Which assessments are used to analyze active knee stability after an anterior cruciate ligament injury to determine readiness to return to sports?

Running title: Assessments for active knee stability

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Abstract

Background

Adequate neuromuscular control of the knee for active joint stability could be one element to prevent secondary injuries after an anterior cruciate ligament (ACL) injury, either treated conservatively or surgically. However, it is unclear which measurements should be used to assess neuromuscular control of the knee for a safe return to sports (RTS).

Purpose

To summarize assessments for neuromuscular control of the knee in athletes after an ACL injury to decide upon readiness towards a successful return to sports (RTS).

Study design

Systematic review, level of evidence 4

Methods

This systematic review followed the guidelines of Preferred Reporting of Items for Systematic Reviews and Meta-analyses (PRISMA) and has been listed in PROSPERO (CRD42019122188). The databases MEDLINE/PubMed, EMBASE, CINAHL, Cochrane Library, Physiotherapy Evidence Database (PEDro), SPORTDiscus and the Web of Science were searched from inception until March 2019. The search was updated with e-mail alerts from the searched databases until December 2019 and yielded to studies identifying assessments using electromyography (EMG) for neuromuscular control during dynamic activities in patients with an ACL rupture or repair. All included articles were assessed for risk of bias with a modified Downs and Black checklist.

Results

A total of 1178 records were identified through database search. After screening for title, abstract and content regarding in- and exclusion criteria, 31 articles could be included for
analysis. Another six articles could be included from hand search of reference lists of the included articles, resulting in a total of 37 articles. Surface EMG was used in all studies as method to assess neuromuscular control. However, there was a wide range of tasks, interventions, muscles measured, and outcomes used. Risk of bias was medium to high due to an unclear description of participants and prior interventions, confounding factors and incompletely reported results.

**Conclusions**

Despite a wide range of EMG outcome measures for neuromuscular control, none was used to decide upon a safe RTS in adult patients after an ACL injury.

**Clinical relevance**

Future studies should aim at finding valid and reliable assessments for neuromuscular control to judge upon readiness towards RTS.

**Key words:** anterior cruciate ligament, assessment, active knee stability, neuromuscular control, return to sports
What is known about the subject:

The recurrence rates even after successful surgery and subsequent rehabilitation in ACL patients are high (up to 30%), with a re-injury of the ipsilateral knee, an injury of the opposite leg, muscle injuries on the ipsilateral side or even bilateral consequences and an increased risk for knee osteoarthritis. Furthermore, the diagnostic outcomes used to determine RTS after an ACL tear are numerous. However, they are not always functional and do not sufficiently reflect neuromuscular control abilities of ACL patients. Currently, decisions regarding joint stability for RTS are based on subjective clinical assessments (passive joint stability) and physical test batteries (e.g. hop tests as surrogates for active joint stability). Additional knowledge regarding objective neuromuscular measures closes the gap between the two mentioned currently available evaluations. Up to date, it is unclear which measurements should be used to assess neuromuscular control of the knee for a safe RTS.

What this study adds to existing knowledge:

Surface electromyography is the choice of method to assess neuromuscular control of the knee during active tasks in adult ACL patients. However, it remains unclear which outcome variables would be best to judge upon readiness towards RTS or which dynamic tasks should be used for RTS.
**Introduction**

ACL injuries happen quite frequently and concern athletes (0.15 injuries per 1000 athletic exposures AEs) but also the active part of the general population.\(^{34,37}\) Most ACL injuries are due to a non-contact, multiplane mechanism\(^ {32}\) and may lead to instability, secondary meniscal injury or even knee osteoarthritis in the long run.\(^ {21}\) Consequently, this injury means several weeks or even months of physical impairment with wide consequences for the patients concerning return to work, return to activity or RTS. Furthermore, the overall incidence rate of a second ACL injury within 24 months after successful ACL reconstruction and RTS is reported to be 1.39 per 1000 AEs, leading to an almost six-fold increased risk compared to a healthy young control group (0.24/1000 AEs).\(^ {64}\) Overall, the recurrence rates even after successful surgery and subsequent rehabilitation are high (29.5% or 1.82/1000 AEs), with an tear of the ACL graft (9.0%), an ACL injury of the opposite leg (20.5%), muscle injuries following ACL repair/rehabilitation on the ipsilateral side or even bilateral consequences and an increased risk for knee osteoarthritis.\(^ {21,63,64}\) Therefore, not only primary but also secondary prevention strategies are warranted.

Approximately 90% of patients with an ACL reconstruction achieve successful surgical outcomes (impairment-based measures of knee function) and 85% show successful outcome in terms of activity-based measures.\(^ {5}\) Of these patients, more than 80% return to some form of sports participation, however, only 44% return to competition.\(^ {5}\) More recently published systematic reviews found a range of RTS values between 63 and 97% for elite athletes with an ACL reconstruction.\(^ {41,50}\) Of these athletes, more than 5% sustained a re-rupture of the graft\(^ {41,96}\) in the ipsilateral knee. The risk for an ACL tear in the contralateral knee was as double as high (11.8%) five years or longer after an ACL reconstruction.\(^ {96}\) It is known that returning to high-demanding sports, including jumping, pivoting and hard cutting, after ACL reconstruction leads to a more than 4-fold increase in reinjury rates over two years.\(^ {24}\) Considering simple decision rules such as RTS not before nine months after reconstruction and achievement of symmetrical quadriceps strength was reported to substantially decrease reinjury rates.\(^ {24}\)
However, a recently published review did not find an association between current objective
criteria based RTS decisions and risk of a second ACL injury, but these findings were based
on only four studies with low quality of evidence.

Most elite athletes RTS on average within one year – this population seems to return earlier
than non-elite athletes. However, it remains unclear, whether this approach is safe. In a
systematic review, time from surgery was the only criterion used to determine RTS after ACL
reconstruction in a third of the studies, sometimes combined with subjective, non-measurable
criteria. Objective criteria such as muscle strength, general knee examination or hop tests were
applied in 13% of the reviewed studies. To measure functional performance after ACL
reconstruction, mainly the single leg hop test for distance or a combination of several hop tests
are used, and functional performance is expressed with the Lower Limb Symmetry Index
(LSI). However, the LSI may overestimate the time point of RTS six months after ACL
surgery, and therefore leads to an increased risk for secondary injury. Furthermore, often
used clinical impairment assessments for disability do not appear to be related to measured
physical performance and do not necessarily reflect readiness for RTS. This could be
shown for isokinetic strength measures which “have not been validated as useful predictors of
successful RTS”. In addition, no standardized isokinetic protocol assessing strength for
patients after ACL reconstruction could be found. Moreover, no measure for assessing quality
of functional performance after ACL reconstruction has been reported so far.

Regarding the determination of RTS after ACL reconstruction, there is some evidence for the
use of functional performance tests: Multiple functional performance measures – a battery
including strength and hop tests, quality of movement and psychological tests - might be
more useful for the determination of RTS than a single performance measure. However, it is
still unclear, which measures should be used to bring athletes safely back to RTS with a low
risk of a second ACL injury. Currently used RTS criteria may be suboptimal at reducing the
risk of a second ACL injury.
It is known that patients with ACL reconstruction show altered kinematics and kinetics\(^{27}\) - these changes are referred to neuromuscular adaptations due to altered sensorimotor control.\(^{25}\) These changes in sensorimotor control are caused by altered afferent inputs to the central nervous system due to the loss of the mechanoreceptors of the native (original) ACL.\(^{79,99}\) Furthermore, patients with a deficient ACL show different neuromuscular strategies during walking\(^{81}\), depending on the functional activity level and being copers (sufficient knee stability) or non-copers (suffering from giving-way episodes).

Neuromuscular control is defined and used in different ways: Biomechanical measures such as three-dimensional kinetics and kinematics are used to predict ACL injury risk\(^{31}\) or physical performance test batteries (including strength tests, hop tests and measurement of quality of movement) are used to clear an athlete for RTS.\(^{92}\) So far, nonspecific vertical jump squats, single leg distance hops, side hops, the assessment of limb symmetry and muscle strength tests\(^{95}\) are often used in daily clinical practice to assess active knee stability. However, there is only limited evidence that passing RTS test batteries reduces the risk for a second ACL injury.\(^{94}\)

Three-dimensional kinetics and kinematics provide some data to judge upon quality of active knee stability (“dynamic valgus”), however, give only little insight in neuromuscular control. In addition, the currently suggested RTS criteria do not seem to be adequate to assess neuromuscular control of the knee joint to judge upon a safe RTS or even competition. Consequently, meaningful, reliable, valid and accurate diagnostic tools for patients with an ACL injury (either treated surgically or conservatively) are needed and may aid clinical decision-making to optimize sports participation following ACL reconstruction.\(^{78}\) Objective measurements of neuromuscular control should include EMG of involved muscles to judge upon quantity, quality and timing of voluntary activation and reflex activity.\(^{15,88}\) So far, it is unclear which measurements for neuromuscular control are used in patients with an ACL injury to clear for RTS.
Therefore, the first aim of this systematic review was to summarize the scientific literature regarding assessments for neuromuscular control in patients with an ACL injury (either treated surgically or conservatively). The second aim is to analyze whether these assessments for neuromuscular control were used to decide upon readiness for RTS in these patients.

Methods

Design, protocol and registration

This systematic review was planned, conducted and analyzed according to the guidelines of Preferred Reporting of Items for Systematic Reviews and Metaanalyses (PRISMA) and followed the recommendations of Cochrane group.

The protocol for this systematic review was registered beforehand in the International prospective register of systematic reviews (PROSPERO) from the National Institute for Health Research NHI (https://www.crd.york.ac.uk/PROSPERO/index.php#index.php) and got the registration number CRD42019122188. The search protocol can be accessed via https://www.crd.york.ac.uk/prospero/display_record.php?RecordID=122188.

Eligibility criteria

To define the relevant key words for the literature search, the PICOS strategy was used as follows (Table 1):

Table 1: Overview of PICOS criteria for key word definitions

Insert table 1 about here.

In addition, the following inclusion and exclusion criteria were applied: As inclusion criteria were used: Study participants have to be athletes or physically active people who participate in sports activities on a regular basis (as defined by each study, e.g. Tegner Activity Score \( \geq 3 \)) to get data to decide upon RTS (synonyms: back to sports, back to competition, return to competition, sports participation, sports activities, or in German: “Sportfähigkeit”),
assessments for neuromuscular control of lower limb muscles using EMG as method, original articles published in peer-reviewed, scientific journals, available as full texts, written in English, German, French, Italian or Dutch without any restriction regarding publication date or year could be included. Exclusion criteria were studies with model-driven approaches, animals, cadavers, comparisons of surgical techniques, passive or non-functional tasks (such as isokinetic measurements for strength and isometric muscle activity), editorials, conference abstracts, book chapters, theses, systematic reviews and meta-analyses.

Information sources

The search was effectuated in the electronic databases MEDLINE/PubMed, EMBASE, CINAHL, Cochrane Library, Physiotherapy Evidence Database (PEDro), SPORTDiscus and in the Web of Science. Furthermore, a hand search was done using the reference lists of included articles to identify additional and potentially eligible articles that had been missed in the electronic database search. To ensure new articles matching the search terms, e-mail alerts were established from each of the databases if possible. The hits from these two additional sources were also screened for eligibility applying the same criteria as for the articles from the database search.

Search

The search was executed based on the inclusion and exclusion criteria in all of the seven electronic sources mentioned above from inception until March 15th, 2019. In all sources, the advanced search mode was used if available. Where applicable, the same search matrix combining relevant search (if possible, MeSH-) terms with the Boolean operators AND and OR. The following search strategy was applied for PubMed and customized for searches in the six other databases: ((anterior cruciate ligament [Mesh] OR anterior cranial cruciate ligament OR ACL) AND (anterior cruciate ligament injuries[Mesh] OR strains and sprains[Mesh] OR rupture OR tear OR injury OR deficiency) AND (anterior ligament reconstruction[Mesh] OR anterior cruciate ligament/surgery[Mesh] OR reconstructive surgical
procedures[Mesh] OR orthopedic procedure OR orthopaedic procedure OR tendon graft or
tendon transfer OR conservative treatment OR non-surgical OR rehabilitation[Mesh] OR
physical therapy modalities[Mesh] OR physiotherapy OR kinesiotherapy OR exercise[Mesh]
OR instruction OR resistance training[Mesh] OR neuromuscular training OR postoperative
care[Mesh]) AND (neuromuscular control OR neuromuscular activity OR sensorimotor control
OR muscle activity OR active stability) AND (electromyography[Mesh] OR EMG OR
electromyogram OR amplitude OR timing OR mean activity OR peak activity R duration of
activity OR onset OR offset OR on-off-pattern OR pre-activity OR latency OR reflex response)).

Study selection

All hits obtained by the database searches were downloaded to the Rayyan reference
management platform (rayyan.qcri.org). Prior to screening, duplicates were removed. Parallel
to these steps, the obtained hits were also inserted into EndNote (Clarivate Analytics,
Philadelphia, USA) and duplicates removed. Two authors (AB and IK) screened title and
abstract of the records, one by using the software EndNote (Clarivate Analytics, Philadelphia,
USA) and the other one with the help of the free software “rayyan”.61 If in- or exclusion of the
record was unclear, the full text was read, and in-/exclusion criteria were applied. Two authors
(IK, AB) independently decided upon in- or exclusion of all studies; if their decisions did not
match, discussion took place until consensus was achieved. If consensus would not have been
achieved, a third author (IB or HB) would have finally decided upon in- or exclusion of the
record in question; however, this was not necessary.

Risk of bias across studies

The risk of bias of all the included articles was independently assessed by two raters (AB, IK)
by using the Downs and Black checklist20 in a former used, modified form.62,73 For this
systematic review, studies with a total score of 17 or above out of 25 (more than 2/3 of the
maximum total score) were considered as being of high methodological quality, low risk of bias
respectively.73 Studies which reached 13 to 16 points (more than 50% of the maximum total
score) were rated as being of medium quality, and total scores below 13 were rated as being of low methodological quality, high risk of bias respectively. As the aim of this systematic review was to summarize the applied measures for neuromuscular control, the methodological quality of the included studies was of secondary interest. Therefore, no study was excluded due to a low total score in the risk of bias assessment.

Data collection process

After final decision of all studies, data extraction for each eligible study was performed by the first author (AB) with predefined Microsoft® Excel (Microsoft Corporation, Redmond WA, USA) spreadsheet. As all included studies were available as full texts and the provided data were enough for the systematic review, no authors had to be contacted in order to obtain or confirm data. The first author (AB) extracted necessary information from each article describing the study design, groups measured and their characteristics, the tasks to be fulfilled by all participants, and all assessments or methods used to evaluate neuromuscular control. Furthermore, the use of the chosen assessment for neuromuscular control was judged whether it was used as tool to clear the participants for RTS. The second author (IK) controlled the extracted data at random.

Results

Initially, a total of 1178 records were identified through database search. After deduplication, 946 remaining articles were screened for title and abstract. Fifty-eight articles were fully read and assessed for eligibility. From the database search, a total of 31 articles, mainly cross-sectional, case-controlled studies, were included for qualitative analysis. Furthermore, a hand search in the reference lists of included articles yielded to another six hits which could be included. E-mail alerts provided five articles, however, none of them met the inclusion criteria. Reasons for exclusion were participants younger than 18 years, not able to achieve RTS, time since injury or surgery less than 6 months, static or non-functional task, study design (e.g.
systematic review, study protocol), unclear or inadequate outcome, healthy participants or without ACL injury. Details about every step of the search are illustrated in the following flowchart (Fig. 1).

Insert Figure 1 about here.

Figure 1: Flowchart of literature search according to PRISMA guidelines.

Risk of bias assessment

Risk of bias of approximately half (18 studies, 48.6%) of the included studies was medium, six (16.2%) showed high methodological quality and 13 studies (35.1%) were of low quality. The main reasons for a medium to low methodological quality were due to an unclear description of participants and prior interventions, confounding factors, and incompletely reported results.

Table 2: Risk of Bias assessment with the adapted Downs & Black checklist.

Insert Table 2 about here.

Characteristics of included studies

All included studies were case-control studies, except two which where case series or a single-case study. Two reported a retrospective or secondary data analysis or provided a subgroup analysis from a larger trial. Thirty-four studies compared the ACL participants with at least one control group (other ACL treatment, e.g. surgical versus conservative, or healthy controls), the remaining three studies made a comparison between the injured and the non-injured leg of the participants or compared the pre-injury status with follow-up data from pre- and post-surgery.
The number of included, adult participants with ACL injury varied from \( N = 1^{98} \) to a maximum of \( N = 70^{39} \) with a wide range of described physical activity from “normal”\(^{13} \), “regular”\(^{46} \), “active in at least one sport”\(^{38} \), TAS of minimal 3\(^{84} \), minimal 2h/week\(^{1,2} \) to athletes at level I sports including jumping, pivoting and hard cutting\(^{6,23,57} \), elite soccer players\(^{6,17,66,98} \) or elite skiers.\(^{36} \)

Some authors restricted study participation to either males\(^{1,2,12,13,17,18,28,65,66,67,68} \) or females\(^{10,46,59,60,84,85,98} \), others measured females and males.\(^{6,9,15,23,36,38,39,42,43,54,55,56,75,76,77} \)

Three studies did not provide any data about the gender of their participants.\(^{40,45,57} \)

More patient characteristics of included studies can be found in table 3.

Insert Table 3 about here.

Table 3: Participants’ characteristics of included studies

| Abbreviations: ACLD = anterior cruciate ligament deficiency (conservative/non-surgical treatment); ACLR = anterior cruciate ligament reconstruction/repair (surgery); BPTB = bone-patella-tendon-bone technique for ACLR; Level I: sports are described as jumping, pivoting and hard cutting sports; Level II sports: also involve lateral motion, but with less jumping or hard cutting than level I; n.a. = not applicable; n.s. = not stated; RTA = return to activity (return to participation); RTS = return to sports; RTP = return to performance; TAS = Tegner Activity Score; TLS = Tegner & Lysholm Score; TSK = Tampa Scale for Kinesiophobia; wk = week; vs. = versus |
|---|

All included studies used surface EMG as method to assess neuromuscular control and provided EMG-related variables such as peak and mean amplitudes, timing and peak of muscle activity, preparatory and reactive muscle activity, on- and offset of muscular activation, co-activation/co-contraction ratios, asymmetry index. The outcome variables were expressed as percentage of maximum voluntary (isometric) contraction (%\( \text{MVIC} \) or %\( \text{MVC} \)) or reported in microvolts or milliseconds according to the variable chosen in amplitude or time domain.

The outcome variables were expressed as percentage of maximum voluntary (isometric) contraction (%\( \text{MVIC} \) or %\( \text{MVC} \)) or reported in microvolts, milliseconds according to the variable chosen.

The number of muscles assessed ranged from one\(^{38,65} \) to ten.\(^{23} \) Mainly muscle activity of four muscles of the thigh, vastus lateralis, vastus medialis, biceps femoris and semitendinosus, had
been assessed. However, there were also studies measuring the adductor longus\textsuperscript{18,39}, gluteus medius\textsuperscript{18,59,60}, gluteus maximus\textsuperscript{23,42,43,55,56,59,60}, and calf muscles such as soleus, medial and lateral gastrocnemius.\textsuperscript{23,28,40,54,55,56,75,76,77} The tasks used were very broad: there were activities of daily life such as walking on even ground and downhill\textsuperscript{2,9,13,39,40,45,76,85}, and stair climbing.\textsuperscript{15,75} Other activities went more towards sports such as running\textsuperscript{26,65,66,67,85} and jumping\textsuperscript{10,12,18,23,36,38,42,43,54,55,56,57,59,60,75,84,85} where mainly the single-leg jump for distance, drop jumps and countermovement jumps were used. Some authors chose typical rehabilitation exercises such as forward lunges\textsuperscript{1}, Nordic hamstrings or hamstrings curls\textsuperscript{6} and squats.\textsuperscript{46} At the other end of the scale, more complex, highly demanding, sport-specific tasks such as an instep soccer kick\textsuperscript{17} or a side cutting maneuver\textsuperscript{98} were reported. Only few research groups used perturbation platforms to simulate injury mechanisms during walking\textsuperscript{45} or squatting\textsuperscript{46,68}, or applied devices to stress the ACL in the posterior-anterior direction.\textsuperscript{84} In addition, two studies even investigated the influence of fatigue on neuromuscular control.\textsuperscript{42,43}

Details regarding methodological aspects of all included studies can be found in table 4 below.

\textit{Insert table 4 about here.}

| Table 4: Characteristics of methods of included studies |

- **Abbreviations:** AL = adductor longus muscle; BF = biceps femoris muscle; sEMG = surface electromyography; GC = gastrocnemius muscles; GM = gluteus medius muscle; GMax = gluteus maximus muscle; GRF = ground reaction force; Hz = Hertz; LG = gastrocnemius lateral head; LH = lateral hamstring muscle; MG = gastrocnemius medial head; MH = medial hamstring muscle; ms = miliseconds; n.a. = not applicable; n.s. = not stated; RF = rectus femoris muscle; RTS = return to activity (return to participation); RTS = return to sports; RTP = return to performance; SI = symmetry index; SM = soleus medialis muscle; SL = soleus lateralis muscle; SO = soleus muscle; SPM = Statistical Parametric Mapping; ST = semitendinosus muscle; VL = vastus lateralis muscle; VM = vastus medialis muscle; vs. = versus; WA = weight acceptance

**Decision for Return to Sports RTS**

None of the included studies used the surface EMG measurements to decide upon readiness for RTS (Table 4). However, the results from about a third of the studies (32.4%, 12 studies)
could provide useful information by the choice of the assessed groups such as copers versus non-copers, intervention and control group from the same team or level/league, data from pre-injury/pre-surgery including post-surgical follow up or participants with full RTS versus limited RTS. In addition, two studies even investigated the influence of fatigue on neuromuscular control.
Discussion

The aim of this systematic review was to summarize the scientific literature regarding assessments for neuromuscular control in patients with an ACL injury (either treated surgically or conservatively). The second aim was to analyze whether these assessments for neuromuscular control were used to decide upon readiness for RTS in these patients.

There were a lot of factors in the study population which could have an influence on neuromuscular control:

**Influence by type of comparison (intra- versus inter-subject)**

The use of the contralateral, non-injured leg in intra-subject comparison, without a “real” control group may lead to an overestimation of the neuromuscular performance in the ACL-reconstructed or -injured leg. After ACL reconstruction, functional performance is often expressed with the Lower Limb Symmetry Index (LSI). However, the LSI may overestimate the time point of RTS ACL surgery, and therefore lead to an increased risk for secondary injury. In acutely injured ACL patients, intra-individual comparison showed bilateral consequences during stair ascent and indicates an alteration in the motor program (“pre-programmed activity”). In addition, in case of a case-controlled study design, the subjects in the control group should be matched to the ACL participants regarding age, body mass, height, activity level and leg dominance.

**Influence by level of activity and fatigue**

Some of the included studies used very challenging, sports-specific task to assess neuromuscular control, some even assessed neuromuscular control after fatiguing tasks. It is known that most of ACL tears are non-contact injuries happening at the end of a training session or a play. Therefore, the closer the task to the sports and injury-risky situation, the safer the decision towards full RTS or even return to competition will be. However, assessing performance-based tests or movement quality may be more difficult to standardize, require more complex equipment and large amounts of space. But if only impairments will be tested, there will be a lack of information regarding an “athlete’s capacity to cope with the physical and
mental demands of playing sport”. Furthermore, impairment measures are also poorly related to participation. It is therefore recommended to search for a standardized assessment close to the injury mechanism.

Influence by sex

Not all included studies reported findings of mixed groups separately by gender. Some did not even state the sex of the participants. This could partly be explained by the date of publication as gender difference in ACL patients has not been in the focus of research 20 years before. But nowadays, a lot of facts concerning females are known: Female athletes are more likely to suffer from an ACL injury than men: their increased risk is probably multifactorial. However, several studies indicate that hormonal factors play a role contributing to an increased laxity of ligaments in the first half of the menstrual cycle. The higher risk for females to suffer from an ACL injury can be explained by motion and loading of the knee joint during performance. The ligament dominance theory says that female athletes typically perform movements in sports with a greater knee valgus angle than men. Therefore, the amount of stress on the ACL in these situations is higher because there is a high activation of the quadriceps despite limited knee and hip flexion, greater hip adduction and a large knee adduction moment. Moreover, females typically land with an internally or externally rotated tibia, leading to an increased knee valgus stress due to greater and more laterally orientated ground reaction forces. A systematic review and meta-analysis reported equal results in women and men for outcomes such as anterior drawer, Pivot-Shift and Lachman test, hop tests, quadriceps or hamstring testing, International Knee Documentation Committee (IKDC) knee examination score and loss of range of motion. However, female patients showed inferior, statistically significant subjective and functional outcomes such as laxity, revision rate, Lysholm score, TAS and incidence of not returning to sports.

Influence by treatment

The included studies reported different treatment options (surgical reconstruction with different graft types, conservative treatment). Depending on the classification of the participants in copers and non-copers, the results in neuromuscular control may differ from a population of
ACL-reconstructed (ACL-R) participants. Therefore, all researchers who worked with copers and non-copers made intra- and inter-group comparisons without an ACL-R group. A Cochrane review revealed low evidence for no difference in young, active adults after two and five years after the injury, assessed with patient-reported outcomes. However, many participants with conservative treatments remain symptomatic (non-copers with unstable knee) and therefore, later opt for ACL surgery. Furthermore, the choice of graft would influence the neuromuscular control of measured muscles due to the morbidity of the harvesting site of the graft (hamstrings e.g.).

**EMG variables**

The provided EMG-related variables were in accordance to the ones mentioned in a systematic review searching for knee muscle activity in ACL-deficient (ACLD) patients and healthy controls during gait. Another study summarized and quantitatively analyzed muscle onset activity prior to landing in patients after ACL injury and provided values in milliseconds and in percentage of gait cycle as some of the included studies did. However, some of the researchers only provided integrated EMG values which would make it difficult to be compared to other studies using the respective units (milliseconds, millivolts) or widely used percentage values (%MVIC, %MVC).

If the researchers mentioned the procedures for collecting EMG data, they referred to standardized applications and guidelines such as SENIAM.

**Return to sports (RTS)**

Regarding the determination of RTS after ACL reconstruction, there is some evidence for the use of functional performance tests, which had also been widely used in the included studies. Multiple functional performance measures – a battery including strength and hop tests, quality of movement and psychological tests - might be more useful for the determination of RTS than a single performance measure. However, it is still unclear, which measures should be used to bring athletes safely back to RTS with a low risk of a second ACL injury. Currently used RTS criteria may be suboptimal at reducing the risk of a second ACL injury. A recently published scoping review reported the following RTS criteria: time, strength tests, hop tests,
patient-reports, clinical examination, thigh circumference, ligamentous stability, range of motion, effusion and performance-based criteria. Recovery of neuromuscular function was mentioned to be important because of the existing connection between the variables time since surgery and the risk for re-injury of the knee joint but adequate assessment procedures to assess neuromuscular function are still a matter of debate.24

Limitations

The sample size of all the studies was quite low, however providing reasonable sample size calculations and depending on the variable investigated, the results were acceptable. Furthermore, the more restrictive the inclusion criteria for the participants, the more homogeneous the intervention and the control groups were, but the more challenging the recruitment process was, leading to smaller groups to be investigated.

The used assessment for the risk of bias, the Downs and Black checklist20 (in a former used, modified form62,73 is designed for randomized and non-randomized controlled studies, however, the latter score lower in some items, get lower total scores and therefore a worse overall rating of the methodological quality. Despite this disadvantage, we decided to use the modified checklist as we could assess all the study designs included in the presented systematic review.

Conclusions

Despite a wide range of assessments for neuromuscular control, none was used to decide upon a safe RTS. Additional studies are needed to define readiness towards RTS by assessing neuromuscular control in adult ACL patients. Clinicians should be aware of LSI problems (non-injured side is affected, probably not a good reference, pre-surgery/-injury scores would be perfect but not realistic in recreational athletes, probably in professional sports) and that physical performance batteries do not reflect neuromuscular control needed for a safe RTS.
More research is needed to find a reliable and valid, EMG-related variable to assess neuromuscular control in a standardized situation, close to the injury mechanism and as sport-specific as possible.

**Conflict of interest**

All authors declare to have no conflict of interest.

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Figure 1: Flowchart of literature search according to PRISMA guidelines. 

N=1178 records identified through database searching
N=173 of additional records identified through other sources:
N=158 out of reference lists of included articles
N=5 from e-mail alerts

N=943 records after duplicates removed

N=1116 records screened (title and abstract)
N=1037 records excluded

N=79 full-texts assessed for eligibility
N=42 full-texts excluded with reasons:
- RTS not achieved (N=10)
- Age < 18 yrs (N=7)
- Time since injury/surgery (N=7)
- Static functional task (N=6)
- Study design (N=7)
- Unclear/wrong outcome (N=2)
- No ACL injury/healthy (N=1)

N=37 studies included in qualitative synthesis
| Parameter   | Criteria                                                                                                                                 |
|-------------|-------------------------------------------------------------------------------------------------------------------------------------------|
| Participants (P) | Adult people (age of 18 – 65 years) who sustained an ACL injury, either treated conservatively or surgically (repaired with an autograft) |
| Intervention (I) | Assessment of neuromuscular control, active knee stability, sensorimotor control, active stability of the lower limb or similar during dynamic activities |
| Control (C)  | Uninjured limb / contralateral side or contralateral lower limb of the ACL-injured participant, or a healthy control group                      |
| Outcomes (O) | Any EMG-related outcome describing neuromuscular activity/control in domains of time, amplitude etc.; parameters describing EMG activity of lower limb muscles; related to EMG variables, such as amplitude, timing, mean or peak activity, duration of activity, onset and offset / on-off-pattern respectively, pre-activity, latency, reflex response (Shanbehzadeh et al., 2017; Theisen et al., 2016) |
| Study design (S) | Any laboratory or interventional study, cross-sectional or longitudinal, randomized controlled trials, clinically controlled trials without randomization, laboratory/experimental controlled trials etc. |
| Authors & year       | Design | Reporting | External validity | Internal validity | Power Score Rating |
|---------------------|--------|-----------|-------------------|-------------------|--------------------|
| Alkjaer et al. 2003 | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 14 medium |
| Alkjaer et al. 2002 | CCS    | 1 1 1 1 | 2 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 15 medium |
| Amason et al. 2014 | CCS    | 1 1 1 1 | 2 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 15 medium |
| Boerboom et al. 2001 | CCS    | 1 1 1 1 | 2 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 11 high |
| Briem et al. 2016  | CCS    | 1 1 1 1 | 2 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 18 low  |
| Bryant et al. 2009 | CCS    | 1 1 1 1 | 2 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 16 medium |
| Bulgheroni et al. 1997 | CCS    | 1 1 1 1 | 2 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 9 high  |
| Busch et al. 2019  | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 14 medium |
| Cordeiro et al. 2015 | CCS    | 1 1 1 1 | 2 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 1 14 medium |
| Dashi Rostami et al. 2019 | CCS    | 1 1 1 1 | 2 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 15 medium |
| Gokeler et al. 2010 | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 12 high  |
| Hansen et al. 2017  | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 12 high  |
| Jordan et al. 2016  | CCS    | 1 1 1 1 | 2 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 1 14 medium |
| Knoll et al. 2004   | CCS    | 1 1 1 1 | 2 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 10 high  |
| Kuster et al. 1995  | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 12 high  |
| Lessi & Serrao 2018 | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 1 14 medium |
| Lessi et al. 2018   | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 1 17 low   |
| Lustosa et al. 2011 | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 17 low   |
| Madhavan & Shields 2011 | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 1 17 medium |
| Nyland et al. 2010  | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 15 medium |
| Nyland et al. 2013  | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 18 low   |
| Nyland et al. 2014  | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 17 low   |
| Oliver et al. 2018  | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 1 14 medium |
| Ortiz et al. 2007   | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 11 high  |
| Ortiz et al. 2017   | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 10 high  |
| Ortiz et al. 2018   | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 15 medium |
| Patas et al. 2012   | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 8 high   |
| Patas et al. 2010   | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 13 medium |
| Patas et al. 2009   | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 12 medium |
| Pincheira et al. 2013 | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 13 medium |
| Rudolph et al. 2000 | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 15 medium |
| Rudolph et al. 2001 | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 15 medium |
| Rudolph & Snyder-Mackler 2000 | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 13 medium |
| Swanik et al. 2004  | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 13 medium |
| Swanik et al. 1999  | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 10 high  |
| Zebis et al. 2017   | CCS    | 1 1 1 1 | 1 1 1 1 | 1 1 | X 0 1 X X 1 X 1 1 X X X X 1 X | 0 11 high  |

Legend: CCS = case-control study, CS = case study, R = retrospective (secondary analysis), P = prospective, RoB = risk of bias, X = not applicable or unclear, IC = intrasubject comparison (injured leg versus healthy leg); green = from database search

Colours: green = database searches; blue = handsearch out of reference lists of included studies
| Author & Year | Number of participants (age, sex, group-specific inclusion criteria) | Diagnosis & treatment (only ACL) | Level of activity or sports (RTA, RTS, RTP) | Intervention Group | Control Group 1 (ACL patients) | Control Group 2 (healthy people) | significant difference between groups? |
|--------------|--------------------------------------------------------------------|----------------------------------|---------------------------------|-------------------|-----------------------------|-----------------------------|-----------------------------------|
| Alkjaer et al. 2002 | N = 23 all male; N = 17 males with complete ACLD, N = 6 healthy controls | complete ACLD, min. 6 months of rehab program after injury; Lysholm and Tegner scores applied to separate ACLD-participants in copers and non-copers | min. 2h/wk | N=8; male copers; weight: 76.6 kg (SD, 14.8); height: 1.81 m (SD, 0.06); age: 26.0 years (SD, 4.0); mean Lysholm & Tegner scores: 85.5 (SD, 5.3) and 6.25 (SD, 0.5), respectively; mean time after injury: 34.0 months (SD, 39.2) (range 6.0-120.0) | N=9; male non-copers; weight: 80.6 kg (SD, 7.1); height: 1.79 m (SD, 0.06); age: 31.2 years (SD, 6.0); mean Lysholm & Tegner scores: 74.0 (SD, 7.1) and 3.8 (SD, 0.6), respectively; mean time after injury: 51.8 months (SD, 44.0) (range 6.0-144.0) | N=6; male healthy; weight: 73.8 kg (SD, 7.9); height: 1.81 m (SD, 0.05); age: 31.0 years (SD, 1) | no |
| Alkjaer et al. 2003 | N = 29; N = 19, all male, complete chronic (post-injury time 6 months or more) ACLD and N = 10 healthy males as controls for EMG | complete chronic ACLD, min. 6 months of rehab program after injury, ACL injury clinically diagnosed by experienced orthopaedic surgeons with Lachman, Anterior Drawer and Pivot-Shift Tests; Lysholm and Tegner scores applied to separate ACLD-participants in copers and non-copers | min. 2h/wk of physical activity | N=9; male copers; (mass: 76.7 (14.3)kg, height: 1.81 (0.06)m, age: 28.3 (6.1) years); mean Lysholm & Tegner scores: 87.1 (5.8) and 6.1 (0.6) respectively; mean time after injury: 39.1 (42.3) (range 6.0-120.0) months | N=10; male non-copers; mass: 80.4 kg (SD, 6.7); height: 1.79 m (SD, 0.05); age: 31.7 years (SD, 5.9); mean Lysholm & Tegner scores: 74.0 (SD, 7.1) and 3.8 (SD, 0.6), respectively; mean time after injury: 55.0 months (SD, 42.7) (range 6.0-144.0) | N=10; male healthy; mass: 77.5 kg (SD, 7.9); height: 1.82 m (SD, 0.05); age: 31.0 years (SD, 2.8) | no |
| Arnason et al. 2014 | N = 36; N = 18, female and male soccer players with ACLR (post-injury time 1 - 6 years) and N = 18 healthy female and male soccer players from the same team (men's and women's top league in Iceland), matched for gender, height, body mass and "involved" side designation, as controls | ACLR: successful return to full participation in soccer; no muscle strain injury in knee flexors in past 3 months, no orthopaedic condition excluding from soccer | full participation in soccer (Icelandic top leagues) | N = 8 males, N = 10 females --> N=18 ACLR participants in total; all participants mean mass: 69.2 (11.8)kg, height: 1.73 (0.09)m, age: 23.7 (3.6) years; mean BMI 23.0 (2.4)kg/m2; left/right dominance 2/16; involved/uninvolved is the dominant leg 8/10; time since injury 1 - 6 years | n.a. | N = 8 males, N = 10 females --> N=18 healthy participants in total; all participants mean mass: 68.6 (11.2)kg, height: 1.73 (0.09)m, age: 20.5 (3.7) years; mean BMI 22.7 (2.0)kg/m2 | no |
| Study                  | N = | N = | N = | Age | Height | BMI | Diagnosis | Treatment | Outcome | Matched Controls | Matched Controls | Matched Controls | Matched Controls | Matched Controls | Matched Controls | Matched Controls | Matched Controls | Matched Controls | Matched Controls |
|------------------------|-----|-----|-----|-----|-------|-----|-----------|-----------|---------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Boerboom et al. 2001   | 20  | 10  | 10  | 22 | 1.71  | 22.8| ACLD: ACL rupture confirmed by physical examination and arthroscopy, conservative treatment | before injury: all ACLD participants at level I (of the International Knee Documentation Committee, IKDC, score). after injury: level I (all copers), level II and III (noncopers) | N = 5 copers (all males) with ACLD, median age 32 years, range 21-46, median time between primary injury and gait analysis: 39 months (13-67), acting at same level of sports and daily activities (level I) as before the injury | N = 5 noncopers (3 males, 2 females) with ACLD, with functional instability, median age 27 years, range 23-35, median time between injury and gait analysis: 22 months (16-47), acting at lower level (4 at level III, 1 at level II) | N = 10 healthy males, without a history of knee injury, median age was 22 years (range 18-24) | no in patient groups (age, time between injury and gait analysis), in comparison with healthy controls: n.s. |
| Briem et al. 2016      | 36  | 18  | 18  | 22 | 1.71  | 22.8| no information about diagnosis or treatment; exclusion criteria: current musculoskeletal injury, lower limb muscle strain within 3 previous months, not being able to do single-limb hops | ACLR: successful return to competition with their teams; healthy: full participation in soccer (Icelandic top leagues) | N = 18 females, ACLR, recruited via advertisement from teams competing in the tip leagues in three sports team handball (n = 5), basketball (n = 4), and football (n = 9). In 12 instances, the surgical limb was the individual’s dominant one. Characteristics: mean mass: 67.2 (7.8)kg, height: 1.714 (0.05)m, age: 22.7 (3.5) years; mean BMI 22.8 (2.4)kg/m2; involved/uninvolved is the dominant leg 12/18; time since injury 1 - 6 years | N = 18 healthy females recruited from the same teams, matched for age, height, weight. Characteristics mean mass: 66.3 (7.1)kg, height: 1.708 (0.05)m, age: 21.5 (2.7) years; mean BMI 22.7 (2.2)kg/m2; no n.s. |
| Bryant et al. 2009     | 59  | 10  | 27  | 25 | 1.71  | 22.8| Cincinnati Knee Rating System (0-100 points); ACLD: full ROM, neg. Lachman, neg. Pivot-Shift; confirmed isolated ACL rupture (arthroscopic) min. 1yr before testing; same orthopaedic surgeon for all ACLR | n.s., but hopping required | N = 10 male with ACLD (18-35 years); N = 27 matched males with ACLR (14 with patella tendon graft, 13 with combined semitendinosus and gracilis graft); N = 22 matched-controls | N = 10 male with ACLD (18-35 years); | N = 22 matched (age, activity level, anthropometrics), healthy controls no history of trauma or disease in either knee and no evidence of abnormality on clinical examination | no |
| Bulgheroni et al. 1997 | 30  | 15  | 10  | 28 | 1.71  | 22.8| ACLR: BPTB graft | normal activity | N = 15 males with ACLR, age 25 ± 3 years, time after reconstruction: 17 ± 5 months, normal activity | N = 10 males with ACLD, age 27 ± 6 months after injury (range 8-48 months), knee instability | N = 5 males, healthy controls, age 28 ± 3 years, no history of musculoskeletal pathology | n.s. |
| Study | N = 20; N = 10 ACL-R (age: 26 ± 10 years; height: 175 ± 6 cm; mass: 75 ± 14 kg) and N = 10 healthy matched controls (age: 31 ± 7 years; height: 175 ± 7 cm; mass: 68 ± 10 kg) with normal activity 5 months, knee instability | N = 10 ACLR participants; age 26 ± 10 years, height 175 ± 7 cm, weight 75 ± 14 kg, 3 females & 7 males, Tegner 7 ± 2 | N = 10 healthy participants (ACL-I) without prior injury of the knee, age 31 ± 7 years, height 175 ± 8 cm, weight 68 ± 10 kg, 3 females & 7 males, Tegner 6 ± 1; matched according to age, height, weight, gender, (sports) activity level and leg dominance |
|-------|--------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|
| Study | N = 17 male players from Portuguese Soccer League; N = 8 with ACLR and N = 9 healthy controls | N = 8 ACL-R: mind. 6 months post-surgery on dominant leg, bone-tendon-bone arthroscopy, no problems at end of physiotherapy phase | N = 9 healthy controls; professional male soccer players (age = 24.0 ± 3.5 years, height = 1.76 ± 0.05 m, mass = 72.9 ± 3.5 kg), no knee or leg injuries or previous ACL surgeries |
| Study | N = 36; N = 12 ACL-D, N = 12 ACL-R; N = 12 healthy controls; all male athletes for patients: primary unilateral ACL injury | athletes, regular sports participation, ACLD = copers | N = 12 healthy controls; no knee injury, no knee pain |
| Study | N = 29; N = 9 ACLR patients, N = 11 healthy controls | level I-II athletes | N = 11 healthy subjects (8 males, 3 females), level I-II athletes, |
| Study               | N = 37; N = 18 male patients, N = 19 healthy participants | ACLR: discharged from rehabilitation facility, ready to return to on-field sports specific activity | N = 19 male ACLR at the end of their rehabilitation and allowed to running, 7 ± 2 months post-surgery; N = 8 with a BPTB graft, age 27 ± 7.69 years, weight 80.40 ± 9.44 kg, height: 178.49 ± 7.29 cm; N = 10 with a hamstring graft, age 26 ± 3.84 years, weight 74.16 ± 7.19 kg, height 176.89 ± 5.6 cm, | n.a. | N = 19 injury-free male controls, age 35.4 ± 7.8 years, weight 77.6 ± 8.4 kg, height 179.1 ± 5.6 cm | n.s. |
|---------------------|----------------------------------------------------------|--------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|------|---------------------------------------------------------------------------------|------|
| Hansen et al. 2017  | N = 22; N = 11 ACLR, N = 11 control; elite skiing athletes from Canada’s national alpine skiing and skier cross team, | ACLR: primary ACL injury, at least 12 months post-surgery, actively competing athletes at the Federation International de Ski World Cup level with full medical clearance to compete | elite ski racers, Tegner activity score 10, competing at international level | n.a. | N = 11 matched controls with no history of ACL injury (females, n = 5; age = 21.8 ± 3.2 yr, mass = 63.7 ± 4.6 kg; males, n = 6; age = 23.3 ± 3.3 yr, mass = 84.7 ± 5.1 kg; active competitors at the international level defined as participation in the Federation International de Ski World Cup circuit | n.s. |
| Klyne et al. 2012   | N = 26; N = 15 ACLD, N = 11 healthy controls             | ACLD: chronic, unilateral ACL rupture demonstrated with a positive pivot shift and confirmed by orthopaedic surgeon, plus a history of subjective stability and a right skill preference in the lower limb, without previous ACL surgery | active in at least one sport | n.a. | N = 11 healthy controls, 9 males, 2 females (29 ± 8 years), active in at least one sport, no other musculoskeletal problems, right skill preferred in their lower limb, matched for age and activity level | n.s. |
| Study | Sample Size | Population | Age, Height, Weight | Activity | Follow-up | Notes |
|-------|-------------|------------|---------------------|----------|----------|-------|
| Knoll et al. 2004 | N = 76; N = 25 ACLR (pre- and postsurgery), N = 51 healthy controls | No previous injury, no meniscal damage, BPTB graft, rehabilitation program | N = 25 with ACLD (before surgery, later ACLR), 18 males, 7 females; first subgroup: 9 male with acute ACLD (mean age: 29.86±6.52 years, mean height: 1.77±0.8 metres, mean mass: 81.40 kg±9.06 kg); second subgroup: 9 males with chronic ACLD (mean age: 39.70±2.1 years, mean height: 1.70±0.21 metres, mean mass: 88.1±20.2 kg) | Non-professional athletes pursuing some sports two to three times a week. | Same population of ACLD, but after surgery → ACLR, measured at 6 weeks, 4, 8 and 12 months postsurgery | N = 25 healthy controls, 31 males, 20 females, mean age: 31.70±4.1 years, mean height: 1.71±0.12 metres, mean mass: 72.1±25.2 kg, no pathology that would affect gait, unfamiliar with treadmill walking | n.s. |
| Kuster et al. 1995 | N = 21 with ACLD, N = 12 healthy controls | ACLD: arthroscopically confirmed complete ACL ruptures at least 1 year previously | N = 19 with 21 ACLD, mean age: 28.2 years (range 19-42), mean height: 174.1cm (156-187.6), mean weight: 77.9kg (50-112), mean time since injury: 45 months (range of 12-108), mean Lysholm score 82 (range 55-100), | Tegner activity scores range 6-10 (mean 8.2) before injury and 3-9 (mean 5.3) after injury; controls: Tegner activity scores range 4-8 (mean 6.1) | N = 12 healthy controls, similar in height and weight, mean height: 171.2 cm and weight 70.8 kg, no lower limb injury | N = 20 healthy controls, 13 male, 7 female, at least 12 months post-surgery, 13 with hamstring ipsilateral autografts, 7 with BPTB ipsilateral autograft | n.a. |
| Lessi & Serrao 2017 | N = 20 with ACLR, N = 20 healthy controls | ACLR: non-contact ACL injury, unilateral reconstruction of the ACL with no prior history of a contralateral ACL injury, no recent history of an ankle, hip, spine, or contralateral knee injury in the past 12 months; rehabilitation completed, cleared to RTS by both their physician and physical therapist | N = 20 with ACLR, 13 male, 7 female, at least 12 months post-surgery, 13 with hamstring ipsilateral autografts, 7 with BPTB ipsilateral autograft | Recreational sports, meaning aerobic or athletic activity at least three times per week | N = 20 healthy controls, 13 male, 7 female, no history of any dysfunction or previous joint trauma, no prior history of ACL injury or injury of lower extremity in last 12 months; were matched by age, sex, weight, and current sporting activity type | n.a. |
| Study                  | N = 14 ACLR (7 males, 7 females) | N = 7 males ACLR | N = 7 females ACLR | n.a. | no, except men were taller than women (P < 0.001) and performed a higher number of sets of the protocol before becoming fatigued their reconstructed limb [P = 0.006]. |
|-----------------------|----------------------------------|------------------|-------------------|------|----------------------------------------------------------|
| Lessi et al. 2018     | from study of Lessi & Serrao, 2017 | non-contact ACL injury; unilateral ACLR with autologous ipsilateral graft at least 12 months before recruitment; undergone a rehabilitation program; returned to sports participation; no contralateral ACL injury | recreational sports | N = 7 males ACLR, age 23.90 ± 2.80 years, height 1.80 ± 0.1m, body mass 83.3 ± 7.8 kg, 3 with BPTB graft, 4 with flexor tendons grafts | N = 7 females ACLR, age 24.7 ± 5.3 years, height 1.63 ± 0.1m, body mass 65.9 ± 9.0 kg, 2 with BPTB graft, 5 with flexor tendons grafts |
| Lustosa et al. 2011   | N = 25 ACLR; N = 15 with Cincinnati Knee Rating System (CKRS) > 90 points (full RTS), N = 10 with CKRS < 85 points (limited RTS) | at least 2 years post-surgery, same rehabilitation program which allowed full RTS activities 7 months post-surgery | full RTS allowed, not further specified | N = 10 ACLR with CKRS 77.30 ± 6.14 points, age 33.4 ± 7.53 years, time between injury and surgery 52.20 ± 31.33 months, 3 with associated meniscal injuries, 7 without | N = 15 ACLR with CKRS 96.87 ± 2.75 points, age 34.5 ± 8.85 years, time between injury and surgery 67.3 ± 28.5 months, 3 with associated meniscal injuries, 12 without |
| Madhavan & Shields 2011 | N = 24 all female; N = 12 with ACLR, N = 12 healthy controls | complete reconstruction of the ACL with BPTB or HS autograft; ability to climb stairs without difficulty, full joint ROM, SR-36, KOOS, IKDC | regular physical activity, TAS | N = 12 females ACLR, age 22.4 ± 2.4 yrs, mean time from surgery 3.7 ± 1.8 yrs, weight 144.1 ± 19kg, height 164.5 ± 5.28cm, Tegner (current) 7.1 ± 2.4 | N = 12 healthy females, no previous history of knee pathology, age 24.1 ± 3.2 yrs, weight 136.5 ± 20.3kg, height 163.8 ± 7.3cm, Tegner (current) 6.9 ± 2.1; matched to age, |
| Nyland et al. 2010    | N = 70 ACLR; N = 35 males; N = 35 females, 5.3 ± 3 years after surgery | minimum of 2 years since unilateral primary ACL reconstruction with allografts performed by same surgeon, standard rehabilitation program with sufficient adherence | met or exceeded standard accepted return-to-sports activity goals of a minimum 85% bilateral equivalence with single-leg hop-for-distance testing and 60°/s isokinetic peak knee extensor and flexor torque testing | N = 35 males with ACLR, age 7, height 180.3 ± 6.9cm, weight 88.9 ± 13.3kg, time after surgery 5.6 ± 3.2 yrs | N = 35 females with ACLR, age 7, height 166.6 ± 7.1cm, weight 68.2 ± 18.9kg, time after surgery 5.1 ± 2.6 yrs |
| Study            | N       | Sex   | Age ± SD (yrs) | Height ± SD (cm) | Weight ± SD (kg) | Time post-surgery ± SD (yrs) | IKDC ± SD (score) |
|------------------|---------|-------|----------------|------------------|--------------------|-------------------------------|-------------------|
| **Nyland et al. 2013** | N = 70 ACLR; 35 male and 35 females | 5.3 ± 3 years after surgery | secondary analysis of Nyland et al., 2010 | minimum of 2 years since unilateral primary ACL reconstruction with allografts performed by same surgeon, standard rehabilitation program with sufficient adherence | met or exceeded standard accepted return-to-sports activity goals of a minimum 85% bilateral equivalence with single-leg hop-for-distance testing and 60°/s isokinetic peak knee extensor and flexor torque testing | N = 24 ACLR well-trained/frequently sporting, 50% males, age at surgery 33.1 ± 13.5 yrs, height 171.7 ± 9.7 cm, weight 79.4 ± 23.2 kg, time post-surgery 5.4 ± 1.1 yrs, IKDC 87.3 ± 11.5 | no healthy control group, but N = 20 ACLR highly competitive subjects, 50% males, age at surgery 26.5 ± 9.4 yrs, height 176.5 ± 9.4 cm, weight 76.8 ± 13.9 kg, time post-surgery 4.6 ± 3.0 yrs, IKDC 91.0 ± 9.4 |
| **Nyland et al. 2014** | N = 65 ACLR; 32 male and 33 females | 5.2 ± 2.9 years after surgery | Subject group assignments were made based on how they responded to the following question: “Compared to prior to your knee injury how capable are you now in performing sports activities”, very capable (group 1), capable (group 2), or not capable (group 3) | minimum of 2 years since unilateral primary ACL reconstruction with allografts performed by same surgeon, standard rehabilitation program with sufficient adherence | met or exceeded standard accepted return-to-sports activity goals of a minimum 85% bilateral equivalence with single-leg hop-for-distance testing and 60°/s isokinetic peak knee extensor and flexor torque testing | N = 23 “capable = group 2”, 52.2% males, age at surgery 29.3 [24.1, 34.4] yrs, height 172.8 [168.4, 177.3] cm, weight 76.8 [68.3, 85.2] kg, time post-surgery 5.4 [4.2, 6.6] yrs, IKDC 87.2 [82.1, 92.4] | N = 22 “not capable = group 3”, 45.5% males, age at surgery 33.6 [26.4, 39.1] yrs, height 172.1 [167.1, 177.1] cm, weight 79.7 [68.0, 91.3] kg, time post-surgery 5.2 [3.8, 6.5] yrs, IKDC 78.6 [71.7, 85.5] | no healthy control group, but N = 20 “very capable = group 1”, 50% males, age at surgery 26.5 [21.9, 31.8] yrs, height 176.5 [170.4, 180.1] cm, weight 76.8 [67.4, 80.3] kg, time post-surgery 4.6 [3.8, 6.2] yrs, IKDC 91.0 [84.1, 94.6] |
| **Oliver et al. 2018** | N = 25 ACLD, mean age 22 ± 4.61 years, mean mass 71.18 ± 10.57 kg, mean height was 177.55 ± 9.69 cm | 4.6 months post-surgery for questionnaires, at 6 months for jumps | complete ACL tear was based on clinical symptoms, on positive Lachman’s and pivot shift tests, and was confirmed by magnetic resonance imaging; reconstruction 2–3 months after the injury by same surgeon using BTB technique, | more than 200 h of sports activity per year, including jumping, pivoting and twisting actions | Injured knee | non-injured knee | n.a. | n.a.

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| Study            | Participants | Methods | Findings |
|------------------|--------------|---------|----------|
| Ortiz et al. 2008 | N = 28 females; N = 13 ACLR, N = 15 non-injured controls | Not controlled for graft/surgery or rehabilitation protocol (only similarities); at least 1 year postsurgery, no multiple surgeries on the same knee. Recreational fitness activities such as jogging, running, and weight lifting, none of the participants formed part of any intercollegiate, varsity, or competitive sport team. | N = 14 physically active young women with ACLR (age, 25.4 ± 3.1 years; height, 167.3 ± 9.3 cm; body mass, 63.2 ± 6.7 kg; mean time after surgery 7.2 ± 4.2 years (1-16 years after reconstruction); N = 9 with BPTB graft, N = 3 with gracilis-ST graft, N = 2 with Achilles tendon graft; N = 1 excluded due to inability to perform tasks. |
| Ortiz et al. 2011 | N = 28 females; N = 13 ACLR, N = 15 non-injured controls (same group as for Ortiz et al., 2008) | Not controlled for graft/surgery or rehabilitation protocol (only similarities); at least 1 year postsurgery, no multiple surgeries on the same knee. Recreational fitness activities such as jogging, running, and weight lifting, none of the participants formed part of any intercollegiate, varsity, or competitive sport team. | N = 14 physically active young women with ACLR (age, 25.4 ± 3.1 years; height, 167.5 ± 5.9 cm; body mass, 63.2 ± 6.7 kg; mean time after surgery 7.2 ± 4.2 years (1-16 years after reconstruction); N = 9 with BPTB graft, N = 3 with gracilis-ST graft, N = 2 with Achilles tendon graft; N = 1 excluded due to inability to perform tasks. |
| Ortiz et al. 2014 | N = 31 females; N = 15 ACLR, N = 16 healthy females | ACLR: same orthopaedic surgeon, same rehabilitation protocol, N = 13 were injured while participating in competitive volleyball at the collegiate or professional level; at least 12 months post surgery, full RTS allowed (without restrictions) to pre-injury level. Sports-specific physical activities as described by the Activity Rating Scale, scores from 12 to 16, consistent with activities such as running, cutting, decelerating, and pivoting more than 2 times per week, = high level of participation. | N = 15 ACLR with SG graft, age range 21 - 35 years (height: 167.71 ± 9.0 cm, body mass: 67.68 ± 11.66 kg), time since surgery was between 12 months and 5 years, full RTS allowed (pre-injury level); N = 1 drop-out due to inability to perform tasks. |

N.a.: Not applicable or not available.
| Study | Group | Description | Control Group | Notes |
|-------|-------|-------------|---------------|-------|
| Patras et al. 2012 | N = 28 males; N = 14 ACLR and N = 14 healthy controls | ACLR: performed subacutely within 6 months after the injury from the same surgeon (range 1 to 4 months), unilateral ACL tear confirmed by MRI and arthroscopy; full RTS allowed 6 months post-surgery | | |
| | N = 14 ACLR with BPTB autograft, age 24.8 ± 5.3 years, weight 77.3 ± 7.5 kg and height 177 ± 5.3 cm, mean time since surgery 18.5 ± 4.3 months; Tegner 8 (range 7-9), Lysholm score 95 (range 94-100). | | |
| | N = 14 healthy controls, age 21.7 ± 4.4 years, weight 72.2 ± 8.3 kg and height 180 ± 9.0 cm | | |
| Patras et al. 2010 | N = 28 males; N = 14 ACLR, N = 14 healthy controls | ACLR: unilateral ACL tear confirmed by MRI and arthroscopy, BPTB graft, performed within 6 months after injury, same surgeon, same rehabilitation, RTS permitted after 6 months post-surgery | | |
| | N = 14 males with ACLR, mean age: 24.8±5.3 years; mean height: 177±5.3 cm, mean weight 77.3±7.5 kg, time since surgery: mean 18.5±4.3 months, pre-injury level of sports participation, median Lysholm score 95 (range 94–100) and Tegner score 8 (range 7–9) | | |
| | N = 14 healthy males, mean age: 21.7±4.4 years; mean height: 180±9.0 cm, mean weight 72.2±8.3 kg, never suffered of any kind of orthopaedic or neurological condition; left leg = control leg | | |
| Patras et al. 2009 | N = 9 males with ACLR | ACLR: unilateral ACL tear confirmed by MRI and arthroscopy, BPTB graft within 6 months after injury, same rehabilitation protocol, RTS permitted 6 months post-surgery | | |
| | N = 9 males with ACLR, mean age: 27.7±3.5 years, mean weight: 79.5±7.3 kg, mean height: 178±5.9 cm, mean time since surgery: 19.2±5.7 months, median Lysholm score: 95 (range 94–96), Tegner score: 8 (range 7–9), resumed their sports activities | | |
| Pincheira et al. 2018 | N = 50 male soccer players; N = 25 with unilateral ACLR, N = 25 uninjured controls | ACLR: unilateral ACLR with ST-gracilis graft, same surgical team, at least 6 months post-surgery, non-contact mechanism during soccer match on the dominant limb | | |
| | N = 25 males with ACLR, age 28.36 ± 7.87 years; weight 77.56 ± 6.35 kg, height 169 ± 7 cm, time after surgery 9 ± 3 months, time between ACL injury and surgery 3.4 ± 1 months, at time of measurements cleared for full RTS | | |
| | N = 25 healthy males, age 24.16 ± 2.67 years; weight 78.16 ± 5.46 kg, height 172 ± 5 cm; without injury or surgery on lower limb | | |
| Study                  | Design                                                                 | Sample                        | Inclusion Criteria                                                                 | Exclusion Criteria                                                                 | Comparison                                                                 |
|-----------------------|------------------------------------------------------------------------|-------------------------------|------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Rudolph et al. 2000   | one component of a larger study; N = 31; N = 10 healthy controls, N = 11 ACLD copers, N = 10 ACLD non-copers | ACLD: full range of motion in both knees, no visible or palpable knee effusion, no symptoms of locking, an uninvolved, healthy knee | athletes, regular activity in level I sports (involving jumping, pivoting, and hard cutting) and level II sports (involving lateral motions) before injury | N = 11 ACLD copers (2 females, 9 males), ages 22–43 years, mean 30.7, high-level athletes with ACLD for at least 1 year (confirmed by MRI), any knee instability during regular participation in level I and II sports, no more than one episode of giving way, even during sports, since injury | N = 10 uninjured individuals, matched by age and activity level to the coper subjects (2 females, 8 men), ages 23–41 years, means 32.2) |
| Rudolph et al. 2001   | one component of a larger study; N = 31; N = 10 healthy controls, N = 11 ACLD copers, N = 10 ACLD non-copers | ACLD: full range of motion in both knees, no visible or palpable knee effusion, no symptoms of locking, an uninvolved, healthy knee | athletes, regular activity in level I sports (involving jumping, pivoting, and hard cutting) and level II sports (involving lateral motions) before injury | N = 11 ACLD copers (2 females, 9 males), ages 22–43 years, mean 30.7, high-level athletes with ACLD for at least 1 year (confirmed by MRI), any knee instability during regular participation in level I and II sports, no more than one episode of giving way, even during sports, since injury | N = 10 uninjured individuals, matched by age and activity level to the coper subjects (2 females, 8 men), ages 23–41 years, means 32.2) |
| Rudolph & Snyder-Mackler 2000 | one component of a larger study; N = 31; N = 10 healthy controls, N = 11 ACLD copers, N = 10 ACLD non-copers | ACLD: full range of motion in both knees, no visible or palpable knee effusion, no symptoms of locking, an uninvolved, healthy knee | athletes, regular activity in level I sports (involving jumping, pivoting, and hard cutting) and level II sports (involving lateral motions) before injury | N = 11 ACLD copers (2 females, 9 males), ages 22–43 years, mean 30.7, high-level athletes with ACLD for at least 1 year (confirmed by MRI), any knee instability during regular participation in level I and II sports, no more than one episode of giving way, even during sports, since injury | N = 10 uninjured individuals, matched by sex, age and activity level to the coper subjects (2 females, 8 men), ages 23–41 years, means 32.2) |
| Swanik et al. 2004    | N = 29; N = 12 female ACLD, N = 17 female controls                   | complete unilateral ACL tear, at least 1 year after injury, mechanical instability (positive Lachman & Pivot-Shift tests), rehabilitation program completed, no ACL surgery | minimum Tegner score of 3 | N = 12 females with ACLD, age 25.2 ± 7.3 years, mean time since injury 33.6 ± 5.2 months, Tegner score 5.4 ± 1.83 points | N = 17 healthy females, age 22.7 ± 4.0 years, Tegner score 5.41 ± 1.5 points |
| Study          | N = 24 females, mean age = 29.4 ± 10.4 years; mean height = 168 ± 10.7 cm; mean weight = 61.2 ± 6 kg; N = 6 ACLD; N = 12 ACLR; N = 6 controls | complete unilateral ACL tear; ACLR: BPTB grafts, testing 6 - 30 months after surgery, rehabilitation program completed, attempt to previous level of activity | recreational activity at least for healthy controls, TAS of experimental groups 6.8 ± 1.5 points, Lysholm Knee Scoring Scale of experimental groups 92.9 ± 5.4 | N = 6 females with ACLD | N = 12 females with ACLR | N = 6 females, healthy controls, recreational activity, no previous history of knee pathology, dominant limb (leg to kick a ball with) | n.s. |
|---------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Swank et al. 1999 | N = 6 females with ACLD, N = 12 ACLR, N = 6 controls                                                                                                                                          | N = 6 females with ACLD                                                                                                                                          | n.a.                                                                                                                                          | n.a.                                                                                                                                          | n.a.                                                                                                                                          | n.a.                                                                                                                                          |
| Zebis et al. 2017 | N = 6 females, mean age = 29.4 ± 10.4 years; mean height = 168 ± 10.7 cm; mean weight = 61.2 ± 6 kg; N = 6 ACLD; N = 12 ACLR; N = 6 controls                                                                 | non-contact ACL injury (video-recorded) in the right knee during match play, ST-gracilis graft, standardized rehabilitation                                                                 | N = 6 females, mean age = 29.4 ± 10.4 years; mean height = 168 ± 10.7 cm; mean weight = 61.2 ± 6 kg; N = 6 ACLD; N = 12 ACLR; N = 6 controls                                                                 | N = 1 female elite soccer player at high level (age 21 years) with no previous history of ACL injury                                                                 | Screening of elite soccer players pre-season --> see Zebis et al., Am J Sports Med 2009;37(10):1967-73; Zebis et al., Clin J Sports Med 2008;18(4):329-37 | n.a.                                                                                                                                          |

Abbreviations: ACLD = anterior cruciate ligament deficiency (conservative/non-surgical treatment); ACLR = anterior cruciate ligament reconstruction/repair (surgery); BPTB = bone-patella-tendon-bone technique for ACLR; Level I: sports are described as jumping, pivoting and hard cutting sports; Level II sports: also involve lateral motion, but with less jumping or hard cutting than level I; n.a. = not applicable; n.s. = not stated; RTA = return to activity (return to participation); RTS = return to sports; RTP = return to performance; TAS = Tegner Activity Score; TLS = Tegner & Lysholm Score; TSK = Tampa Scale for Kinesiophobia; wk = week; vs. = versus
| Author & Year          | tasks: number of repetitions, duration, frequency | muscles/legs measured                           | Outcome measure, variables                                      | direct link to RTS?                          |
|-----------------------|--------------------------------------------------|------------------------------------------------|-----------------------------------------------------------------|---------------------------------------------|
| Alkjaer et al. 2002¹  | 15 consecutive forward lunges with recordings from hitting a force plate (rest between trials as long as wanted) | VL, VM, ST, BF of injured leg of patients and right leg of healthy controls | peak and mean values of EMG amplitudes (microvolts)              | (no) --&gt; copers and non-copers           |
| Alkjaer et al. 2003²  | six trails of walking across two force plates at a speed of 4.5km/h | VL, VM, ST, BF of injured leg of patients and right leg of healthy controls | mean amplitudes during weight acceptance (%maxEMG); coactivation between VL & BF (method by Rudolph et al. 2001) (%maxEMG) | (no) --&gt; copers and non-copers           |
| Arnason et al. 2014⁶  | 3 trials of Nordic hamstring exercise, 3 trials of TRX hamstring curl exercise; order of exercises was randomized, time | MH, LH of both legs                           | peak normalized muscle activation (%MVIC)                        | (no) --&gt; soccer                           |
| Boerboom et al. 2001⁹ | walking at normal, slower, and faster than normal speed | VM, VL, BF, ST, GC medialis, GC lateralis; of injured leg (patients) | deviations of the normative EMG profiles (individual averaged EMG pattern during gait) | (no) --&gt; copers and non-copers           |
| Briem et al. 2016¹⁰  | 3 consecutive maximal hops (triple jump, single-limb crossover hop for distance) --&gt; two practice trials, a single maximal test trial; same procedure for each limb. ACLR participants started with non-surgical limb, each matched control participant with matched limb. | MH, LH                                        | Peak activation of the normalized signal (%MVIC)                | no                                          |
| Study (Year) | Design | Participants | Outcome Measures | Reference |
|-------------|--------|--------------|------------------|-----------|
| Bryant et al. 2009<sup>12</sup> | ACLD and ACLR: involved limb; healthy controls: both limbs; maximal single limb hop for distance on their involved limb from a standing position. 5 trials with 1 min rest in between trials, landing in a fixed position on the takeoff foot. | VL, VM, ST, BF | timing of the onset of muscle activity relative to IC (onset-IC; ms) and timing of the peak of muscle activity relative to IC (ms) | no |
| Bulgheroni et al. 1997<sup>13</sup> | at least 5 trials of walking at natural cadence (112 ± 5.1 steps/min), 20-m distance used to reach steady state of walking | VL, RF, BF, ST | amplitude of EMG activity, EMG normalized to the maximum recorded signal amplitude during a single walking cycle | no |
| Busch et al. 2019<sup>15</sup> | 10x stair descent, Warm-up on treadmill with 5km/h for 10 min -> individual, submaximal normalisation of EMG data (KOOS, Tegner Activity Score, VAS for pain & general well-being) | VM, VL, BF, ST of both legs | Normalized root mean squares for each muscle, limb and movement phase (preactivation, weight acceptance, push-off) were calculated (%subMVC) | no |
| Cordeiro et al. 2015<sup>17</sup> | 3x instep soccer kick with dominant leg, (KOOS, TSK) | RF, VL, VM, BF, ST | muscle activation during knee extension phase (% MVC) | (no) --&gt; soccer, instep kick |
| Dashti Rostami et al. 2019<sup>18</sup> | single-leg vertical drop landing; 3 proper trials | GM, AL; only the injured limb of ACLR and ACLD individuals and the dominant limb of controls were tested | Preparatory and reactive muscle activity and coactivation from 100 milliseconds prior to initial contact to 250 milliseconds postcontact; mean and peak activity (%MVIC); coactivation of GM:AL (method by Rudolph et al. 2001) | no |
| Study | Test Description | Muscle Sites | Outcome Measures | Notes |
|-------|------------------|--------------|------------------|-------|
| Gokeler et al. 2010<sup>23</sup> | Single-leg hop test for distance (arms behind back, maintained balance for at least 1s after landing<sup>26</sup>, 3 maximal trials for each limb; (IKDC, Rolimeter device for laxity testing) | Gmax, BF, ST, SM, VM, VL, RF, MG, LG, SO | Mean onset times (=preparatory activity before landing) of the EMG signals of each muscle | No |
| Hansen et al. 2017<sup>28</sup> | Running on weight-supporting ("anti-gravity", Alter G, respectively) treadmill at 16km/h with 6 different body weight conditions from 50% (half weight) to 100% (full weight-bearing) in random order | SM, SL, MG, LG, MH, LH | Soleus, gastrocnemius and hamstring cluster formed, SPM used to analyze entire time-dependent EMG signal, comparison of injured vs. non-injured leg and left vs. right leg; EMG signal normalized to ist MVC value during 100% BW running trials for each participant | No |
| Jordan et al. 2016<sup>36</sup> | 80-s repeated squat jump test (jump test) on a dual force plate system | VL, VM, BF, ST | Normalized EMG amplitudes at takeoff, at the 25-ms interval prelanding, and at postlanding for the ACLR limb (affected limb), contralateral limb, and limbs of the control subjects (control limb), (Asymmetry index, jump height of body center of mass) | (no) --> fatigue, downhill skiing |
| Study Reference         | Task Description                                                                 | Muscle Variables | EMG Parameters                                  | Follow-Up/Control Conditions |
|-------------------------|----------------------------------------------------------------------------------|------------------|-------------------------------------------------|------------------------------|
| Klyne et al. 2012\(^{38}\) | Controlled single leg hop on each limb (arms behind back, landing position hold for at least 1-2s)\(^{26}\), length of the horizontal distance hopped was equal to the measured length of the lower leg; 3 successful trials | MG               | Onset and offset of MG activation relative to take-off, during flight and landing, muscle activity (RMS), 7 temporal variables (ms, %activity) | no                           |
| Knoll et al. 2004\(^{39}\) | Walking on treadmill at least 10 minutes at a constant speed of 2 km/h           | VL, VM, BF, AL   | Linear envelope EMG curve determined by root mean square method and normalized to average of peak EMG signal values of six gait cycles --> EMG patterns during % of gait cycle | (no) --> pre-operatively & follow-up (6 weeks, 4, 8, 12 months post-surgery) |
| Kuster et al. 1995\(^{40}\) | At least 5 trials of each task in order to obtain at least ten cycles of EMG data for ensemble average processing; level walking and downhill walking on dismountable slope (6m length, -19° gradient) | RF, BF, GC       | Peak muscular activity at heel strike, just before heel strike; values normalized to subject's individual peak levels | no                           |
| Lessi & Serrao 2017\(^{43}\) | Single-leg landing before and after fatigue protocol: 10 squats, 2 vertical jumps, 20 steps | VL, BF, Gmax     | EMG average amplitude of activation, expressed as a %peak EMG during landing | no                           |
| Lessi et al. 2018\(^{42}\)  | Single-leg drop vertical jump landing before and after fatigue protocol (fatigue protocol: 10 squats, 2 vertical jumps, 20 steps) | VL, GM, Gmax     | Mean amplitude of activation during landing (% of the peak RMS obtained during the landing task) | no                           |
| **Lustosa et al. 2011**<sup>45</sup> | walking with self-selected speed on a 3m-walkway with two stable platforms and one electromechanical balance board that could apply a sudden perturbation (20° tilt in the frontal plane (medial/lateral) -> varus stress in the slightly flexed knee, leading to external rotation of the femur (=common etiology of ACL injury) | VL, BF | co-contraction pre- and postperturbation between groups and limbs (co-contraction levels in the 250 ms before perturbation and in the 250 ms after perturbation periods), %MVIC; muscular co-contraction calculated<sup>22,90</sup> | (no) --> stratification of included patients (full RTS or limited RTS) |
| **Madhavan & Shields 2011<sup>46</sup>** | single leg squat maneuver with random/unexpected perturbations at the start of the flexion phase (triggered compensatory reflex activity) | VM obliquus, RF, VL, Ih, MH of exercised limb (reconstructed leg of ACLR subjects, pseudorandomly selected limb of healthy controls to counterbalance ACLR limbs) | normalized long latency responses (= difference between the mean EMG of perturbation trials and the mean EMG of unperturbed trials, divided by the mean EMG of the unperturbed trials) between 50 and 200 ms after the onset of perturbation of quadriceps and hamstrings; peak velocity (cm/s); latency of peak LLR (= time to peak EMG activity between 50–200 ms following the perturbation); mean muscle EMG activity (% MVIC) in the 200 ms prior to perturbation, 50–200 ms after the perturbation, and 200–400 ms post perturbation | no |
| Nyland et al. 2010<sup>54</sup> | single-leg countermovement jump (CMJ) performance | Gmax, VM, MH, GC | mean EMG signal amplitudes (%MVIC); EMG activation duration during propulsion and landing phase (ms) | no |
| Nyland et al. 2013<sup>56</sup> | single-leg countermovement jump (CMJ) performance | Gmax, VM, MH, GC | EMG amplitude comparison during single-leg countermovement jumping propulsion (Difference = involved - uninvolved lower extremity) (%MVIC) | no |
| Nyland et al. 2014<sup>55</sup> | single-leg hop test for distance | Gmax, VM, MH, GM | Standardized EMG amplitudes during single leg hop for distance propulsion [%MVIC involved lower extremity – %MVIC uninvolved lower extremity]; standardized EMG amplitudes during single leg hop for distance landing [%MVIC involved lower extremity – %MVIC uninvolved lower extremity]. | no |
| Study | Protocol | Outcome Measures | Key Findings |
|-------|----------|------------------|--------------|
| Oliver et al. 2018<sup>57</sup> | Single leg jump from a 25-cm tall box, with hands on hips and without gaining momentum; five times with each leg (injured/non-injured); | VM, VL, RF, ST, BF | Mean values per each patient, leg, and muscle were considered in the analysis; muscle latency time over time of each muscle was defined as the time from touchdown to peak amplitude of EMG activity (RMS) in each muscle. RMS was normalized at the maximum activity of the muscles (%MVC) |
| Ortiz et al. 2008<sup>59</sup> | 5 trials of a single-legged 40-cm drop jump: standing initially on both feet on the 40-cm platform and then standing on the jumping leg, and then to drop when ready to do so, maximal-effort vertical jump on landing single-legged on the center of the force plate, use of arms allowed for balance; 2 trials of a 20-cm up-down hop task<sup>35</sup>, participant stood facing a 20-cm step and performed 10 consecutive jumps up to and down when ready. The 10 consecutive up and down hops composed 1 trial. | GM, GMax, RF, LH, MH; dominant leg in noninjured women and reconstructed leg in ACLR women | Quadriceps/hamstring cocontraction ratios (values between 0 and 1; closer to 1 = excellent co-contraction, closer to 0 = poor co-contraction) and normalized EMG activity of lower extremity muscles (values between 0 and 1; effect sizes respectively) |
| Study (Year) | Procedure Description | Parameters Measured | Cocontraction Ratios | EMG Activity | Ankle Flexion | ACLR Women | Notes |
|-------------|-----------------------|---------------------|----------------------|--------------|---------------|------------|-------|
| Ortiz et al. 2011<sup>60</sup> | Side-to-side hopping task that consisted of hopping single-legged 10 times consecutively from side to side across 2 lines marked 30 cm apart on 2 individual force plates. The task was designated as a side hopping when the hop was to the opposite side of the stance leg and as crossover hopping when the hop was toward the side of the stance leg | GM, GMax, RF, LH, MH; dominant leg in noninjured women and reconstructed leg in ACLR women | Quadriceps/hamstring cocontraction ratios (values between 0 and 1; closer to 1 = excellent co-contraction, closer to 0 = poor co-contraction) and normalized EMG activity of lower extremity (values between 0 and 1; effect sizes respectively) | Rectified normalized electromyographic activity of the quadriceps and hamstrings (amplitude and latency) in %maximum contraction; quadriceps/hamstrings electromyographic co-contraction ratio (values between 0 and 1); time to maximum neuromuscular activation (time-to-peak muscle activation) in seconds for hamstring and quadriceps muscle groups | No |
| Ortiz et al. 2014<sup>58</sup> | 60-cm double-legged and a 40-cm single-legged drop jumps to assess bilateral and unilateral landing strategies, respectively | VM, VL, RF, MH, LH measured in the involved leg of women with ACLr and the dominant leg of the control subjects | Rectified normalized electromyographic activity of the quadriceps and hamstrings (amplitude and latency) in %maximum contraction; quadriceps/hamstrings electromyographic co-contraction ratio (values between 0 and 1); time to maximum neuromuscular activation (time-to-peak muscle activation) in seconds for hamstring and quadriceps muscle groups | No |
| Patras et al. 2012<sup>66</sup> | Two 10-min treadmill runs on 2 occasions in the lab, one at a moderate (80%VO2max) and one at a high intensity (85-88% VO2max), EMG recordings at the 3rd, 5th, 7th, and 10th minute of the runs | VL, BF bilaterally: left leg of controls selected for analysis | Peak EMG amplitude during the stance phase | No |
| Study Reference | Protocol Description | Muscles Monitored | EMG Parameters | Additional Notes |
|-----------------|----------------------|------------------|----------------|-----------------|
| Patras et al. 2010<sup>65</sup> | 10 min running at moderate intensity and 10 min running at high intensity on separate occasions separated by a time span of 48 h; moderate intensity = at 80% of the lactate threshold; high intensity = at 40% of the difference between VO2max and lactate threshold | VL bilaterally | EMG amplitude during stance, over time respectively in microvolts | no |
| Patras et al. 2009<sup>67</sup> | 10 min running at moderate intensity (20% below the lactate threshold) and 10 min running at high intensity (40% above the lactate threshold) on separate occasions separated by a time span of 48 h and completed within 10–12 days; moderate intensity = at 20% below the lactate threshold; high intensity = at 40% above the lactate threshold | VL, BF bilaterally | values from 15 strides averaged to calculate the mean peak amplitude during stance for each recording period | no |
| Pincheira et al. 2018<sup>68</sup> | Two destabilizing platforms (one for each limb) generated a controlled perturbation at the ankle of each participant (30° of inversion, 10° plantarflexion simultaneously) in a weight bearing condition; time between the release and the stop (impact) of the mechanism was 200 ± 10 ms | VM, ST | muscle activation onset times (ms) | no |
| Study                        | Task Description                                                                 | Muscle Targets                          | Data Normalization/Calculation                                                                 | Compared Groups          |
|------------------------------|----------------------------------------------------------------------------------|-----------------------------------------|---------------------------------------------------------------------------------------------|--------------------------|
| Rudolph et al. 2000<sup>75</sup> | Single-leg hops                                                                  | LH, VL, SO, medial head of gastrocnemius muscles of both limbs | Peak EMG activity over 30-ms from either the dynamic or maximum isometric trials was used to normalize the EMG data (%MVIC); muscle timing variables, muscle intensity: integrating the linear envelope of the EMG curves over a weight acceptance interval (defined as the range from 100 ms prior to initial contact to the point of peak knee flexion. Muscle cocontraction: using normalized EMG data, between the VL and LH, and VL and medial gastrocnemius | (no) --&gt; copers and non-copers |
| Rudolph et al. 2001<sup>76</sup> | 5 trials of walking and jogging with 1 - 3 min rest intervals between trials      | LH, VL, SO, medial head of gastrocnemius muscles of both limbs | Peak EMG activity; onset and termination of muscular activation; duration of muscular activity; co-contraction (integrals calculated) | (no) --&gt; copers and non-copers |
| Rudolph & Snyder-Mackler 2004<sup>77</sup> | Step up and over a 26 cm high step; ten trials, five each with the right and left leg ascending a 26 cm step (higher than a typical step, provide a more challenging condition), EMG collected from landing limb | LH, VL, SO, medial head of gastrocnemius muscles of both limbs | Peak EMG activity (%max); onset and termination of muscular activation; duration of muscular activity; co-contraction | (no) --&gt; copers and non-copers |
| Study          | Description                                                                 | Muscle Activity Measures                                                                 | Randomization |
|---------------|-----------------------------------------------------------------------------|------------------------------------------------------------------------------------------|---------------|
| Swanik et al. 2004<sup>84</sup> | landing from a hop: The subject stood on a 20-cm step, balanced momentarily on test limb, and hopped to target placed 30 cm horizontally: knee perturbation (special knee perturbation device, 100-N force on the posterior aspect of the tibia → anterior displacement of the tibia) | VL, VM, MH, LH muscle activity before and after landing from a hop (area of integrated EMG recordings), hamstring latency after joint perturbation (reflexive muscle activity in the hamstrings assessed by measuring the onset time after anterior translation of the tibia) | no            |
| Swanik et al. 1999<sup>85</sup> | 4 functional activities: downhill walking (15°, 0.92 m/s), level running (2.08 m/s), and hopping (self-paced) and landing from a jump (20.3 cm) | VL, VM, MH, LH integrated EMG (IEMG, microvolts x milliseconds) normalized to mean amplitude of 3 - 6 consecutive test repetitions → mean area & peak IEMG of a 250ms-period after ground contact = reactive muscle activity; testing order and leg assessed by random | no            |
| Zebis et al. 2017<sup>98</sup> | standardized side cutting maneuver, countermovement jumping with the hands placed at the hip (akimbo), and maximal jump height was calculated | VL, BF, ST EMG preactivity | (no) → single case, risk profile retrospective, pre-post surgery and post-intervention |
Abbreviations: AL = adductor longus muscle; BF = biceps femoris muscle; sEMG = surface electromyography; GC = gastrocnemius muscles; GM = gluteus medius muscle; GMax = gluteus maximus muscle; GRF = ground reaction force; Hz = Hertz; LG = gastrocnemius lateral head; LH = lateral hamstring muscle; MG = gastrocnemius medial head; MH = medial hamstring muscle; ms = milliseconds; n.a. = not applicable; n.s. = not stated; RF = rectus femoris muscle; RTA = return to activity (return to participation); RTS = return to sports; RTP = return to performance; SI = symmetry index; SM = soleus medialis muscle; SL = soleus lateralis muscle; SO = soleus muscle; SPM = Statistical Parametric Mapping; ST = semitendinosus muscle; VL = vastus lateralis muscle; VM = vastus medialis muscle; vs. = versus; WA = weight acceptance