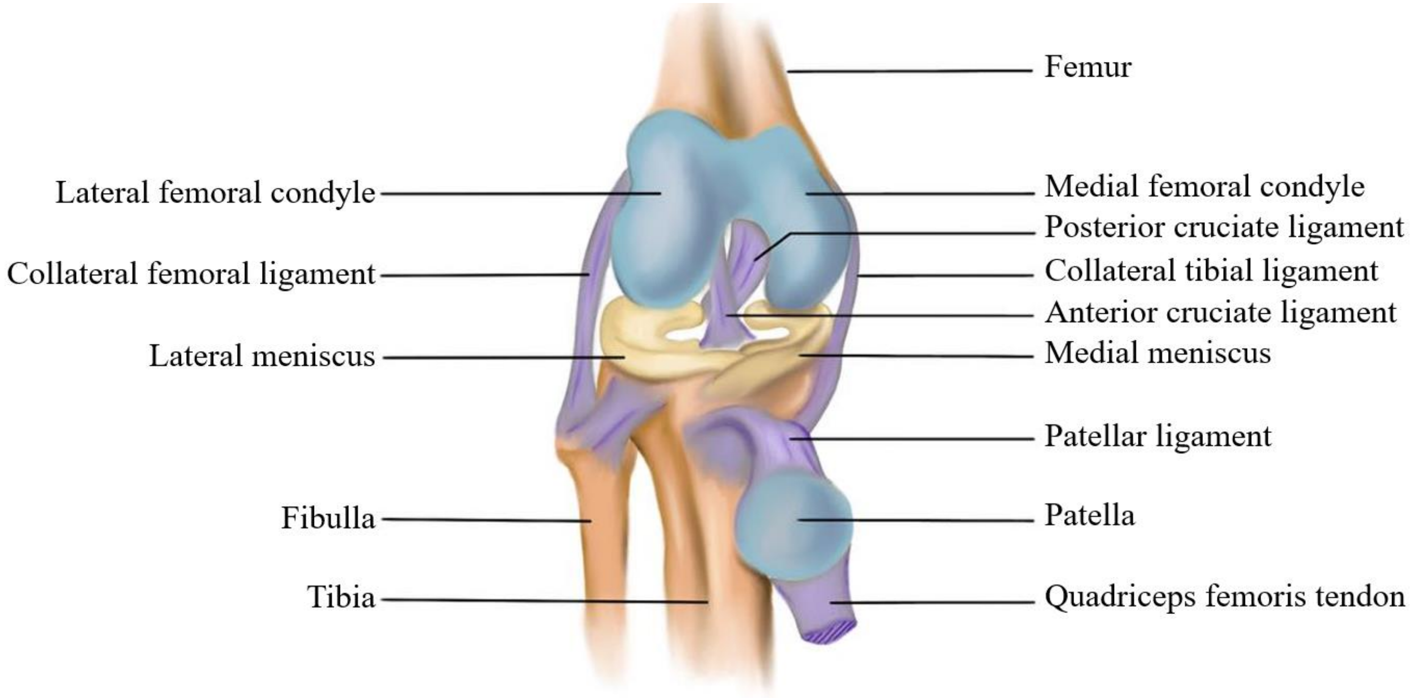

Figure 1. *Simplified representation of knee anatomy (originally from [MAR 19])*

1.1.2. *Ligaments*

Ligaments are fibrous connective tissues that connect bones and limit the range of motion to maintain joint stability. However, when a movement exceeds the physiological limits of a joint, ligaments may be subjected to excessive tension, leading to stretching or even rupture. It is important to note that a stretched ligament generally does not return to its original length, and healing is often slow and incomplete due to poor vascularisation [MAR 19].

In the knee, ligaments can be classified into two main categories: central ligaments and peripheral ligaments. The central ligaments comprise the ACL and the Posterior Cruciate Ligament (PCL). The ACL attaches to the anterior edge of the medial tibial plateau, anterior to the anterior horn of the medial meniscus, and runs posteriorly and superiorly toward the medial aspect of the lateral femoral condyle [BOD 19]. It limits anterior translation of the tibia relative to the femur, particularly when the knee is extended and plays a crucial role in stabilising the knee under load. The PCL, by contrast, attaches posteriorly to the retro-spinal surface of the tibia and to the lateral surface of the medial femoral condyle. It controls posterior translation of the tibia, particularly when the knee is flexed, but does not contribute significantly to the stabilisation of the loaded knee.

Peripheral ligaments include the Medial Collateral Ligament (MCL) and the Lateral Collateral Ligament (LCL). The MCL connects the medial epicondyle of the femur to the upper and medial aspect of the tibia, and its primary function is to resist valgus stresses, i.e., forces that tend to open the joint medially. The LCL extends from the lateral epicondyle of the femur to the head of the fibula and opposes varus movements, which correspond to an outward, lateral opening of the joint.

1.1.3. *Muscles*

Muscles play a fundamental role in generating movement, maintaining posture and providing stability to the knee joint. The primary movement of the knee is flexion-extension, which occurs through a combined rolling and sliding mechanism of the femoral condyles on the tibial articular surfaces. In addition to these primary movements, the knee also allows slight rotational movements, particularly when it is flexed [MAR 19].

Twelve primary muscles are involved in knee movements. Among these, the hamstrings, comprising the biceps femoris, semitendinosus and semimembranosus are the main agonists for knee flexion. The semitendinosus also contributes to internal rotation, while the biceps femoris assists with external rotation. In contrast, the quadriceps femoris group, consisting of the rectus femoris, vastus lateralis, vastus medialis and vastus intermedius, is responsible for knee extension [MAR 19].

Other muscles, although considered secondary or accessory, also contribute to knee flexion. These include the sartorius, gracilis, gastrocnemius, plantaris and popliteus. The popliteus also plays an active role in internal rotation of the knee. The coordinated action of these muscle groups allows precise control of movement and contributes to the overall stability of the joint [MAR 19].

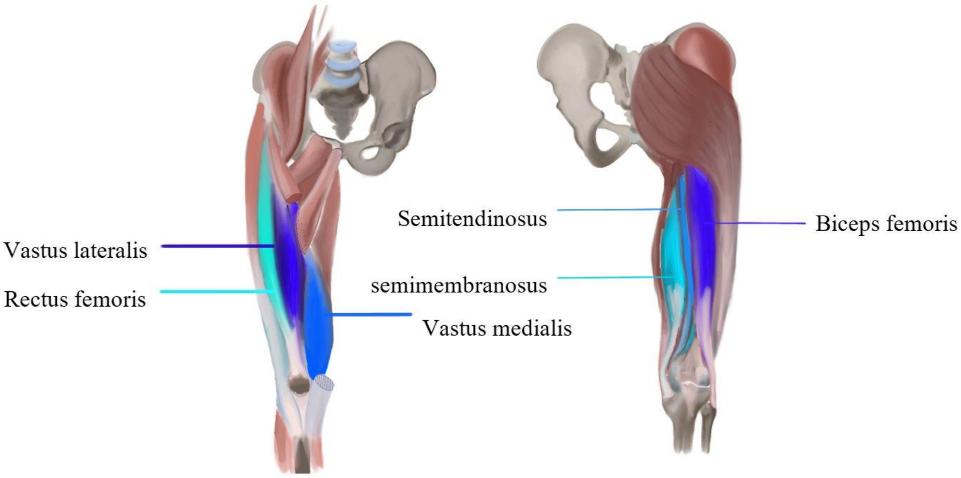

Figure 2. *a) Knee extensor (quadriceps femoris) and b) knee flexor (hamstring group) (adapted from [MAR 19])*

1.2. *Kinematics of the knee*

In anatomy, joint movements are described using reference planes and axes. The sagittal plane is a vertical plane passing through the midline of the body, dividing it into left and right parts. Movements in this plane include flexion, which corresponds to a folding of the joint that reduces the angle between two segments, and extension, which is the opposite movement. The frontal plane is a vertical plane separating the body into anterior and posterior parts; it is in this plane that abduction (movement of a limb away from the the median plane) and adduction (movement towards the midline) occur. Finally, the transverse plane is horizontal, dividing the body into upper and lower parts. It is associated with rotational movements around the longitudinal axis [MAN 12], [MAR 19].

To define knee movements more precisely, Grood and Suntay proposed a sequence of three successive rotations (Euler angles) [GRO 83]. The first rotation corresponds to flexion/extension, defined about the medio-lateral axis of the femoral segment. The final rotation corresponds to internal/external rotation, defined about the longitudinal axis of the tibial segment, while varus-valgus rotation is defined about a floating axis, which corresponds to the common perpendicular of the other two axes. They also proposed defining knee translations along these same axes. This approach was later adopted and generalised in the recommendations of the International Society of Biomechanics for all joints [WU 02].

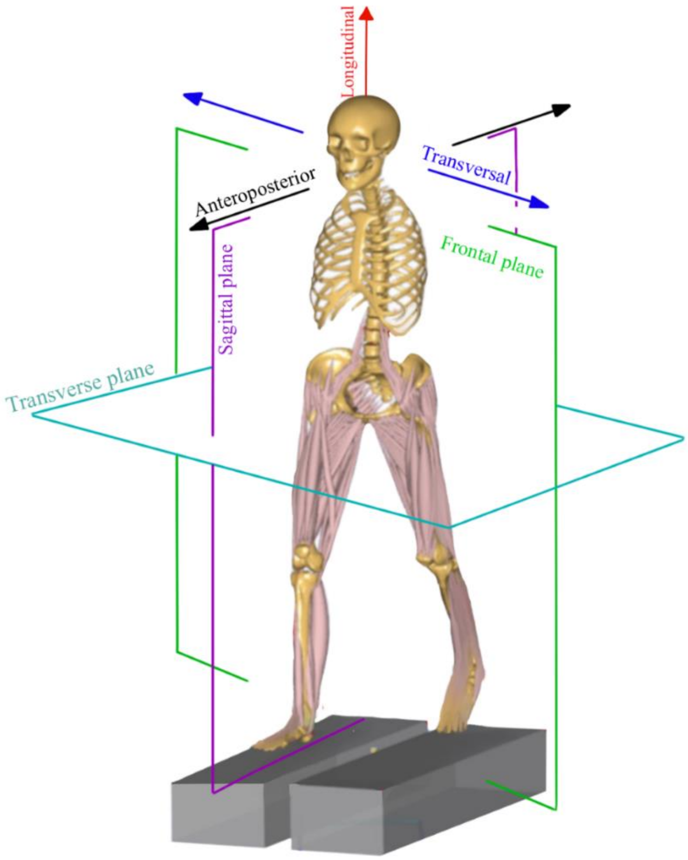

Figure 3. *Anatomical reference planes and axes*

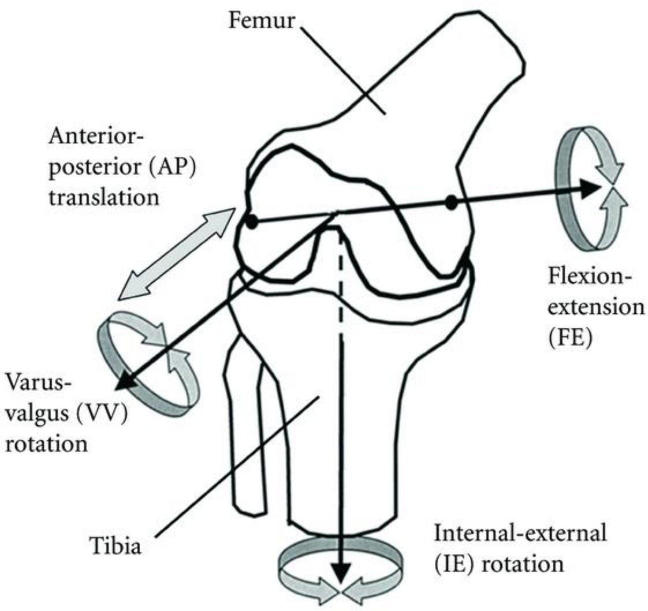

Figure 4. *Possible knee movement (from [AMI 12], [GRO 83])*

1.3. *Causes of injury*

The knee is a joint capable of absorbing substantial vertical forces, reaching up to seven times body weight, particularly during running or jumping [MAR 19]. However, it remains more susceptible to lateral forces, especially when these exceed the resistance capacity of the ligaments. It is under such conditions that an ACL rupture may occur.

Several mechanisms can lead to ACL injury, depending on the type of sport, the severity of the trauma, and the morphology and anatomy of the knee [ROD 14]. The most common mechanisms are as follows:

Varus internal rotation (Figure 5): This mechanism occurs when torsion is applied to the trunk and thigh while the foot remains fixed on the ground. It is typically observed in skiing, when the ski remains planted in the snow and the boot does not release, or in cleated sports such as football or rugby, where the foot's grip on the ground prevents it from moving during rotation (cf. [BOD 19], [ROD 14]).

Figure 5. *Diagram of the varus-internal rotation mechanism*

Valgus–flexion–external rotation (Figure 6): This mechanism involves a sudden pivoting movement of the knee towards the inside, often occurring during a rapid change of direction, a slip or a traumatic event. It is commonly observed in team sports such as handball, basketball and football [BOD 19], [ROD 14].

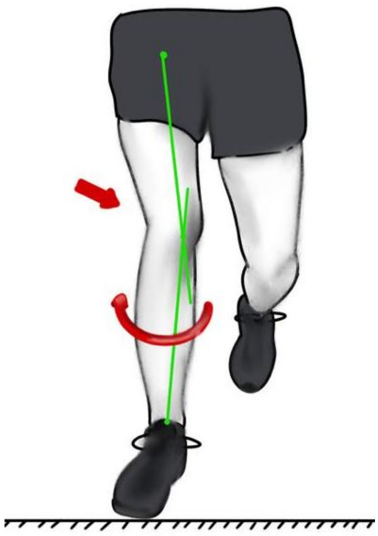

Figure 6. *Diagram of the valgus-flexion-external rotation mechanism*

Hyperextension of the knee can occur in two distinct situations (Figure 7). Firstly, it may occur anteriorly, particularly during a sudden movement such as a powerful football shot. Alternatively, it may occur posteriorly, most often as a result of a direct impact on the anterior aspect of the knee, as commonly observed when the leg is resting on the ground after a tackle in rugby. In both cases, these extreme movements can exceed the resistance of the anterior cruciate ligament, potentially leading to its rupture [BOD 19], [ROD 14].

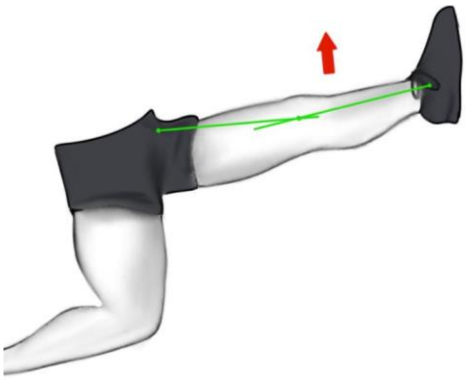

Figure 7. *Diagram of hyperextension mechanism*

Hyperflexion: Although less common, an ACL injury can occur when the knee flexes excessively, for instance during a fall from a crouched position with poorly controlled landing [BOD 19], [ROD 14].

Isolated ACL lesions are the most frequent, representing approximately 70% of cases [BOD 19]. However, in more complex injuries, other anatomical structures of the knee, such as the menisci, Medial Collateral Ligament (MCL), Lateral Collateral Ligament (LCL), and others, may also be involved.

Owing to the limited vascularisation of the ligaments, spontaneous healing is seldom possible in cases of complete rupture. In most instances, reconstructive surgery is required to restore knee stability and enable a return to sporting activity. However, this return must be preceded by a period of rehabilitation. The challenge, therefore, lies in determining when the patient can safely resume sport, highlighting the importance of using appropriate criteria. What remains to be fully understood in practice is the manner in which patients RTS and how their progress is assessed.

2. Return to sport

Returning to sport after an ACL injury can be a considerable challenge for many patients. Statistics from the scientific literature supports this: according to a study by Toale *et al.*, although 83.7% of patients resume sporting activity, only 57.3% return to their previous level of intensity, while 34.6% do so at a lower level [TOA 21].

In most cases, psychosocial factors are recognised as the primary contributors to failure to RTS. Fear of re-injury, lack of confidence in the reconstructed knee, and changes in life priorities all constitute obstacles to a full recovery [BUR 18], [TOA 21].

However, this fear is not unfounded, as the risk of recurrence is substantial. For example, Tan *et al.*, reported that in patients under the age of 20, the re-injury rate reaches 20%, with an estimated risk of knee osteoarthritis ranging from 50% to 80% within ten years following the injury [TAN 23]. Other studies estimate the rate of surgical revision at approximately 15% [ARH 23], [FIG 25], [HON 23], with a higher risk of re-rupture observed in women [HON 23].

The study by Grindem *et al.*, confirms this risk: among their cohort of 213 patients who underwent ACL reconstruction, 10.8% suffered a second injury. Recurrence was defined as either a new rupture of the graft (ipsilateral) or a rupture of the contralateral ACL, with the former being the most common [GRI 20].

Kotsifaki *et al.*, report even higher figures, with an ipsilateral recurrence rate of up to 19% and a contralateral injury risk of up to 22%. Regarding joint complications, they estimate the prevalence of tibiofemoral osteoarthritis at 35% and patellofemoral osteoarthritis at 15% [KOT 22].

Overall, individuals who have previously suffered an ACL injury are 15 times more likely to experience another injury than those who have never been injured [MAN 19].

In this context, it is crucial to support patients not only physically but also psychologically. Being able to demonstrate their progress objectively, particularly through quantitative comparisons between the operated and healthy leg, can help boost their confidence and reduce anxiety about returning to sport. A multidisciplinary approach based on measurable data can therefore play a key role in reassuring patients and ensuring the success of their rehabilitation.

Persistent functional limitations, particularly muscle strength deficits, imbalances between the limbs and impaired proprioception, represent another major obstacle to a RTS [REA 21]. These factors clearly justify the need for a multidisciplinary approach when assessing RTS [GOL 24].

It is therefore essential to determine precisely when a patient can resume physical activity and at what intensity. For example, a gradual return to low-intensity activity may be envisaged at around six months, followed by a full return to pre-injury performance levels at approximately twelve months, depending on the progress of functional recovery.

The success of a structured RTS protocol can reduce the risk of ACL re-injury by up to 60% [GOK 22]. However, although several clinical criteria for RTS are now widely used in rehabilitation, there remains limited scientific validation of their true predictive value for a successful RTS. While their use is supported by clinical consensus, few studies have demonstrated their effectiveness in accurately predicting the risk of re-injury.

The aim of this article is therefore to provide an overview of the main criteria currently used in clinical practice to assess readiness for RTS in patients who have undergone ACL reconstruction. It also seeks to identify the criteria selected by self-learning models and to compare these with those commonly employed in clinical practice.

2.1. *Criteria*

As there remains no consensus on the criteria for determining when a patient is ready to RTS, a literature review was conducted to identify the most commonly used measures.

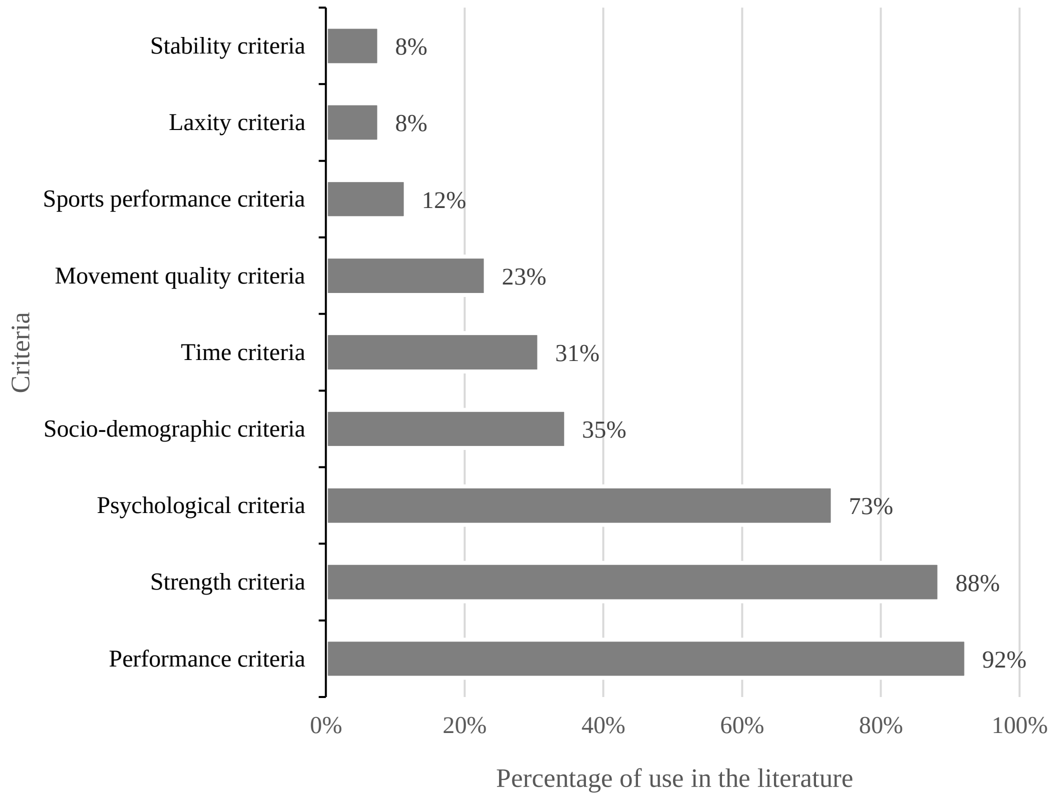

Figure 8. *The various criteria identified from the bibliographic search*

Based on this research, nine main criteria were identified to guide the decision to RTS following an ACL injury. The most frequently used criterion was functional performance, often assessed using jump tests (Figure 8), and was reported in 92% of cases (cf. [ARH 23] and [BEL 24]).

Based on this research, nine main criteria were identified to guide the decision to RTS after an ACL injury. The most frequently used criterion was functional performance, often assessed using jump tests (Figure 8), and was reported in 92% of cases (cf. [ARH 23]; [BEL 24], [BRI 22], [CRO 24], [DAV 17], [GOK 17], [GOK 22], [GOL 24], [GRI 20], [HON 23], [KAP 19], [KIN 21], [LOS 22], [LYN 15], [MAN 19], [MEI 22], [O'MA 18], [PAT 22], [PUL 24], [RAM 17], [REA 21], [VAN 25], [WEB 19] and [WEL 24]). This was followed by assessment of knee extensor and flexor muscle strength, used in 88% of studies (Figure 8) (cf. [ARH 23], [BEL 24], [CRO 24], [DAV 17], [GOK 17], [GOK 22], [GRI 20], [HON 23], [KAP 19], [KIN 21], [LYN 15], [MAN 19], [MEI 22], [O'MA 18], [PAT 22], [PUL 24], [REA 21] and [VAN 25]). Psychological factors, including confidence, fear of re-injury, and motivation, were considered in 73% of cases (Figure 8) (cf. [ARH 23], [BRI 22], [CRO 24], [DAV 17], [GOL 24], [GRI 20], [HON 23], [KAP 19], [LYN 15], [MEI 22], [NOT 16], [O'MA 18], [PAT 22], [RAM 17], [TOA 21], [VAN 25], [WEB 19] and [WEL 24]). Around 35% (Figure 8) of the studies also highlighted the importance of socio-demographic criteria, such as age or level of sport [ARH 23], [BEL 24], [BRI 22], [CRO 24], [GRI 20], [KAP 19], [NOT 16], [TOA 21] and [VAN 25]. Temporal criteria, although widely applied in clinical practice, were cited as the primary decision-making factor in only 23% of publications (Figure 8). (cf. [GOK 22], [GOL 24], [KAP 19], [MAN 19], [MEI 22], [RAM 17], [REA 21] and [WEB 19]). Other factors, although considered secondary, were also reported, such as the assessment of joint laxity [DAV 17], [RAM 17], knee stability [BEL 24], [PUL 24], and sport-specific criteria tailored to the patient's discipline [DAV 17], [PUL 24].

The following paragraphs provide a detailed overview of the definitions and relevance of each criterion identified in the literature, together with an assessment of their respective usefulness.

2.1.1. *Performance criteria*

The performance criteria used to assess RTS after ACL reconstruction are mainly based on jumping exercises, which serve as key tools for evaluating a patient's locomotor abilities [GOL 24]. There are several types of jump tests, including the single leg hop for distance, the vertical jump (Countermovement Jump, CMJ), repeated jumps within a set time, jumps incorporating changes of direction and rotational jumps. However, not all of these tests are equally relevant in accurately reflecting the functional status of the reconstructed knee. Straightforward jumps, although frequently used, are considered less sensitive for detecting dysfunction or asymmetry between the lower limbs. In contrast, more complex jumps, such as medial (inward or outward) or rotational jumps, are more likely to reveal biomechanical compensations or deficits [STR 25].

Another important consideration concerns the assessment method. When evaluation is based solely on visual observation, it can introduce significant bias in terms of reliability and reproducibility. Objective parameters, such as jump height, number of repetitions within a set period, or ground reaction forces measured using force platforms, provide more accurate and comparable data. In summary, although jump tests remain central to performance-based criteria, their selection and method of analysis must be carefully adapted to ensure a valid and reliable assessment of post-operative knee function.

2.1.2. *Strength criteria*

Following the performance criteria used to assess RTS after ACL reconstruction, the evaluation of muscle strength is a central component. It can be assessed in various ways, including through leg press exercises, open-chain tests, or isokinetic dynamometers, which are regarded as the gold standard owing to their accuracy and reliability. However, this technique remains costly and requires specialised equipment, which limits its accessibility. Isokinetic strength tests measure the patient's ability to generate force against resistance, particularly in the knee flexors and extensors. Increasingly, studies are extending this analysis to other muscle groups, such as those responsible for internal and external rotation of the hip [CRO 24], to achieve a more comprehensive understanding of functional deficits. Results are typically expressed using the Limb Symmetry Index (LSI), which compares the maximum force generated by the operated leg with that of the healthy leg. According to the literature, an LSI of 90% or higher is generally considered an acceptable threshold for validating muscle recovery. However, this method has a significant limitation. Surgery, combined with an extended period of inactivity, leads to muscle atrophy in both limbs, including the non-operated leg. Consequently, comparing two weakened limbs may overestimate the recovery of the operated leg [GOK 22]. This bias is particularly concerning because rehabilitation often targets only the injured leg, whereas overall physical fitness, especially of the healthy limb, plays a crucial role in preventing re-injury. Therefore, while muscle strength tests are essential, their results must be interpreted carefully and considered within the context of a comprehensive assessment of the patient's overall condition.

2.1.3. *Psychological criteria*

The patient's psychological state is also receiving increasing attention. In recent years, a growing body of research has emphasized the importance of confidence, stress perception, and motivation in determining the success of RTS (cf. [CRO 24] and [BUR 18]). Validated assessment tools, such as the IKDC, ACL-RSI, KOOS, and the Perceived Stress Scale (PSS-10), are used to evaluate patients' psychological responses to their physical condition and the prospect of returning to activity. These questionnaires offer valuable insight into the patient's mental state, which can significantly influence functional performance. Some studies indicate that patients with high confidence in their knee perform better in physical tests before returning to sport. However, other research suggests that patients who are less confident but achieve objective test thresholds may actually face a lower risk of re-injury [PAT 22]. This underscores the complexity of interpreting these questionnaires: while they offer valuable insight into the patient's psychological state, their results must be considered cautiously and cross-referenced with objective criteria to inform the final decision on RTS.

2.1.4. *Socio-demographic criteria*

Among the criteria influencing RTS after ACL reconstruction, socio-demographic factors play a significant role, although they are non-modifiable or difficult to quantify. Elements such as age and gender can impact the speed of recovery, the response to rehabilitation, and consequently the ability to regain an adequate level of performance. Other factors, such as occupation, availability of rehabilitation time, and family circumstances, can also affect the rigour and regularity of post-operative follow-up [BUR 18]. Lifestyle habits, such as smoking, as well as the type of activity undertaken (pivoting sport, leisure, competitive), must also be considered [NOT 16]. Finally, the quality of social and family support can positively influence a patient's motivation, commitment to rehabilitation, and therefore their RTS. Although these parameters are sometimes difficult to quantify objectively, taking them into account in the overall assessment of the patient allows treatment to be better tailored to the individual, and potential obstacles to a return to performance can be anticipated

2.1.5. *Time criteria*

The time factor is a frequently cited criterion in assessing RTS after ACL reconstruction, although its use alone is increasingly questioned. Two timeframes are generally considered: the time between injury and surgery, which may influence initial muscle and joint recovery, and, above all, the time elapsed since the operation (ACL reconstruction). Many studies agree that RTS should not be considered before nine months post-operatively, as an earlier return is associated with a significantly increased risk of re-injury [GOK 22]. This recommendation underscores the importance of regular, structured follow-up, with repeated functional assessments at different stages of rehabilitation. The time criterion alone cannot guarantee optimal recovery; it must be combined with objective assessments of performance, strength, biomechanics, and psychological state to guide a gradual, safe and personalised return to sporting activity.

2.1.6. *Movement quality criteria*

Movement analysis is an advanced criterion for obtaining precise data on joint kinematics, such as joint angles during movement. This technology allows for the identification of altered motor patterns and the detection of persistent asymmetries between limbs [LOS 22] and [TED 20], sometimes invisible to the naked eye. This is particularly relevant in the context of RTS, as certain biomechanical alterations may persist even in patients who have passed other functional tests. However, these analyses often require expensive equipment and complex, time-consuming data processing, which limits their use in routine clinical practice. Alternatives, such as 2D markerless video analysis, exist but remain difficult to standardise and apply reliably in a clinical context. Despite these constraints, integrating these tools into the assessment of RTS offers significant added value by providing a more detailed understanding of movement quality and the risk of compensation or re-injury [GOK 22].

2.1.7. *Sports performance criteria*

In addition to standardised tests, there are performance criteria specific to the sport practised by the individual. These tests allow for the design of a personalised assessment protocol, directly linked to the functional and movement demands of the sport in question. For example, the movements assessed will differ between a footballer, a skier, and a basketball player. Incorporating these sport-specific criteria not only enables the athlete to be better prepared to return to their previous level but also helps identify any motor deficits in real-life sporting situations that would not be detected during generic tests.

2.1.8. *Laxity criteria*

Knee laxity is a criterion that is rarely assessed in clinical practice, even though it is directly related to ligament stability [DAV 17]. It can be measured objectively using instrumented tools such as the KT-1000 arthrometer, which quantifies static ligament laxity. In the absence of specialised equipment, this assessment can be performed using manual clinical tests such as the Lachman test, the anterior drawer test, or the pivot shift test. The aim of these tests is to document knee stability, a fundamental element for a safe RTS. However, their sensitivity and reproducibility are highly dependent on the clinician's experience, and the results are sometimes less reliable than those obtained with instrumented measurements. Nevertheless, assessing laxity can be useful, particularly if there is any doubt about the quality of the reconstruction or the persistence of functional instability, even when other performance criteria are considered satisfactory.

2.1.9. *Stability criteria*

Stabilometry is not often used to assess RTS after ACL reconstruction. However, it can be employed to measure an individual's ability to maintain balance, which partly reflects the quality of neuromuscular control and proprioception. This assessment becomes particularly relevant when combined with an analysis of ground reaction forces, especially using force platforms. This allows for precise data on the dynamic stability of the knee in single-leg support, under conditions that closely replicate the stresses encountered in sporting activity. Although its use in clinical practice remains limited due to cost, stabilometry could provide a valuable objective complement to more traditional tests, particularly for detecting persistent imbalances or asymmetries.

Having introduced and described the criteria currently in use, we can now turn to those employed and selected by studies utilising AI models.

3. The benefits of artificial intelligence

The lack of clinical consensus regarding the most relevant criteria and protocols for guiding the decision to RTS after an ACL injury is prompting researchers and clinicians to explore new approaches to improve assessment and decision-making. Among these emerging avenues, there is growing interest in the use of machine learning models. These models are based on the analysis of large quantities of clinical and functional data, enabling predictive patterns to be identified from accumulated experience [KOK 22]. They could therefore not only facilitate clinical assessment but also help to objectively validate certain criteria or protocols currently in use. By integrating a variety of data, including biomechanical, psychological, temporal, and socio-demographic factors, these innovative methods offer a promising opportunity to individualise the RTS process and make it more reliable, while simultaneously strengthening the scientific basis for clinical decisions [AND 24].

Wu *et al*., [WU 18] [WU 23] developed an innovative and automated method for classifying gait patterns between individuals with Anterior Cruciate Ligament-Deficient knees (ACL-D group) and healthy subjects (ACL-I group). By combining Phase Space Reconstruction (PSR), Euclidean Distance (ED), and neural networks (RBF), the authors extracted non-linear features from the knee kinematics recorded in six degrees of freedom during walking. Their method enabled gait patterns to be classified with an accuracy of up to 95.65%, surpassing conventional approaches. The study demonstrates that ACL-D knees exhibit significant alterations in joint kinematics, particularly in flexion-extension, internal-external rotation, and antero-posterior and proximal-distal translations. This non-invasive approach therefore offers promising potential as an aid in the clinical diagnosis of ACL deficiencies.

The study conducted by Richter *et al*., [RIC 19] aimed to objectively classify movement deficiencies in patients who had undergone ACL reconstruction using machine learning techniques. Various biomechanical exercises were employed to distinguish between the movements of patients undergoing rehabilitation and those of healthy subjects. The approach is based on feature extraction from kinematic and kinetic data, followed by the application of several classification algorithms. The performance of the models was assessed using cross-validation, analysing in particular the Area Under the Receiver Operating Characteristic (AUROC) curve, interpretability, sensitivity to outliers and computation time. The results indicate that certain exercises, such as the Double-Leg Drop Jump (DLDJ), provide the best classification performance. The study highlights the need to balance model complexity with the interpretability of the results.

In their study, Mandalapu *et al*., [MAN 19] explored the application of AI to the personalised classification of ACL injury patients, based on gait analysis using wearable inertial sensors. The aim was to distinguish healthy subjects from ACL patients and to identify the injured limb (left or right) using machine learning algorithms. The authors collected walking and light running data from 131 individuals (109 of whom were injured) via inertial sensors placed on the wrists, ankles, and sacrum. An original inter-segment causality approach (Phase Slope Index) was used to generate causality matrices between limbs. Several machine learning models (AutoMLP, Random Forest (RF), Support Vector Machine (SVM), etc.) were then trained on these data. The best classification results were obtained using neural networks and AutoMLP, with an AUC of up to 0.897 for predicting the affected limb in women. This study demonstrates that AI can extract complex data from motor imbalances that are often difficult to detect clinically, and that it could be used to assess functional recovery and guide RTS after ACL reconstruction.

With a view to monitoring the recovery of athletes after ACL reconstruction, Tedesco *et al.*, [TED 20] conducted a study exploring the use of wearable motion sensors combined with machine learning techniques to differentiate the gait patterns of healthy rugby players and those who had undergone ACL reconstruction, even several years post-injury. Twelve male participants (six per group) performed direction-changing exercises on the field, equipped with inertial sensors on their legs. By extracting temporal and frequency characteristics from the captured signals, several machine learning models were tested, achieving an accuracy of up to 73.07% and a sensitivity of 81.8%. The results demonstrate that biomechanical differences persist in the long term after ACL reconstruction, despite a successful RTS

In the study by Taborri *et al.*, [TAB 21], the ability of machine learning algorithms to predict the risk of ACL injury was evaluated in female basketball players, using data from wearable inertial sensors and optoelectronic bars during unipodal jump (mCMJ) and Single Leg Squat (SLS) tasks. The Landing Error Scoring System (LESS) score, derived from video analysis, was used as a reference to classify athletes as at risk or not. Nine machine learning algorithms were tested to classify the players into two groups (at risk or not), including linear SVM, which achieved the best performance (accuracy of 96%, F1-score of 95%). The most important predictive features identified by the Variable Importance Method (VIM) were stability ellipse area (measured during landing), load absorption parameters (RMSxy, RMSz), and angular amplitude of the knee during the squat (θymax).

Kunze *et al.,* [KUN 21] developed and compared six machine learning algorithms to identify the main predictors of clinically significant improvement in patients two years after ACL reconstruction. To achieve this, the authors monitored whether the IKDC score at two years showed a clinically significant improvement (MCID).

Sritharan *et al.,* [SRI 22] used an approach based on pattern recognition and musculoskeletal modelling to identify biomechanical differences between individuals who had undergone ACL reconstruction and healthy control subjects during the landing phase of a unipodal forward jump. The data were then transformed into principal components using Principal Component Analysis (PCA) to reduce dimensionality and identify discriminating factors. In total, ten principal components and eight associated components were identified, revealing subtle but significant alterations in ACL reconstruction patients, including reduced knee flexion, reduced extensor moment, decreased activation of the quadriceps and soleus, and instability in the frontal and transverse planes. This AI-based method enables the detection of biomechanical asymmetries that are invisible to the naked eye and could ultimately contribute to the decision to RTS after ACL reconstruction.

Then, in order to analyse and identify the biomechanical gait parameters associated with ACL injuries, a method combining machine learning and statistical analysis was introduced by Kokkotis *et al*., [KOK 22b].The authors analysed data from 151 participants divided into three groups (healthy, ACL-deficient, and ACL-reconstructed) on the basis of kinematic and kinetic measurements in the sagittal plane. Eight classification algorithms were tested, of which the SVM achieved the best performance with an accuracy of 94.95% on a set of 21 parameters. To interpret the model's decisions, SHAP (SHapley Additive exPlanations) analysis was used to identify the parameters that contributed most to the predictions. This approach highlighted important variables that are sometimes overlooked by conventional statistical analysis, demonstrating the added value of explainable methods. The study suggests that some biomechanical parameters are not fully restored after surgery and thus offers a promising tool for improving the diagnosis and rehabilitation assessment of patients after ACL injury.

In the study by Martin *et al*., [MAR 22], the use of machine learning to predict subjective failure of ACL reconstruction was examined, using data from the Norwegian Knee Ligament Registry (NKLR). Subjective failure was defined as a score below 44 on the KOOS quality of life scale two years after surgery. Among more than 20,000 patients, approximately 22% reported subjective failure. Four machine learning models were tested, with the generalised additive model (GAM) showing the best performance (AUC = 0,68). The study resulted in the development of a simple clinical calculator designed to estimate the individual risk of subjective failure, with the aim of improving patient counselling prior to surgery.

In their study, Lu *et al.,* [LU 22] developed two machine learning models based on Random Survival Forests (RSF) to predict the risk of secondary meniscal injury in patients who had undergone either ACL reconstruction or non-surgical management. The RSF models outperformed the K-Nearest Neighbours (KNN) model used for comparison, particularly for long-term predictions. In the ACL reconstruction group, the model achieved an AUROC of 0,80, indicating strong discriminative performance. This approach also enables the generation of individualised survival curves in real time, integrated into a dedicated web application. The study illustrates that AI can refine prediction of postoperative complications and support personalised clinical decision-making, such as determining the optimal timing for RTS to reduce the risk of secondary meniscal injury.

The article by Jurgensmeir *et al.*, [JUR 23] aimed to describe a machine learning method for predicting risk factors for secondary meniscal lesions following ACL reconstruction. By analyzing a cohort of 1187 patients with a median follow-up of 147 months, the authors identified a secondary meniscal tear rate of 11.7%, occurring on average 65 months post-ACL reconstruction. The best-performing model was a RF algorithm, which outperformed conventional logistic regression in terms of discriminatory power (AUROC = 0.79). The study thus highlights various risk factors and proposes a digital clinical decision support tool to inform patients and personalize postoperative recommendations. Overall, this work underscores the utility of AI in predicting long-term complications following ACL reconstruction.

Still using a machine learning approach, Zhang *et al.*, [ZHA 24] employed an ensemble algorithm (WAV – Weighted Average Voting) to predict individual risk of clinical failure following ACL reconstruction. Using a cohort of 432 patients who underwent double-bundle anatomical reconstruction, the authors compared four classical machine learning models (XGBoost, RF, LightGBM and AdaBoost) and developed an ensemble learning model incorporating their weighted predictions. Eight major key predictor variables were identified, including preoperative laxity, time from injury to surgery, participation in competitive sports and posterior tibial slope. The WAV model demonstrated excellent performance (AUC = 0.9139), outperforming the individual models, and served as the basis for an interactive web application accessible to clinicians and patients. This application provides a personalised assessment of failure risk, offering a practical tool for preoperative counselling and optimising post-surgical management.

The studies reviewed highlight the substantial progress of machine learning methods in the field of movement analysis, particularly for the assessment of ACL injuries. These innovative approaches are capable of detecting subtle changes in gait and predicting the risk of post-operative failure with increasing accuracy. However, their application remains largely confined to experimental research. Indeed, their implementation in routine clinical practice is still limited, primarily due to practical constraints such as lack of time, financial resources, dedicated space and the complexity of measurement devices. Consequently, although promising, these technologies continue to face challenges in becoming integrated into the day-to-day management of patients with ACL injuries, particularly within conventional care settings, where technical and human resources are often limited.

3.1. *Selected criteria*

Based on the studies included in this literature search on the use of machine learning models in the post-operative phase after anterior cruciate ligament reconstruction, it is interesting to examine the types of factors identified as predictive by these models (Figure 9).

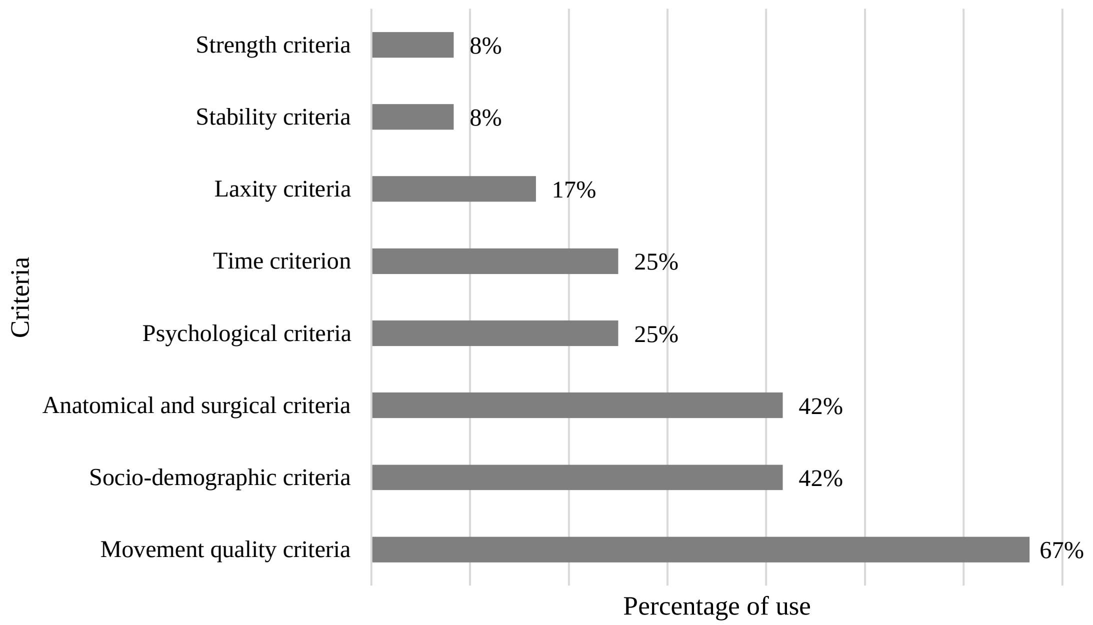

Figure 9. *Percentage of use of the different criteria used in the studies selected for the literature review*

In approximately 67% of cases (Figure 9), quality of movement was selected as a predictive factor through the analysis of various functional movements, such as walking or jumping. These biomechanical parameters frequently included knee flexion ([KOK 22b], [SRI 22] and [TED 20]), joint amplitude in different planes, and joint moments (extension, abduction/adduction, rotation) at the knee, as well as at the hip, trunk, and ankle. Ground reaction force, where it could be measured, was also identified as a recurrent predictive factor.

Socio-demographic criteria were also widely considered, with Body Mass Index (BMI) and age being the most frequently cited factors. Secondary factors included the type of sport practiced and previous surgical history. Similarly, anatomical and surgical factors, such as reconstruction technique and associated lesions, were taken into account in several models.

Psychological criteria were considered in 25% of the studies (Figure 9), primarily through self-assessment of pain. Temporal criteria, also reported in 25% of cases, encompassed two main predictive variables: the time interval between injury and surgery, and the time interval between surgery and RTS. Laxity, assessed both pre- and post-operatively, was used as a criterion in 17% of studies, whereas muscle stability and strength were included in only 8% of cases. Regarding muscle strength-related factors, their evaluation varied considerably depending on the specific protocol employed in each study.

It is important to note that each study employed its own evaluation protocol, with distinct methodological choices and measured parameters. This variability complicates direct comparisons of predictive factors across studies and limits the ability to identify, through a simple literature review, the most decisive variables in a universal manner.

4. Comparison of criteria

In the literature, the criteria most commonly used clinically to assess RTS following ACL reconstruction are performance, muscle strength and psychological factors. However, research incorporating machine learning models has relied only marginally on these parameters. These models primarily focus on analysing movement quality, which constitutes a key predictive criterion.

Nevertheless, the clinical integration of such measurements remains limited due to logistical constraints, including the need for specialised equipment (such as motion capture cameras or force platforms) and substantial preparation time.

Some studies have attempted to overcome these limitations by using more accessible tools. For example, the study by Chaaban *et al.*, [CHA 21] investigates the combined use of inertial sensors (IMU) and machine learning algorithms to estimate knee biomechanical parameters (vGRF, flexion angle, extension moment, absorption) during a bilateral jump-landing task. These findings highlight the potential of AI to provide a lighter, post-operative assessment tailored to the clinical context.

Performance criteria, although widely employed in clinical practice, are also underrepresented in machine learning models. Parameters such as jump height are not captured at all in these studies. Conversely, jumping exercises are extensively used to assess movement quality. This observation is further supported by the study by Straub and Powers [STR 25], who confirmed these findings in their literature review of prospective studies evaluating factors influencing a first ACL injury.

Socio-demographic criteria play a relatively important role in studies employing machine learning models, often to a greater extent than in traditional clinical approaches. Among the most frequently identified predictive factors are age and Body Mass Index (BMI), as well as elements related to patients' sports profiles, such as the type and level of practice. These criteria are particularly relevant given that certain sports carry a substantially higher risk of ACL rupture than others, which fully justifies their inclusion in predictive models.

Then there are the psychological criteria, which, although essential in the decision to RTS, are still little used in automated approaches. They are often used to create sub-groups (e.g. via self-assessment scores) but rarely included as explanatory variables in predictive models. This caution is partly explained by the subjective nature of these measures, which are liable to introduce biases. Some studies have also shown that high psychological scores are associated with better performance in RTS tests, but also with an increased risk of ACL recurrence, which highlights the complexity of their interpretation.

Psychological criteria, although essential for decisions regarding RTS, remain scarcely incorporated into automated approaches. They are often employed to define subgroups (e.g., via self-assessment scores) but are rarely included as explanatory variables in predictive models. This caution is partly attributable to the inherently subjective nature of these measures, which may introduce bias. Some studies have also demonstrated that high psychological scores are associated with better performance in RTS tests, yet paradoxically with an increased risk of ACL reinjury, underscoring the complexity of their interpretation.

The so-called anatomical and surgical criteria primarily include factors such as knee morphology (e.g., posterior tibial slope), the type of graft fixation, and the presence of associated lesions at the time of ACL rupture, such as cartilage damage. However, these parameters are not widely employed in clinical practice, largely because some, such as the precise measurement of the tibial slope, require advanced medical imaging. Other information, such as injury history or type of surgery, could however be readily incorporated into predictive models within a clinical context.

Although temporal criteria are widely recognised as important benchmarks in decisions regarding RTS [GOL 24], they are underrepresented in studies employing machine learning. Nevertheless, the time between injury and surgery, and between surgery and RTS, appear to be relevant indicators of a patient's functional status.

Laxity criteria, such as preoperative laxity, are sometimes considered but remain generally underrepresented, as are parameters of joint stability. Surprisingly, muscle strength, which plays a central role in knee stability, is seldom included in these models. In clinical practice, however, it remains one of the essential indicators of a patient's ability to resume physical activity without risk.

It should be noted that these different criteria are never used in isolation in predictive models. Their predictive power always emerges in combination with other factors, which underlines the importance of a multifactorial approach to accurately assess the status and prospects of patients returning to sport after ACL reconstruction.

5. Conclusion and perspectives

One of the main current challenges in assessing RTS following ACL reconstruction is the lack of standardised RTS criteria. These criteria sometimes lack scientifically validated objectivity, which limits their effectiveness and transposability to clinical practice. Although recommendations in the literature concur on the importance of using performance, muscle strength and psychological assessment criteria, their validity and actual capacity to predict successful RTS remain uncertain. Furthermore, the time taken to RTS appears to vary considerably between patients, ranging from six months to over a year [FIG 25]. Early resumption of sporting activity is associated with an increased risk of graft rupture. Rather than considering this delay solely as a predictive factor, it may be pertinent to redefine it as a target variable in a predictive model, i.e., as an outcome to be estimated. This approach could be based on the concept of the RTS continuum, which distinguishes three phases: return to activity (and training), RTS (without necessarily achieving the previous level of performance), and return to performance (competitive level) [MER 21].

From this perspective, machine learning models could play a pivotal role in validating or excluding specific criteria based on objective and reproducible data. Their application would allow the RTS process to be personalised according to factors validated by consensus, while enhancing the ability to anticipate the risk of reinjury. Consequently, this approach would promote more precise, individualised, and safe decision-making for each patient.

However, it is important to note that most current studies on machine learning have been conducted in predominantly experimental contexts, with a primarily exploratory aim. Few have resulted in models directly applicable to clinical practice. It would therefore be pertinent, in a real-world clinical setting, to evaluate different supervised machine learning models by incorporating as many of the currently recommended criteria as possible (performance, muscle strength, psychological factors, etc.). This approach would allow not only the assessment of the true validity of each criterion, but also a more accurate quantification of each patient's ability to RTS, based on their performance in the various return-to-activity tests.

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