

Optimization of the Return-to-Sport Paradigm After Anterior Cruciate  
Ligament Reconstruction: A Critical Step Back to Move Forward

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1 **Optimization of the return to sport paradigm after anterior cruciate ligament reconstruction: a critical step back**  
2 **to move forward**

3

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12 **Running heading:** Return to sport after anterior cruciate ligament reconstruction

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1 **ABSTRACT**

2

3 Athletes who have sustained an anterior cruciate ligament injury often opt for an anterior cruciate ligament reconstruction  
4 with the goal and expectation to resume sports. Unfortunately, the proportion of athletes successfully returning to sport  
5 is relatively low, while the rate of second anterior cruciate ligament injury has been reported to exceed 20% after clearance  
6 to return to sport, especially within younger athletic populations. Despite the development of return to sport guidelines  
7 over recent years, there are still more questions than answers on the most optimal return to sport criteria after anterior  
8 cruciate ligament reconstruction. The primary purpose of this review is to provide a critical appraisal of the current return  
9 to sport criteria and decision-making processes after anterior cruciate ligament reconstruction. Traditional return to sport  
10 criteria mainly focus on time after injury and impairments of the injured knee joint. The return to sport decision-making  
11 is only made at the hypothetical “end” of the rehabilitation. We propose an optimized criterion-based multifactorial return  
12 to sport approach based on shared decision-making within a broad biopsychosocial framework. A wide spectrum of  
13 sensorimotor and biomechanical outcomes should be assessed comprehensively, while the interactions of an individual  
14 athlete with the tasks being performed and the environment in which the tasks are executed are taken into account. A  
15 layered approach within a smooth continuum with repeated athletic evaluations throughout rehabilitation followed by a  
16 gradual periodized re-integration into sport with adequate follow-up may help to guide an individual athlete toward  
17 successful return to sport.

1 **KEY POINTS**

2

3 No gold standard exists for evaluating return to sport readiness after anterior cruciate ligament reconstruction.

4

5 Traditional return to sport criteria are mainly focused on time after anterior cruciate ligament reconstruction and knee  
6 impairments, while the return to sport decision-making process is only made at the hypothetical “end” of the  
7 rehabilitation.

8

9 We propose an optimized criterion-based continuous and multifactorial return to sport approach based on shared-decision  
10 making, with a focus on a broad spectrum of individual sensorimotor and biomechanical outcomes, within a  
11 biopsychosocial framework.

## 1 **1 Introduction**

2 Most athletes who wish to continue sports after an anterior cruciate (ACL) injury are advised to undergo ACL  
3 reconstruction (ACLR) [1]. Unfortunately, the overall secondary ACL injury risk after ACLR is around 15% [2]. For  
4 young athletes (< 25 years) returning to competitive sports involving jumping and cutting activities, secondary ACL  
5 injury rates of 23% have been reported, especially in the early return to sport (RTS) period [2]. Compared to their  
6 uninjured adolescent counterparts, this indicates a 30 to 40 times greater risk of sustaining an ACL injury after ACLR  
7 [2]. In addition, an ACL injury and ACLR are associated with an increased risk to develop tibiofemoral and patellofemoral  
8 joint osteoarthritis [3], which can affect knee symptoms, function and quality of life 10-20 years after ACLR [4, 5].

9 The decision when an athlete is allowed to RTS is multifactorial, difficult and challenging [6, 7]. Despite the development  
10 of RTS guidelines over recent years, there are still more questions than answers on the most optimal RTS criteria after  
11 ACLR. There is a lack of a scientific consensus on the RTS criteria used to release a patient to unrestricted sport activity  
12 after ACLR. Moreover, current RTS criteria may fail to identify residual biological, functional and psychological deficits.  
13 As a result of all these factors, the current clinical approach used to release athletes to RTS after ACLR may contribute  
14 to increased secondary ACL injury risk.

15 The primary purpose of this review is to provide a critical appraisal of current RTS criteria after ACLR. Recommendations  
16 for future optimizations are then presented based on current trends in the literature.

17

## 18 **2 What is RTS?**

19 One of the most fundamental questions in terms of RTS is the definition of RTS. Do we consider a RTS successful even  
20 when the athlete lowers the level of sports activity, returns to another less demanding sport, to the same sport with a lower  
21 performance level, or sustains a second ACL injury, another subsequent injury or knee osteoarthritis a few months or  
22 even years after RTS? A systematic review and meta-analysis by Ardern et al. [8] showed that on average 81% of athletes  
23 returned to some sort of sports, but only 65% returned to the pre-injury level of sport activity. Barely 55% returned to a  
24 competitive sports level.

25 The use of the term RTS must be accompanied by a detailed description of the individual characteristics of the athletes  
26 being studied (e.g. sex and age), the use of protective equipment (e.g. taping, bracing), the intensity, duration and  
27 frequency of each exposure, the type of activity (e.g. pivoting or non-pivoting, contact or non-contact sports), level of  
28 activity (e.g. elite, competitive or recreational), performance level (e.g. match statistics) as well as the timing and duration  
29 of sport participation after ACLR. It is unclear how long an athlete needs to maintain a specific level of sport activity

1 before it can be claimed that the RTS was successful. The RTS rate in men professional soccer players was very high (>  
2 90%) at 1 year after ACLR, but only 65% were still playing at the highest level 3 years after ACLR [9]. Similarly,  
3 decreased player performances and significantly shorter career durations were reported after ACLR in professional  
4 basketball players compared to uninjured controls [10]. Furthermore, it needs to be clarified whether the athlete perceives  
5 the RTS as successful [11]. Some athletes may not be satisfied with the outcome after ACLR even after returning to their  
6 previous performance level because of pain, instability, stiffness or swelling, or in some cases despite a lack of any  
7 abnormal findings during physical examination [12]. The clearance to RTS by clinicians does not necessarily mean that  
8 patients go back to sport at the same time, or resume sports at all [13]. This can be due to practical, social or contextual  
9 reasons, that may modify the final RTS decision (e.g. end of the season, individual goals, lifestyle changes, a shift in  
10 priorities or external pressures) [14], but also due to a mismatch between the clinician's and the patient's understanding  
11 of when a person is ready to RTS. Success can mean different things to different people (e.g. athlete, trainer or clinician)  
12 and is context- and outcome-dependent [15]. Unfortunately, no gold standard exists for identifying an individual  
13 successful outcome after ACLR [16]. However, if the athlete has the goal to RTS, all people involved in the RTS decision-  
14 making process should prioritize a safe RTS, i.e. a RTS with minimal risk of sustaining a re-injury and/or developing  
15 long-term complications such as degenerative joint disease [17].

## 16 **2.1 Summary and Recommendations for Future Research**

17 RTS after ACLR is complex and multifactorial. There is no gold standard for identifying an individual successful outcome  
18 after ACLR. A clear definition of RTS and detailed descriptions of the individual characteristics and sport participation  
19 after ACLR is needed.

20

## 21 **3 RTS criteria**

22 In line with the definition of RTS, no consensus exists on the most appropriate criteria for releasing patients to unrestricted  
23 sports activities after ACLR [18]. Of the 264 studies included in a systematic review by Barber-Westin & Noyes (studies  
24 published between April 2001 and April 2011) [18], 40% provided no criteria for RTS after ACLR, 60% used time  
25 postoperatively at least as one of the RTS criteria and 32% used time as the only criterion. Only 13% used objective  
26 criteria.

27 The ability to decide whether an athlete is ready to safely RTS is further compromised by the paucity of prospective  
28 studies in literature validating current RTS criteria. Among a group of 46 males and 54 females with a pre-injury  
29 participation in level 1 and level 2 sports, delaying RTS until 9 months after surgery and a more symmetrical quadriceps  
30 strength prior to return to level 1 sport were associated with a reduced secondary knee injury risk [19]. However, of the

1 74 patients who returned to level 1 sports, the 51 patients who did not sustain a second knee injury had a mean quadriceps  
2 limb symmetry index (LSI) of 84.4%, which was below the recommended LSI of > 90% [19]. Another recent prospective  
3 study of 158 professional male soccer players who returned to sport after ACLR showed that those players failing to  
4 achieve the proposed RTS criteria were 4 times more likely to sustain a secondary ACL injury compared to those who  
5 met all 6 proposed criteria (including quadriceps and hamstrings muscle strength tests, 3 hop tests, an agility test, and the  
6 completion of on-field sport-specific rehabilitation) [20]. However, 12 of the 26 players with a second ACL injury met  
7 the RTS criteria, while 28 of the 132 players with no second ACL injury were not discharged by the RTS criteria, leading  
8 to a sensitivity of only 53% and a specificity of 79%.

9 The RTS tests and criteria used to evaluate RTS readiness are mostly based on subjective opinions. There is a lack of  
10 evidence supporting the relation between RTS and standard subjective and objective assessments [21]. This raises the  
11 question whether the current RTS tests address the appropriate issues and cut-off values [13], or whether they are sensitive  
12 or demanding enough to elucidate clinically relevant differences [11].

13 Shrier [14] recently proposed a Strategic Assessment of Risk and Risk Tolerance framework for RTS decisions, where  
14 factors affecting injury risk are grouped in the assessment of health risk, activity risk and risk tolerance. Within this  
15 overview, we mainly focus on the first two steps within this framework (the risk assessment process). In the following  
16 paragraphs, a structural summary of individual potentially modifiable RTS criteria within this risk assessment process is  
17 presented. However, we acknowledge that focusing only on very specific factors in isolation within a linear and  
18 unidirectional way is probably too simplistic. Several factors that are individually related to RTS may be interrelated to  
19 each other. The use of non-linear, multivariate and complex models in future studies, where the interactions between the  
20 different individual RTS criteria are taken into account, may provide a better framework for understanding the complex  
21 decision-making process of RTS after ACLR [14, 22, 23]. The relative importance of each of these criteria may depend  
22 on the individual. Therefore other researchers have proposed that individual patient-tailored RTS criteria should be used  
23 instead of the traditional “one-size-fits-all” RTS approach [6, 24].

### 24 **3.1 Summary and Recommendations for Future Research**

25 No consensus exists on the most appropriate criteria for releasing patients to unrestricted sports activities after ACLR.  
26 Only a paucity of prospective studies have validated RTS criteria after ACLR. Multivariate models should be used to  
27 unravel the complex RTS decision-making process. Prospective studies are needed to determine and evaluate evidence-  
28 based RTS criteria.

### 29 **3.2 Time after ACLR**

1 Time after ACLR is the most used criterion to assess RTS readiness [18]. Although this timing is highly variable (from  
2 12 weeks to 12 months), the majority of studies traditionally allowed RTS after 6 months [18]. However, the risk of  
3 sustaining a second ACL injury is highest during the early period after RTS (6-12 months) [19, 20, 25-27]. Based on  
4 these data, and the persistence of biological and functional deficits until approximately 2 years after ACLR, other authors  
5 have proposed delaying high level unrestricted sport activity until 2 years after ACLR [28], which is in contrast with  
6 current RTS practices. However, time after ACLR is not necessarily related to functional outcome measures [29]. In a  
7 prospective study by Capin et al. [30], 14 young female athletes were only allowed to RTS after passing their RTS criteria  
8 (> 90% quadriceps strength LSI, > 90% LSI on hop tests, and > 90% on Knee Outcome Survey – Activities of Daily  
9 Living Scale (KOS-ADLS)). The 7 athletes who sustained a second ACL injury during a 2-year follow-up after ACLR  
10 had earlier normalization of gait biomechanics, met the RTS criteria more quickly and returned significantly earlier to  
11 sport compared to the 7 athletes who returned to sport without second ACL injury (mean  $\pm$  SD  $6.8 \pm 1.9$  months versus  
12  $9.5 \pm 1.9$  months) [30]. These findings are in line with the study by Grindem et al. [19] and imply that an earlier RTS  
13 (before 9 months) should be avoided, even in the absence of clinical and functional gait impairments. We propose  
14 combining time after ACLR with other objective RTS criteria to guide the RTS decision-making process. Furthermore,  
15 the re-orientation from a “wait-and-see-policy” to a goal-oriented rehabilitation and RTS criteria-based decision-making  
16 approach might promote the autonomous athlete’s motivation and adherence to the rehabilitation program [31]. The  
17 implementation of more stringent objective RTS criteria across a broad spectrum of functional athletic capabilities will  
18 automatically delay the timing of RTS for the majority of athletes. Indeed, several studies have shown that most patients  
19 fail to achieve RTS criteria at 6 months after ACLR [19, 22, 32].

### 20 *3.2.1 Summary and Recommendations for Future Research*

21 Time after ACLR is the most used RTS criterion. No consensus exists on the ideal time frame to RTS after ACLR, but  
22 recent studies have shown that a RTS before 9 months after ACLR increases ACL re-injury risk. Time after ACLR is not  
23 associated with functional outcome measures. Integrated criterion-based RTS assessments should be developed.

### 24 **3.3 Patient reported outcome measures**

25 Patient-reported outcome measures (PROMs) are self-report questionnaires that measure an individual’s perception of  
26 symptoms, function, activity and participation [16, 33]. Various PROMs have been developed that are specific for ACL  
27 injuries or more generic for knee injuries. In a survey the following PROMs were proposed: KOS-ADLS, Knee Outcome  
28 Survey - Sports Activities Scale (KOS-SAS), global rating of perceived function (GRS), Lysholm score, International  
29 Knee Documentation Committee 2000 Subjective Knee Form (IKDC2000), Cincinnati Knee Score, Knee Injury and  
30 Osteoarthritis Outcome Score (KOOS), the Tegner Activity Scale and Marx Activity Rating Scale [16].



1 Although items like reliability, responsiveness and validity have been reported, it is currently unknown what the optimal  
2 cut-off scores are in the context of RTS after ACLR [34-36]. The decision to allow RTS after ACLR solely based on  
3 PROMs has been questioned [37]. Low IKDC2000 scores were reasonably indicative of failing on a battery of functional  
4 performance RTS tests including quadriceps strength and single-legged hop indices, while good IKDC2000 scores were  
5 not predictive of successfully passing the functional performance test battery [37]. These data indicate that PROMs and  
6 functional performance tests evaluate different aspects of athletic function. It has been suggested that a combination of  
7 PROMs and objective performance-based measurements is needed to evaluate an athlete's RTS readiness more  
8 comprehensively [33].

### 9 *3.3.1 Summary and Recommendations for Future Research*

10 The most optimal combination and cut-off scores of PROMs are not known. RTS decision-making should not be based  
11 only on PROMs. Future studies should integrate PROMs with objective RTS measurements in the RTS decision-making  
12 process.

## 13 **3.4 Clinical examination**

14 Clinician-based assessment has traditionally focused on overall impairments of the knee (e.g. swelling, pain, strength,  
15 range of motion and joint laxity). Recent literature has called for increased attention to a more functional and whole-  
16 person health care approach in sports medicine within a biopsychosocial context [38]. Hence, RTS decision-making  
17 following ACLR requires consideration of not only physical but also psychosocial factors [15].

### 18 *3.4.1 Muscle strength*

19 Even though most athletes achieve an (what is currently considered) acceptable muscle function, the RTS rates after  
20 ACLR are disappointing [11]. The majority of studies measure the peak torque and/or total work of the hamstrings and  
21 quadriceps with isokinetic or isometric dynamometry to evaluate muscle strength after ACLR, even though debate exists  
22 on the most optimal outcome measures and the functional relevance of testing strength in an open chain situation [39].  
23 Despite the fact that isokinetic knee strength evaluations after ACLR are commonly used to evaluate RTS readiness, these  
24 measures have not been sufficiently validated as useful predictors of successful RTS [39]. Kyritsis et al. [20] showed a  
25 10.6 times greater ACL re-injury risk after ACLR for every 10% decrease in the hamstrings to quadriceps ratio of the  
26 involved leg. Greater asymmetric quadriceps muscle strength prior to level 1 RTS after ACLR was also a significant  
27 predictor of knee re-injury [19].

28 Most studies have exclusively focused on the evaluation of knee muscle strength after ACLR, although a systematic  
29 review of Petersen et al. [40] also revealed deficits in hip muscle strength after ACLR. A prospective study of

1 Khayambashi et al. [41] reported that a decreased hip external rotator and abductor strength increased primary non-contact  
2 ACL injury risk. Future studies should explore the value of including these parameters in the RTS decision-making  
3 process.

#### 4 *3.4.1.1 Summary and Recommendations for Future Research*

5 A decreased hamstrings to quadriceps strength ratio and a greater asymmetric quadriceps strength can increase ACL re-  
6 injury risk, but the most optimal outcome measures and criteria to evaluate muscle strength in function of RTS after  
7 ACLR are not known. Most studies have exclusively focused on the evaluation of knee muscle strength. The validity of  
8 including muscle strength measurements of other joints, such as the hip, should be evaluated. The most optimal outcome  
9 measures and criteria to evaluate muscle strength should be determined in future research.

#### 10 *3.4.2 Hop tests*

11 Noyes et al. [42] developed a set of 4 hop tests (single-leg hop for distance, triple hop for distance, cross-over hop for  
12 distance and 6m timed hop) with the purpose of representing an objective measure of the functional capabilities of an  
13 athlete related to the demands of high-level sport activities. These hop tests can provide a reliable performance-based  
14 outcome for ACLR patients and only require a minimal amount of equipment [43]. However, Hegedus et al. [44] found  
15 limited and conflicting evidence for the measurement properties of hop tests, making it difficult to decide whether an  
16 observed result is meaningful for an individual athlete.

17 Another potential limitation of the original set of hop tests is that this test battery mainly consists of straight movements  
18 in the sagittal plane, thereby potentially hindering elicitation of clinically relevant functional performance deficits. During  
19 pivoting sport activities, an athlete has to move in multiple directions. The inclusion of a combination of hop tests whereby  
20 an athlete is forced to move as quickly as possible in multiple directions might better represent the challenges encountered  
21 during functional movements and increase the sensitivity for detecting deficits [45]. Examples here are the figure-of-8  
22 hop [45], side hop [45, 46] or square hop test [46]. A systematic review by Abrams [47] indicated that discrepancies  
23 between the operated and non-operated leg became more apparent when using more challenging tests such as the fatigue  
24 single-leg hop and side hop tests. However, only the traditional hop tests have been related with RTS after ACLR [19,  
25 20]. Another disadvantage of the traditional outcomes of hop tests is the strict focus on quantitative outcomes (distance,  
26 time and limb symmetry), while outcomes related to the quality of movement are not captured [48].

#### 27 *3.4.2.1 Summary and Recommendations for Future Research*

28 There is conflicting evidence regarding the measurement properties of hop tests. The most optimal hop test RTS criteria  
29 after ACLR are not known. Hop tests have mainly been performed in the sagittal plane for the purpose of RTS decision-

1 making. The measurement properties and most optimal criteria of hop tests, including multidirectional hop tests, should  
2 be determined to assess RTS readiness.

### 3 *3.4.3 Limb symmetry index (LSI)*

4 From a clinical point of view, using the LSI by comparing the operated and non-operated leg after ACLR is the most  
5 obvious way to evaluate RTS readiness. For quantitative outcomes of isokinetic muscle strength evaluations and hop  
6 tests, LSI > 85-90% were traditionally considered as safe cut-off values to RTS [49-51]. However, one may question the  
7 acceptance of 10-15% difference between legs. It is possible that these so called “small” differences in physical function  
8 may have a high impact on the ability to return to high-level sport activities. More stringent recommendations which were  
9 categorized based on type of activity (pivoting, contact or competitive versus non-pivoting, non-contact or recreational)  
10 have been presented [11]. For the pivoting/contact/competitive group, these authors recommended a 100% LSI for knee  
11 extensor and knee flexor muscle strength and a single-leg hop LSI > 90% on 2 maximum hop tests (e.g. single hop for  
12 distance, vertical hop, etc.) and 1 endurance hop test (e.g. triple hop, stair hop, side hop, etc.). For the non-pivoting/non-  
13 contact/recreational group, they recommended at least 90% LSI for the involved limb knee extensor and knee flexor  
14 muscle strength and at least 90% LSI for the involved limb hop performance on 1 maximum or 1 endurance hop tests  
15 [11]. At 6 months after ACLR, with success defined as those patients who scored LSI of > 90% in a set of 3 hop tests and  
16 3 strength tests, none of the patients met the criteria [32]. In fact, only 23% of all patients were successful at 2 years in  
17 meeting the criteria [32].

18 Even though a more symmetrical hopping performance has been related to returning to pre-injury sport level [8], this  
19 symmetry-based approach is debatable and may lead to underestimations of clinical relevant deficits, as bilateral  
20 neuromuscular, biomechanical and functional performance deficits have been demonstrated after unilateral ACLR [52-  
21 57]. This implies that a clinician is forced to refer to “normal” performances on certain tasks or pre-injury data of the  
22 athlete. However, only very limited scientific data are available in the literature on normative absolute values for strength  
23 and hop tests. Caution is therefore warranted when generalizing data from a specific population to other study groups or  
24 individuals.

#### 25 *3.4.3.1 Summary and Recommendations for Future Research*

26 The most optimal LSI is unknown and might differ between individuals with varying type and level of sport activity.  
27 Caution is warranted when using LSI as bilateral deficits can be present. The validity of LSI during the RTS decision-  
28 making process should be further explored.

29

#### 1    3.4.4 Assessment of movement quality

2    An increased knee valgus movement, a decreased internal hip external rotation moment, a greater asymmetrical internal  
3    knee extensor moment at initial contact during a drop vertical jump, and postural stability deficits during single-leg stance  
4    significantly increased second ACL injury in a group of 35 female and 21 male athletes who returned to sport after ACLR  
5    [58]. Another prospective study by Paterno et al. [59], including 61 female athletes with an ACLR, showed an altered  
6    hip-ankle coordination during a dynamic single-leg postural coordination task compared to similar athletes who did not  
7    suffer a second ACL injury during follow-up. Although no other prospective biomechanical studies after ACLR exist,  
8    these preliminary findings are in line with the trend in the current literature to emphasize the importance of movement  
9    quality during rehabilitation of ACLR patients [51, 60-62].

10   It is increasingly recognized that a knee does not function as an isolated joint, but rather as an intermediate joint within a  
11   linked system of segments which need to interact with each other within different planes of movement during dynamic  
12   sport activities [63, 64]. However, multi-dimensional time-varying biomechanical data are often reduced to zero-  
13   dimensional data (e.g. peak single-joint and single-planar joint angles or moments), which might compromise our  
14   understanding of multi-joint and multi-dimensional athletic movement behavior. From this perspective, the use of vector  
15   field statistical analysis approaches might provide additional insights in future studies [65].

16   In addition to this fundamental research, it is imperative that efforts are made to translate these complex laboratory-based  
17   procedures to more clinical-friendly methodologies. Most currently available biomechanical studies after ACLR used  
18   sophisticated equipment in laboratory environments. The use of two-dimensional video analysis and visual observational  
19   scales to evaluate multi-segmental movement quality in clinical settings shows promising results [56, 66-69]. Future  
20   studies should assess the value of these measures in relation to RTS readiness.

##### 21   3.4.4.1 What is the reference?

22   From a movement quality point of view, a recent systematic review attempted to determine “normal” ranges of hip and  
23   knee kinematics based on studies using three-dimensional motion analysis of females during athletic tasks commonly  
24   used to assess ACL injury risk [70]. However, normal ranges of kinematic outcomes can be influenced by numerous  
25   variables including sex, age, sport specificity, sports or activity level, injury history, individual anatomical  
26   characteristics, the methodology used to measure kinematics, the tasks being performed and the natural variability of  
27   human movement behavior [70]. It is therefore not surprising that wide ranges of normal values were reported [70].  
28   Based on the current scientific literature, the “norm-based” approach is therefore not yet supported when evaluating an  
29   individual athlete from a primary or secondary injury prevention perspective. Furthermore, only pursuing the  
30   “normalization” of biomechanical and/or neuromuscular outcomes during interventions to decrease (re-)injury risk, and

1 neglecting the individual characteristics of an athlete, may again lead to suboptimal outcomes. When pre-injury data for  
2 an individual athlete were available, one would be able to refer to these outcomes, but in most cases these data are  
3 lacking. Furthermore, the pre-injury individual characteristics may have been less optimal, thereby contributing to the  
4 multifactorial reason why the initial injury would have occurred. A return to the same level after injury as before injury  
5 therefore cannot be a good enough outcome. The advanced clinical reasoning skills of a clinician remain essential when  
6 assessing an individual athlete.

#### 7 *3.4.4.2 Task and environmental constraints*

8 Movement quality, objectively evaluated with biomechanical measurements, may vary according to the task being  
9 selected after ACLR [71]. During athletic activities, an athlete has to visually perceive the constantly and quickly  
10 changing, unpredictable environment (e.g. movement of another player, opponent or a ball), quickly process these  
11 situational-specific visual-spatial cues within the central nervous system and develop an appropriate physical response  
12 while maintaining dynamic stability of the body. Several studies have shown that experimentally visually cued temporal  
13 constraints can affect whole body kinematics and knee loading during athletic activities such as cutting [72, 73].  
14 Therefore, one could argue that environments should be as realistic and context-specific as possible when evaluating the  
15 ability to RTS. However, most currently used dynamic RTS tests are performed within a predictable, fixed or “closed”  
16 environment. Training or testing in closed environments may decrease the ability to transfer the learned patterns towards  
17 highly unpredictable three-dimensional open environments encountered during athletic activities. In addition, most  
18 athletes are familiar with the tests, as the same movement tasks are often performed and learned during rehabilitation. As  
19 a consequence, an athlete may be aware of the criteria to perform these tests with an “optimal” movement quality. This  
20 may lead to situations whereby clinicians rather evaluate a conscious, internally focused and learned movement behavior  
21 of the athlete instead of the dynamic capabilities of an athlete which are related to real game situations.

22 Athletes recovering from injury typically have an increased internal focus of attention [74]. This can be a result of the  
23 fear to sustain a re-injury, lack of confidence in the injured body part or the predominantly internally focused instructions  
24 provided by the clinician during a prolonged time of rehabilitation. Nevertheless, during athletic activities it is highly  
25 important to be able to redirect attention to the most relevant environmental cues. Several studies have shown that the  
26 performance on postural control tasks decreases significantly more in ACL injured and ACLR patients compared to  
27 healthy controls when the neurocognitive loading increases [52, 53, 75-79]. This can be established by including temporal  
28 constraints, distracting or occluding the visual system, increasing the level of task uncertainty, performing dual tasks or  
29 including fatigue, psychological stressors, decision-making or combinations of those factors in RTS tests.

#### 30 *3.4.4.3 Sensorimotor system*

1 The cascade of neurophysiological alterations after ACL injury, in combination with the reported deficits across the whole  
2 spectrum of the sensorimotor system after ACL injury and ACLR, support the theory that an ACL injury should be  
3 considered as a neurophysiological injury, and not as a “simple” musculoskeletal pathology with only local mechanical  
4 or motor dysfunctions [80, 81]. These alterations may contribute to the increased need to rely on visual feedback and  
5 conscious movement planning with an internal focus of attention after ACLR. The central nervous system may become  
6 overloaded in these particular situations where task and environmental constraints are altered. This neurocognitive  
7 overload may lead to a momentary loss of visual-spatial disorientation and decreased dynamic joint stability, potentially  
8 increasing secondary ACL injury risk [82, 83]. However, the ability of an individual to handle neurocognitive overloading  
9 may be missed with the traditional RTS test batteries. Most RTS batteries mainly focus on the motor end of the  
10 sensorimotor system, and fail to comprehensively address the interaction of an individual with the task and environmental  
11 constraints. This is in contrast with the current injury prevention and rehabilitation literature, where for example the  
12 inclusion of an external focus of attention and visual-motor interaction training is increasingly supported to enhance motor  
13 learning and stimulate the transfer of a learned motor behavior towards a variety of functional athletic tasks and dynamic  
14 environments [81, 84, 85]. The recognition and application of this framework might allow developing more efficient RTS  
15 criteria in the future.

#### 16 *3.4.4.4 Fatigue*

17 RTS tests are mostly performed in a non-fatigued state. However, fatigue can have detrimental effects on multiple  
18 biomechanical and neuromuscular variables during tests that are currently used to assess RTS readiness in ACLR athletes  
19 [86-90]. In a study by Augustsson et al. [86], all ACLR patients met the RTS criteria (defined as a LSI > 90% on the  
20 single-leg hop test) in a non-fatigued state, while 68% showed an abnormal LSI when fatigued. Similarly, Gokeler et al.  
21 [89] found an increase in the Landing Error Scoring System score during a bilateral drop vertical jump when fatigued in  
22 an ACLR and non-injured control group. Moreover, the influence of fatigue on lower extremity biomechanics is even  
23 more pronounced during unanticipated landings, further emphasizing the interactive role of fatigue and decision-making  
24 after ACLR [91]. Based on the current literature, it can be argued that testing athletes in a fatigued state may enhance  
25 the ability to detect clinical relevant deficits after ACLR [92].

#### 26 *3.4.4.5 Summary and Recommendations for Future Research*

27 Less optimal movement quality during functional movements can increase re-injury risk. Most RTS tests have mainly  
28 focused on single-joint (the knee) and single-planar biomechanical outcomes, and on the motor end of the sensorimotor  
29 system. The validity of RTS tests focusing on multi-segmental and multidirectional movement quality should be  
30 evaluated. Athletes should be evaluated across a broad sensorimotor spectrum, including the interactions between an

1 individual and the task and environmental constraints. It is recommended to develop RTS tests that employ the effect of  
2 fatigue.

### 3 *3.4.5 Psychological factors*

4 Traditional rehabilitation after ACLR and subsequent RTS criteria has predominantly focused on the recovery of the  
5 physical capacity to cope with the physical demands of a specific sport, maximize performance and decrease re-injury  
6 risk [17]. During recent years, it has become clear that physical recovery alone is not sufficient to ensure successful RTS  
7 [7]. Many athletes with good physical function do not RTS after ACLR [93]. The importance of psychological factors  
8 after ACLR is increasingly recognized in the literature [7, 94]. A recent review on contextual factors affecting RTS after  
9 ACLR identified that lower fear of re-injury, greater psychological readiness and a more positive subjective assessment  
10 of knee function favored a return to pre-injury level of sport after ACLR [7]. Sonesson et al. [95] found that higher  
11 motivation during rehabilitation was associated with returning to pre-injury sport activity. Another study showed that  
12 patients who had returned to knee-strenuous sports after ACLR reported higher self-efficacy, evaluated with the Knee  
13 Self-Efficacy Scale (K-SES) [96], compared with those who had not returned [97]. The ACL-Return to Sport after Injury  
14 (ACL-RSI) scale has been developed to assess the athlete's psychological readiness to RTS [98]. This 12-item  
15 questionnaire assesses emotions, confidence and risk appraisals associated with RTS after ACLR and has been proved to  
16 discriminate between athletes who returned to sports after ACLR and those who did not [99]. At 4 months after ACLR,  
17 an ACL-RSI cut-off score of 56 points predicted RTS at 12 months with a sensitivity of 58% and specificity of 83% [99].  
18 Nevertheless, psychological factors are typically not systematically evaluated during rehabilitation and RTS decision-  
19 making after ACLR [100]. A paradigm shift from the traditional physical-focused RTS evaluation towards a more holistic  
20 approach where psychological factors are comprehensively assessed as well has been proposed [100]. Early evaluation  
21 and recognition of maladaptive or dysfunctional psychological responses during rehabilitation may allow the clinician to  
22 address these modifiable deficits with targeted interventions before RTS [100, 101].

#### 23 *3.4.5.1 Summary and Recommendations for Future Research*

24 Psychological factors play a significant role in RTS outcomes but are typically not evaluated during the RTS decision-  
25 making process. It is advised to integrate psychological factors within a holistic biopsychosocial RTS decision-making  
26 approach.

27

## 28 **4 How to organize a RTS decision process?**

1 Nyland [102] considers the RTS decision-making process as a continuum, which is too large to perform in only 1 step.  
2 Each rehabilitation exercise or phase can be considered as a small step in the direction of RTS [102, 103]. Pre-operative,  
3 operative as well as post-operative factors during rehabilitation can affect RTS [103, 104]. This more layered approach  
4 within a smooth continuum of recovery throughout the whole rehabilitation is in line with the contemporary criteria-based  
5 rehabilitation approaches [103, 105, 106], but in contrast with the traditional “yes” or “no” question at the hypothetical  
6 “end” of rehabilitation [102, 103, 107]. Repeated athletic evaluations during the rehabilitation should be considered as  
7 small steps on the road to RTS. The decision to allow full return to unrestricted athletic activities should not be considered  
8 as the endpoint of this continuum [15]. Even though we currently do not know how RTS criteria develop over time after  
9 RTS, maintenance programs and longer follow-ups are advised to further improve or at least maintain functional levels  
10 following an intense rehabilitation period [107]. Secondary prevention programs have been proposed [108, 109], but their  
11 effectiveness for reducing re-injury risk and increasing RTS rates have yet to be investigated. A graphical overview of  
12 the proposed continuum is presented in Figure 1.

13 Gradual planning and periodization to progress from training in a controlled environment in clinical practice to athletic  
14 activities in highly uncontrolled environments is needed during rehabilitation. Too often, the end phase of the  
15 rehabilitation is not extensive or specific enough, thereby exposing athletes to specific training loads and training  
16 characteristics that they cannot handle from a physical, physiologically, neurocognitive as well as psychological  
17 perspective. The failure to fully recover after ACLR, while allowing a RTS based on non-specific criteria without a  
18 progressive re-integration into sport, may lead to a lack of confidence in the athlete, fear of re-injury and the persistence  
19 of risk factors that ultimately increase the re-injury risk. To finally integrate an athlete into a team sport, progressions can  
20 be made from (1) return to reduced team training without contact, (2) return to full (normal) team training with contact,  
21 (3) return to friendly games (initially not over the full duration) and (4) return to competitive matches (initially not over  
22 the full duration) [60]. This may reflect a more comprehensive phasic periodization of RTS, in line with the recently  
23 proposed continuum of RTS [15].

24 In addition, exclusively focusing on the performance on the aforementioned RTS tests may fall short in terms of  
25 effectively monitoring how an athlete can handle the increasing training and competition workloads [110, 111]. An athlete  
26 may be able to successfully perform functional RTS tests, but when performing greater workloads than they are prepared  
27 for, the risk for an unsuccessful RTS and re-injury is still increased [110]. For that reason, Blanch & Gabbett [110]  
28 proposed the inclusion of the acute/chronic workload ratio in the RTS decision-making process. This ratio describes the  
29 relation between the workload of the last week (acute workload), in relation to the rolling average workload of the last 4  
30 weeks (chronic workload). This concept can be applied to a wide range of individually functional relevant training  
31 variables representing external workload (e.g. number of jumps or high speed running covered) or internal workload (e.g.



1 rating of perceived exertion). Rapid spikes in acute/chronic workload ratios during the RTS process should be avoided.  
2 For a clinician, it is therefore important to know the physical demands of the specific sport and to gradually expose an  
3 athlete to the sport-specific workloads in order to successfully integrate a player back into sport. This concept highlights  
4 again the dynamic interaction between rehabilitation and the RTS decision-making process.  
5 Taken together, these findings strongly argue for a close cooperation between all members within a multidisciplinary  
6 team, facilitating a shared decision-making process [17, 112]. A graphical overview of the aforementioned traditional and  
7 optimized RTS approach is presented in Figure 2.

#### 8 **4.1 Summary and Recommendations for Future Research**

9 The RTS decision is typically made at the hypothetical “end” of rehabilitation, without adequate follow-up. Researchers  
10 should focus on the development of test batteries across the whole continuum of criterion-based rehabilitation, and not  
11 only at the hypothetical “end”. RTS decision should be based on shared decision-making. Workload should be objectively  
12 measured during the rehabilitation to enable a gradual periodized RTS after ACLR.

#### 14 **5 What RTS criteria can clinicians use now?**

15 Numerous limitations in the literature have been presented in this manuscript, followed by suggestions for future research.  
16 Nevertheless, clinicians cannot wait for years of research to make daily clinical decisions. Until more evidence-based  
17 RTS criteria are available, shared decisions can be made based on the integration of the best available evidence, clinical  
18 experience and patient preferences [17]. While acknowledging the current limitations, we propose a combination of  
19 different existing parameters at the hypothetical “end” of rehabilitation in Table 1, which need optimization and validation  
20 across the whole continuum in the future, based on the suggestions proposed in the current manuscript. The definition of  
21 successful RTS outcomes should be discussed before and throughout the rehabilitation process to tailor an individual RTS  
22 decision-making process.

#### 24 **6 Conclusion**

25 The critical appraisal of the current literature provided in this article has shown that no gold standard exists when  
26 evaluating RTS readiness after ACLR. The identification of the current limitations in the literature and the proposed  
27 optimizations within this review may serve as a solid baseline from which to improve the RTS decision-making process  
28 after ACLR in the future.

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2

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7 Bart Dingenen and Alli Gokeler declare that they have no conflicts of interest relevant to the content of this review.

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- 14

1 **FIGURE LEGENDS**

2

3 **Fig. 1** A graphical overview of the proposed return to sport (RTS) continuum after anterior cruciate ligament (ACL)  
4 injury and ACL reconstruction. A layered individual continuous approach starting with the ACL injury, followed by  
5 preoperative rehabilitation, the ACL reconstruction, a criterion-based postoperative rehabilitation, RTS testing, a careful  
6 shared decision-making process and gradual periodized re-integration into sport-specific activities with adequate follow-  
7 up is presented.

8

9 **Fig. 2** A graphical overview of the most important differences between components of the traditional and proposed  
10 optimized return to sport (RTS) approach after anterior cruciate ligament reconstruction (ACLR). Traditionally, the RTS  
11 decision-making process is mainly based on time after ACLR (1) and impairments of the knee (2). The RTS decision is  
12 only made at the hypothetical “end” of the rehabilitation without adequate follow-up (3), which may lead to a narrow  
13 view of RTS readiness after ACLR (4). The optimized criterion-based (1) and multifactorial (2) approach presented in  
14 this paper focuses on a wider spectrum of individual sensorimotor (3) and biomechanical outcomes, including for example  
15 the evaluation of multi-segmental movement quality (4), but also takes into account the interactions of an individual with  
16 the task and environmental constraints (5) (e.g. multi-directional single-legged RTS tests, inclusion of task uncertainty,  
17 decision-making, external focus of attention and open environments). The RTS decision is not simply made at the  
18 hypothetical “end” of the rehabilitation, but is considered as a step-by-step continuous process (6) (Figure 1). The whole  
19 RTS decision-making process is made within a broad multifactorial biopsychosocial framework, and based on shared  
20 decision-making (7). This optimized RTS approach may allow a “big picture view” of the RTS readiness of an individual  
21 athlete (8).

**Table 1. Return to sport criteria that clinicians can use today**

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Time after anterior cruciate ligament reconstruction > 9 months [19, 30]

Patient reported outcomes measures:

Symptoms, function, activity, participation:

IKDC2000: 18-24 years (> 89.7 males; > 83.9 females), 25-34 years (> 86.2 males; > 82.8 females), 35-50 years (> 85.1 males; > 78.5 females), 51-65 years (> 74.7 males; > 69.0 females) [37]

Tegner Activity Scale: according to the desired activity level

Psychological factors:

Anterior cruciate ligament return to sport after injury (ACL-RSI) scale > 56 [99]

Knee self-efficacy scale (K-SES): males > 7.2; females > 6.8 [97]

Objective measures:

Clinical evaluation of knee impairments [49, 51]:

Full range of motion

No pain

No swelling

No abnormal laxity: KT-1000 arthrometer < 3 mm increased anterior laxity compared to contralateral side, < 3 mm Lachman test, grade 0 pivot-shift test

Quantitative outcomes [11, 19, 20, 22]:

Muscle strength:

Pivoting, contact, competitive sports: > 100 % LSI on knee extensor and knee flexor strength evaluated with concentric isokinetic dynamometry at 60°/s, 180°/s and 300°/s.

Non-pivoting, non-contact, recreational sports: > 90 % LSI on knee extensor and knee flexor strength evaluated with concentric isokinetic dynamometry at 60°/s, 180°/s and 300°/s.

Hamstrings/quadriceps strength ratio > 58% evaluated with concentric isokinetic dynamometry at 60°/s [20]

Hop tests: multidirectional: LSI > 90%

Movement quality:

Evaluation of multi-segmental movement quality during double- and single-leg dynamic activities: individual assessment with advanced clinical reasoning

Inclusion of sport-specific fatigue

Sport re-integration:

Gradual training towards real game situations

Gradual increase workloads (avoid rapid spikes) [110]

Assess tolerance of sport-specific training: no pain, swelling, stiffness, giving way

Medical and sport risk modifiers [14]:

Age, sex, personal medical history, type of sport, level of sport, position played, ability to protect (e.g. taping / bracing).

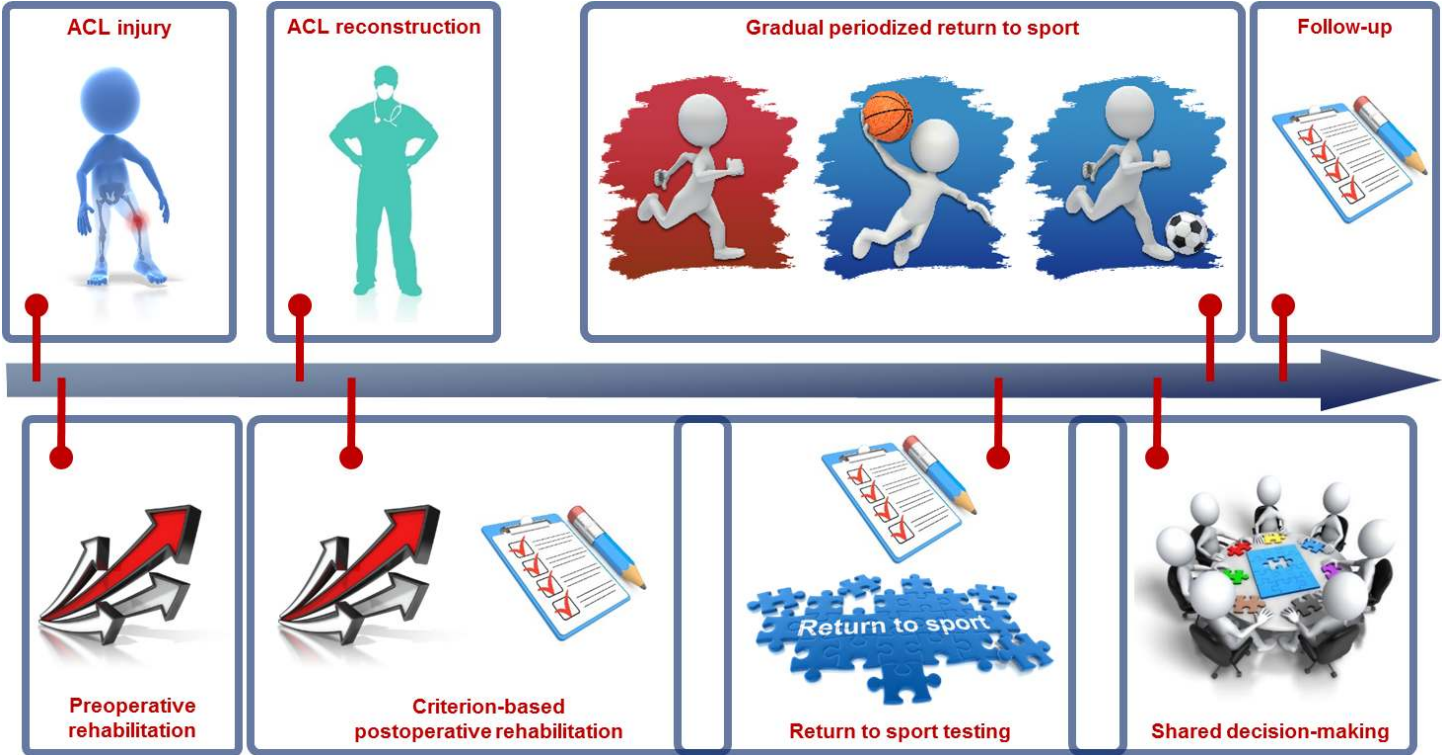
Decision modifiers [14]:

Timing of the season, external pressure from club, trainers, parents, conflict of interest (e.g. financial), lifestyle changes, priorities, individual goals.

Shared decision-making [112]

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IKDC2000: International Knee Documentation Committee 2000 Subjective Knee Form; LSI: limb symmetry index





(1) Time-based



(2) Knee-focused



(3) A yes or no RTS decision only at the hypothetical "end" of the rehabilitation



(4) Narrow view of RTS readiness after ACL reconstruction

**Traditional return to sport approach**

**Biopsychosocial framework**



(1) Criterion-based



(2) Multifactorial



(3) Sensorimotor spectrum



(4) Multi-segmental



(5) Interaction individual - task - environment



(6) RTS continuum



(7) Shared decision



(8) Big picture view

**Optimized return to sport approach**