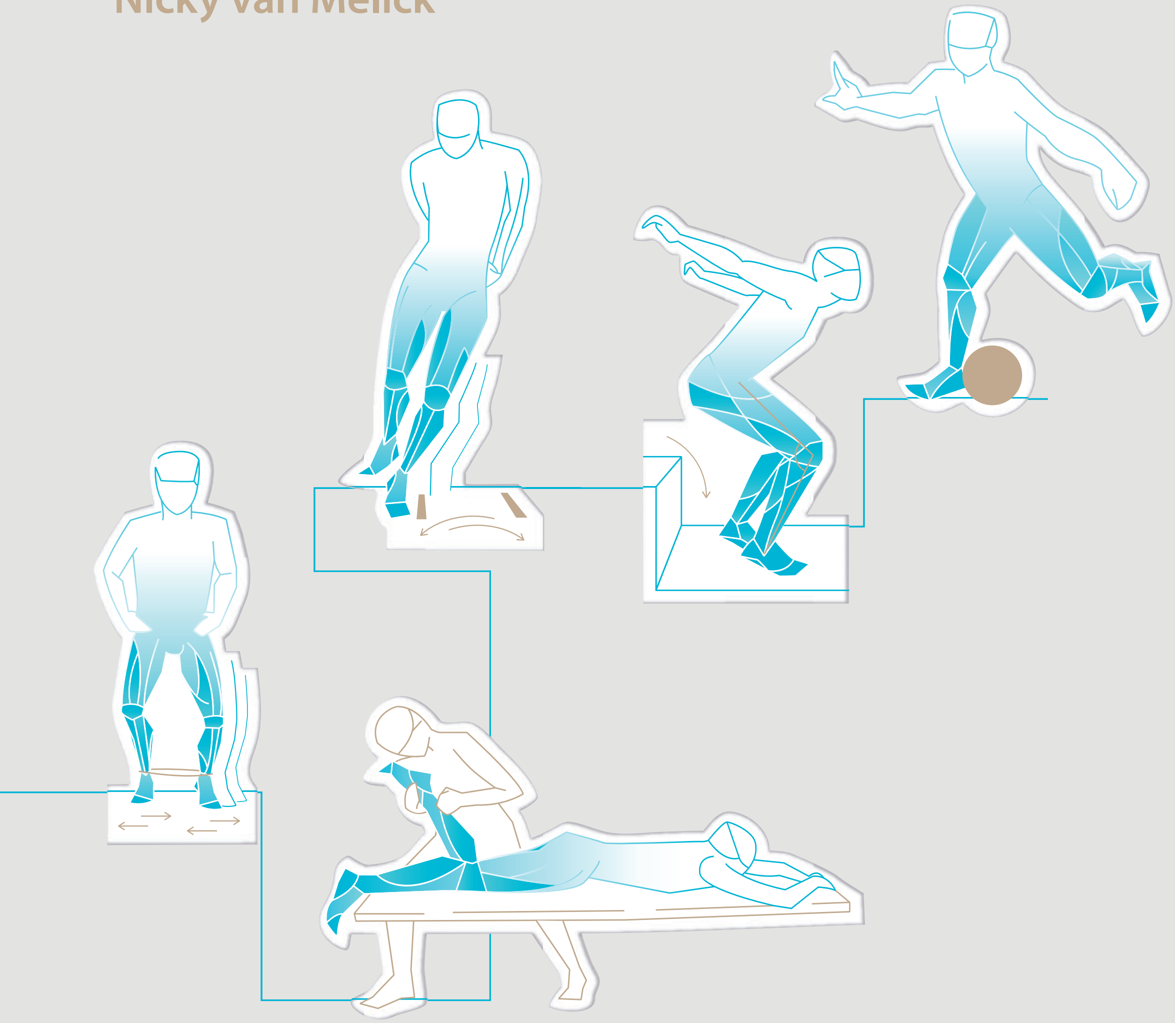
Nicky van Melick



Return to play after anterior cruciate ligament reconstruction in pivoting athletes

It's time to reconstruct rehabilitation

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Promotor

Prof. dr. M.W.G. Nijhuis-van der Sanden

Copromotores

Dr. T.J. Hoogeboom
Dr. R.E.H. van Cingel (Sport Medisch Centrum Papendal)

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Prof. dr. M.J.R. Edwards, voorzitter
Prof. dr. E. Witvrouw (Universiteit Gent)
Prof. dr. F.J.G. Backx (UMC Utrecht)

Because all things happen for a reason..

Contents

Chapter 1

General introduction

As a physical therapist, from day one I was intrigued by the treatment of pivoting athletes after anterior cruciate ligament reconstruction (ACLR). I became aware of different experts recommending different treatment strategies or return to play measurements. Moreover, during my 11 years of clinical practice experience, I noticed many changes in the rehabilitation protocol and decision to return to play. Apparently, there seemed to be no clear rehabilitation protocol for pivoting athletes after ACLR.

The lack of a clear rehabilitation protocol might, to some extent, explain why only 65% of all pivoting athletes manage to reach their preinjury level after ACLR; 16% return to a lower level of sport and 19% completely cease participating in sports.[4] Problems with the operated knee, fear of re-injury and fear of job loss with re-injury are the reasons to change or cease sport participation for about 50% of the athletes.[4,5] Unfortunately, their fear is well-founded as the rate of graft failure and contralateral ACL rupture within five years of ACLR is reported as up to 24% and 15% respectively.[8,46] A more recent meta-analysis shows that athletes aged 25 years or younger, who return to their preinjury level of pivoting sport following ACLR, have a secondary ACL injury rate (both ipsi- and contralateral) of 23% and a 30 to 40 times greater risk of future ACL injury compared with uninjured adolescents.[44]

These clinical challenges inspired me to start this PhD project, with the primary objective being to optimise care for pivoting athletes after ACLR. Therefore, the aim of this thesis is to contribute to the current rehabilitation program for pivoting athletes after ACLR, including functional performance measures that need to be used for determining the moment for return to play.

In this general introduction we will first describe the ACL anatomy, function, injury mechanism and incidence, and provide a short description of surgical options. Then, we will outline the history of postoperative rehabilitation protocols, detailing the clinical challenges in determining when an athlete is ready to return to play. Finally, we will present the content of this thesis.

Anatomy and function of the ACL

The ACL is one of the passive stabilisers found inside the knee, measuring approximately 25 to 35 mm in length and connecting to both the femur and the tibia (Figure 1). The ACL consists of two bundles: the anteromedial bundle is taut during flexion, and the posterolateral bundle is taut during extension of the knee. Thus, some portion of the ACL is under tension in every knee flexion angle, enabling the ACL to restrict rotation of the knee and anterior translation of the tibia relative to the femur at almost every knee flexion angle.[25,49] Besides its mechanical function in maintaining knee stability, the ACL contains mechanoreceptors (2.5%) and therefore directly influences the neuromuscular control of the knee.[48]

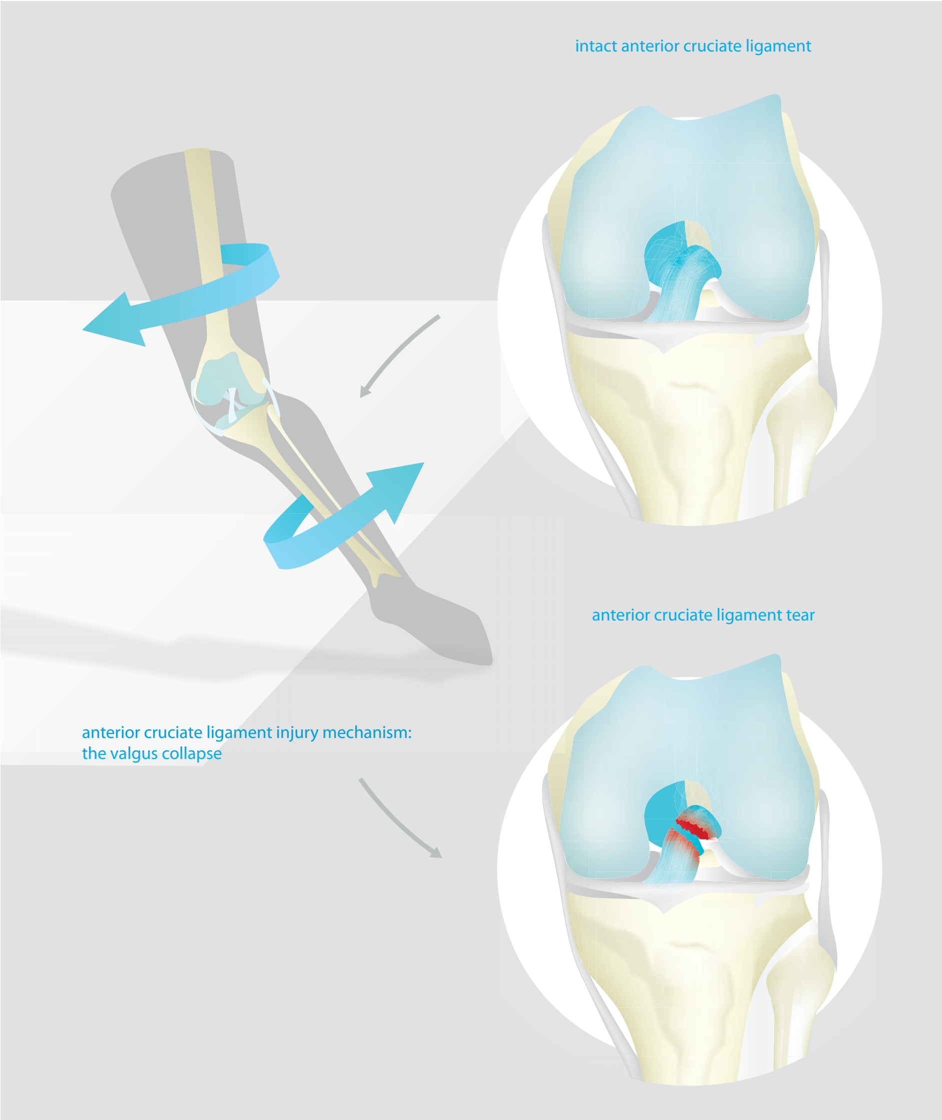

Figure 1: *Anterior cruciate ligament anatomy and injury mechanism.*

ACL injury mechanism and its incidence

ACL tears are the most common ligamentous ruptures in the knee, with 70% of them occurring during a non-contact trauma.[33,39] In pivoting athletes, a predominant injury pattern is found: a combination of knee valgus, hip internal rotation and tibial rotation, called the valgus collapse (Figure 1).[7,33] Due to the loss of mechanoreceptors, which normally detect changes in tension, acceleration, direction of movement and knee joint position, ACL deficiency causes partial de-afferentation and alters spinal and supraspinal motor control. The changes in motor control strategy can reveal changes in proprioception, postural control, muscle strength, movement and recruitment patterns.[14,47] An ACL injury might therefore be regarded as a neurophysiological dysfunction and not a simple peripheral musculoskeletal injury.[12,23]

The incidence of ACL injuries in pivoting sports (e.g. soccer, handball, basketball) is high; 0.8-2.4% of male and 2.0-3.2% of female amateur athletes rupture their ACL during a season, with individuals aged between 15 and 45 years at most risk.[28,32] In the Netherlands, about 6.5 million people are aged between 15 to 45 years and 60 percent of this demographic practices sport on a weekly basis. Of this 60 percent, seven percent are soccer players.[11,18] Since about 1.5 percent of them suffer an ACL injury, this equates to an annual rate of more than 4,000 athletes with a torn ACL in soccer alone.

Surgical options after ACL injury

An ACL injury results in reduced passive knee stability and loss of mechanoreceptors, which may contribute to functional instability.[47] To maximise knee stability and to avoid new knee trauma with possible additional meniscal or cartilage damage, most young pivoting athletes opt for ACLR.[5,35] Timing of surgery is crucial for an optimal recovery after ACLR and is described in detail in multidisciplinary guidelines.[26,27,39] Over the past ten years, the number of ACLRs has increased with 13% for males and 34% for females, and this increase was most prominent in athletes under the age of 18 years.[21] Bone-patellar tendon-bone (BPTB) and hamstring (HS) autografts are the most commonly used methods for ACLR, but the choice of graft type also strongly depends on the surgeon's personal preferences.[19,35] BPTB grafts were most popular until about ten years ago, with HS grafts increasing in popularity thereafter.[19,34,35] Recent evidence has shown only marginal differences in failure rates and residual symptoms between BPTB and HS autografts. Athletes with a BPTB graft have less chance of knee laxity or a flexion strength deficit, while athletes with a HS graft have a lower incidence of patellofemoral pain or an extension strength deficit.[19,35]

Although ACLR is an anatomical replacement of the native ACL, there will be no significant mechanoreceptor reinnervation in the ACL graft.[47] This lack of mechanoreceptors compared to the native ACL has consequences for the postoperative rehabilitation protocol.

The ICF model in ACL rehabilitation

The World Health Organization's (WHO) International Classification of Functioning, Disability and Health (ICF) is a framework designed to understand and describe function and disability (Figure 2). The ICF integrated the medical and social perceptions of disability and thereby provides a model with different perspectives of health: biological, individual and social. As the model shows, there is a continuous interaction between health conditions and contextual factors.[45] The ICF prescribes that treatment should be guided by a patient's specific aim regarding symptoms and impairments, activity limitations and participation restrictions, also considering the contextual factors.[45] Shortly after ACL injury, symptoms including pain, effusion and a limited range of motion are the most prominent, with a significant reduction in activities and participation as a consequence. Within 3 to 6 weeks, these symptoms decrease, and activities of daily living are resumed. It is in this timeframe that functional instability could become obvious and ACLR is opted for.[39] After ACLR, the knee will be functionally stable, but pain, effusion, limited range of motion and decreased upper leg strength are present once again. Neuromuscular impairments or gait problems are often named as activity limitations and the inability to work or play sports is mostly reported as the main restriction in participation.[26] Rehabilitation after ACLR plays a major role in improving these symptoms, addressing activity limitations and participation restriction, eventually preparing an athlete for safe return to play, while minimising the risk for a second ACL injury.[7]

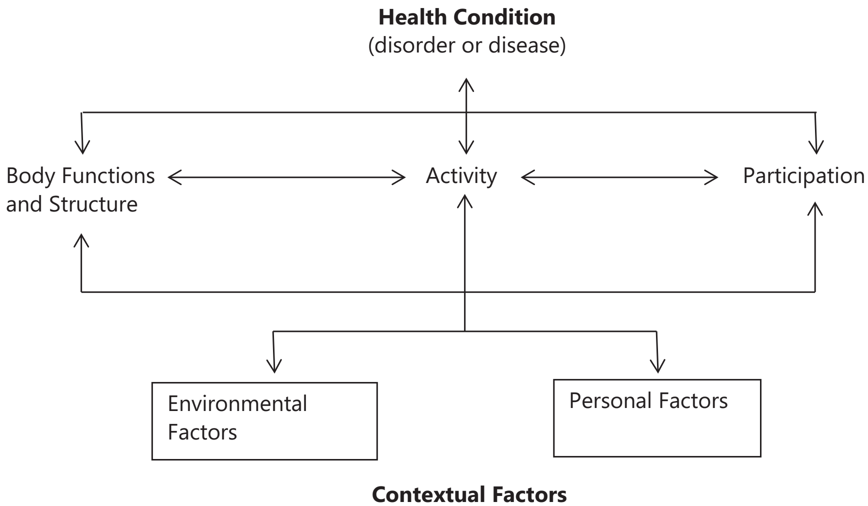

Figure 2: *The International Classification of Functioning, Disability and Health (ICF) model by the World Health Organisation (WHO).*[45]

The history of postoperative rehabilitation protocols

During the 90's, post-operative ACLR rehabilitation changed dramatically when Shelbourne introduced an accelerated rehabilitation programme for patients that underwent ACLR using a BPTB graft. Before this, the traditional rehabilitation protocol continued for 12 months and required an immobilization period of six to eight weeks in ten degrees of flexion or more. Full weight bearing without a brace was only permitted thereafter. However, Shelbourne found that patients who did not comply with this traditional rehabilitation protocol returned to normal function sooner than patients who did, with no increased incidence of graft laxity or failure. He named this noncompliant regimen, which lasted six months at maximum, the accelerated rehabilitation. In this cohort of patients knee extension and quadriceps strength recovered quicker, the rate of anterior knee pain reduced and the number of additional surgical procedures in the first postoperative year decreased compared with the traditional rehabilitation.[40,41] When the two rehabilitation protocols of Shelbourne were compared with patients from other orthopaedic surgeons and in a longer follow-up period, the results were also in favour of the accelerated protocol.[9,10,13,42] However, when a HS graft was used, the patients in the accelerated protocol had more knee effusion during rehabilitation than patients in the traditional protocol.[24] Based on the success of the accelerated rehabilitation protocol in athletes with a BPTB graft, early full range of motion was emphasized, immediate weight bearing was permitted and return to play was allowed when the patient felt ready and reached various objective criteria. Return to play was usually allowed within four to six months after ACLR, as long as the athlete used a functional knee brace during all sports activities for the first postoperative year.[40,41] The accelerated rehabilitation program of Shelbourne mainly focussed on the 'body functions and structure' domain of the ICF, describing methods to improve range of motion and upper leg strength, thus in this protocol information on how to address the lack of mechanoreceptors and accompanying decrease in neuromuscular control is lacking.

Improving neuromuscular control can be achieved with neuromuscular training. In 2001, Risberg et al. were the first to introduce neuromuscular training into an ACLR rehabilitation protocol. They defined neuromuscular training as training enhancing unconscious motor responses by stimulating both afferent signals and central mechanisms responsible for dynamic joint control and distinguish between static balance training (the ability to maintain a position) and dynamic joint stability training (the ability to voluntarily move). In addition, their program includes jump training and agility training.[38] When the neuromuscular training program was compared with a strength training program in patients with a BPTB graft, there were no differences in strength and hop measurements at two-year follow-up, but the neuromuscular training group had better self-reported knee function.[36,37] Therefore, they concluded that an ACLR rehabilitation protocol should include both neuromuscular and strength exercises.[37]

In 2010, Van Grinsven et al. published their evidence-based accelerated rehabilitation protocol, which can be used following ACLR using BPTB or HS grafts. This rehabilitation protocol is a compilation of earlier protocols updated with new scientific evidence and consists of four time-based phases, lasting six months in total.[20] They also placed emphasis on neuromuscular training in the early phases following ACLR.

The biopsychosocial model and return to play after ACLR

Return to sports (RTS) and return to play (RTP) are two concepts used by experts, meaning the same: return to the preinjury sport in both training and matches, but not at the desired performance level. Return to play (RTP) can be viewed as a continuum paralleled with rehabilitation and is not simply a decision taken in isolation at the end of the rehabilitation process. Before RTP, the goal of rehabilitation is to return to participation, which means an athlete is able to participate in training (modified or unrestricted), but not yet ready for RTP. After RTP, improvement continues when return to performance is reached: the athlete is performing at or above the preinjury level.[3]

The biopsychosocial model (Figure 3) describes psychological and contextual factors that have a role in return to play.[3] Psychological factors such as self-efficacy, locus of control and fear of re-injury and contextual factors including age, sex, graft type or level of sport have an influence on the rehabilitation process and RTP after ACLR.[2,17,43]

Physical, psychological and contextual factors directly affect an athletes' functional performance. Functional performance is a relatively new concept in rehabilitation after ACLR and has a common ground with the ICF model, because it incorporates all ICF domains: body functions and structure, activity, participation and contextual factors. Functional performance can be defined as the result of neuromuscular training and consists of two components: movement quantity and movement quality.[1,16,31,36,38] Examples of movement quantity are the amount of upper leg strength or the distance jumped on two legs, while movement quality emphasizes how an athlete performs a skilled movement, such as walking, running or jumping.[26] Both movement quantity and quality are important factors during rehabilitation after ACLR and should be considered when determining if an athlete is ready to return to play. Since the ICF distinguishes between capacity, capability and performance for all activity and participation domains, these qualifiers also need to be considered during rehabilitation after ACLR.[45] Capacity refers to what an athlete can do in a standardized, controlled environment (the physical therapy practice), capability refers to what a person can do in his or her daily environment (the soccer field for example), while performance refers to what the person actually does in his or her daily environment.[22] Better neuromuscular control increases capacity, capability and performance and thereby might reduce the risk for a second ACL injury.

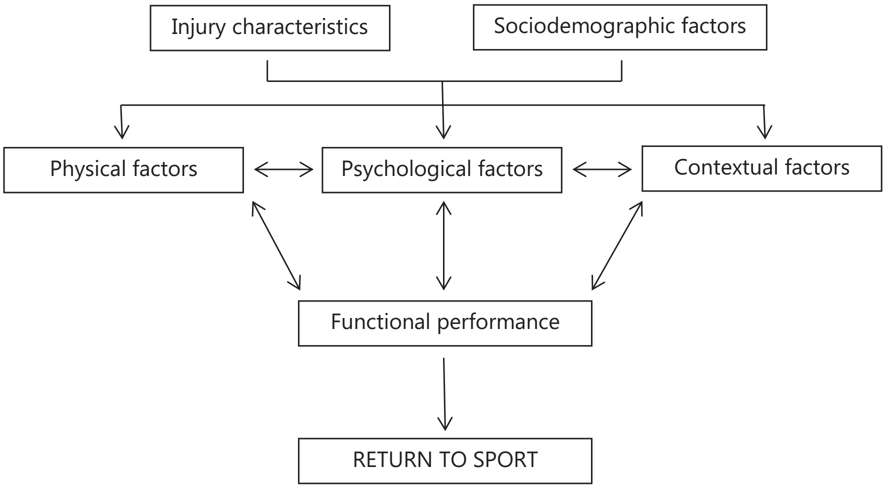

Figure 3: *Biopsychosocial model of return to sport after injury.*[3]

Return to play criteria

Objective measures of functional performance are necessary to drive the ACLR rehabilitation progression and to determine the moment of return to play. Most previous research on outcomes following ACLR focusses on the 'body functions and structure' domain only.[15,29] Barber-Westin and Noyes performed two systematic reviews and noticed that only a small number of studies used objective criteria. Amongst these were symptom measurements, knee laxity, pain, effusion or range of motion. The only functional performance criteria used were strength tests for quadriceps and hamstrings and single-leg hop tests, expressed as a Limb Symmetry Index (LSI).[7,8] The LSI is calculated by dividing the value of the operated leg by that of the non-operated leg and multiplied by 100%.[6] No movement quality measurements were used, despite the fact that movement quality gives an insight into the level of motor control after neuromuscular training. It has been demonstrated previously that movement quality plays an important role in a safe return to play, since altered hip and knee biomechanics can predict second ACL injuries after return to play.[30]

Table 1 shows which functional performance tests are used in the history of post-operative rehabilitation protocols. It is clear that the use of RTP criteria has progressed through time. Both the traditional and accelerated rehabilitation protocols of Shelbourne and the protocol of Risberg et al. only use isokinetic quadriceps strength testing as a measure of functional performance.[38,40] Van Grinsven et al. add hamstring strength tests to the isokinetic test protocol.[20] Besides strength testing, both Risberg et al. and Van Grinsven et al. advise the use of hop tests as a measure of functional performance.[20,36,38] Apart from these measures of quantity of movement, Van Grinsven et al. use "exercises of previous phase are carried out properly" as a RTP criterion of movement quality, but they do not describe which factors contribute to proper performance.[20] From these four rehabilitation protocols, however, it remains unclear whether these measurements decrease the risk on re-injury (ipsi- or contralateral) and thereby can guarantee a safe return to play.

Table 1: *Measurements of functional performance in different ACLR rehabilitation protocols.*

Month	Traditional rehabilitation, Shelbourne[40]	Accelerated rehabilitation, Shelbourne[40]	Neuromuscular & strength rehabilitation, Risberg[38]	Evidence-based rehabilitation, van Grinsven[20]
1-4	None	From week 6: Isokinetic quadriceps testing at 180 and 240 °/s (with 20° extension block at 6 weeks and adding 60 °/s from 12 weeks); KT-1000	Not described	Pain, effusion, goniometer for ROM, gait pattern, IKDC subjective knee evaluation form
4-6	None	RTP when no pain, no effusion, no instability, full ROM, quadriceps strength LSI >80%	Not described	Pain, effusion, goniometer for ROM, isokinetic quadriceps and hamstrings testing at 60, 180 and 300 °/s, hop tests, IKDC subjective knee evaluation form
6-9	Isokinetic quadriceps testing at 180 and 240 °/s with 20° extension block; KT-1000		RTP when quadriceps strength LSI >85%, single-leg hop for distance, triple-hop for distance and stair hop LSI >85%	RTP when no pain, no effusion, full ROM, quadriceps and hamstring strength LSI >85%, hop tests LSI >85%
9-12	RTP when no pain, no effusion, full ROM, quadriceps strength LSI >80%			

RTP=return to play, ROM=range of motion, LSI=Limb Symmetry Index

Outline of this thesis

The objectives of this thesis are to create an evidence-based rehabilitation program for pivoting athletes after ACLR and to contribute to the development of functional performance measurements that need to be used for determining the moment for return to play. To answer these objectives, this thesis is divided into two parts.

Part I "Reconstructing the rehabilitation program" consists of two chapters.

- In Chapter 2 we describe the development of an evidence-based practice guideline for ACL rehabilitation.
- In Chapter 3 we present the current knowledge on accelerated brace-free rehabilitation after ACLR with HS graft in a systematic review.

In part II "Playing with return to play criteria" the functional performance measurements as proposed in the evidence-based practice guideline (both movement quantity and quality) that are needed to contribute to a safe return to play and the influence of leg dominance and fatigue on these measurements will be investigated.

- In Chapter 4 we present a systematic review aimed to identify which functional performance measurements are used more than two years after ACLR.
- In the cross-sectional study of Chapter 5 we compare athletes two to nine years after ACLR with healthy controls for both movement quantity and quality.
- In the prospective study of Chapter 6 we describe whether physical therapists in the Netherlands are able to use the functional performance measurements in general practice and how many athletes after ACLR actually meet the RTP criteria.
- In Chapter 7 we explain how to determine leg dominance in healthy adults and discuss the potential implications this may have for athletes returning to play after ACLR.
- In the cross-sectional study of Chapter 8 we investigate the influence of fatigue on both movement quantity and quality in ACLR soccer players compared to healthy soccer players.

In the General Discussion (Chapter 9) the rehabilitation program and RTP criteria, as stated in this thesis, will be compared with previous protocols, conclusions are drawn and recommendations for clinical practice and further research are made.

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1

Part I

Reconstructing the rehabilitation program

Chapter 2

Evidence-based clinical practice update: practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus

Nicky van Melick
Robert E.H. van Cingel
Frans Brooijmans
Camille Neeter
Tony van Tienen
Wim Hullegie
Maria W.G. Nijhuis-van der Sanden

British Journal of Sports Medicine 2016;50(24):1506-1515

Abstract

Aim: The Royal Dutch Society for Physical Therapy (KNGF) instructed a multidisciplinary group of Dutch ACL experts to develop an Evidence Statement for rehabilitation after ACL reconstruction.

Design: Clinical practice guideline underpinned by systematic review and expert consensus.

Data sources: A multi-disciplinary working group and steering group systematically reviewed the literature and wrote the guideline. Medline and the Cochrane Library were searched for meta-analyses, systematic reviews, randomized controlled trials (RCT's) and prospective cohort studies published between January 1990 and June 2015.

Eligibility criteria for selecting studies: Included literature must have addressed one of 9 pre-determined clinical topics: (1) pre-operative predictors for post-operative outcome, (2) effectiveness of physical therapy, (3) open and closed kinetic chain quadriceps exercises, (4) strength and neuromuscular training, (5) electrostimulation and electromyographic feedback, (6) cryotherapy, (7) measurements of functional performance, (8) return to play, (9) risk for re-injury.

Summary: Ninety studies were included as the basis for the Evidence Statement. Rehabilitation after ACL injury should include a prehabilitation phase and 3 criterion-based postoperative phases: (1) impairment-based, (2) sport-specific training, (3) return to sport. A battery of strength and hop tests, quality of movement and psychological tests should be used to guide progression from one rehabilitation stage to the next. Post-operative rehabilitation should continue for 9-12 months. To assess readiness to return to play and the risk for re-injury, a test battery including strength tests, hop tests and measurement of movement quality should be used.

Introduction

Anterior cruciate ligament reconstruction (ACLR) is a common treatment for athletes after ACL injury. The incidence of noncontact ACL injuries appears to be the greatest in athletes who are between 15 and 40 years of age and participate in pivoting sports like soccer, handball, volleyball and alpine skiing.[102,119] Every year, about 3% of amateur athletes injure their ACL; for elite athletes this percentage could be as high as 15%.[102] Females are two to eight times more likely to sustain an ACL injury than their male counterparts, probably because male and female neuromuscular patterns diverge during and following puberty.[67,71,84,107,144,157] Besides its mechanical function in maintaining knee stability the ACL contains mechanoreceptors (2.5%) and therefore directly influences the neuromuscular control of the knee.[159] ACL deficiency causes partial de-afferentation and alters spinal and supraspinal motor control. The changes in motor control strategy can reveal changes in proprioception, postural control, muscle strength, movement and recruitment patterns.[34] An ACL injury might therefore be regarded as a neurophysiological dysfunction and not a simple peripheral musculoskeletal injury.[31,76] It is also not self-evident that an ACLR will automatically lead to a return to preinjury activity level.

Recent research shows that 35% of athletes after ACLR do not return to preinjury sport level within two years.[5,8,129] Half of these athletes report their ACL injury as the primary reason for a lower activity level.[5,7,8,23,94] Apart from the physical recovery, also the psychological response (e.g. fear of re-injury) after ACLR has an influence on whether an athlete chooses to return to play.[6,9,26,46,81,83,151] Return to play is defined as the ability to play a competitive match at the preinjury level. Moreover, recent research shows that 3-22% of athletes rerupture the reconstructed ligament and 3-24% rupture the contralateral ACL in the first five years after ACLR.[3,13,23,113,138,153]

The difficulty with determining the moment of return to play is that it is unknown which measures should be used to predict a safe return to play with a low risk of a second ACL injury. Three recent systematic reviews show that the return-to-play decision by clinicians is hardly based on objective clinimetric criteria.[12,13,41] Furthermore, these studies concluded that return to play is only connected to quantitative criteria, while it is known that qualitative criteria (e.g. dynamic knee valgus, knee flexion angle, trunk control) play an important role in prevention and rehabilitation. Movement quality actually may affect the ACL (re)injury rate.[112,122] The occurrence of dynamic knee valgus when landing from a jump, for instance, increases the risk of ACL (re)injury.[66,114]

Return to play is the ultimate goal of rehabilitation programs. So the above mentioned factors are important topics to incorporate in the rehabilitation process after ACLR. However, currently, there is no consensus regarding the content of a rehabilitation program. Therefore, the Royal Dutch Society for Physical Therapy (KNGF) instructed a multidisciplinary group of ACL experts in the Netherlands to develop an Evidence Statement for anterior cruciate ligament rehabilitation. The goal of this Evidence Statement was to describe the rehabilitation after ACLR and to encourage uniformity in physical therapy treatment and use of measurements of functional performance. The following three questions were formulated by a steering group of the KNGF to guide the realization of the Evidence Statement:

1. What should be the content of the rehabilitation protocol after ACLR based on scientific evidence and, if not present, based on best-practice?
2. Which measurements and assessments can be applied to monitor progression during the rehabilitation program and to determine outcomes at the end of rehabilitation program?
3. What criteria should be used to determine the moment of return to play?

Methods

Expert participants

The process started with the formation of a multidisciplinary working group and steering group. The working group consisted of six Dutch ACL experts with 8 to 35 years of experience in ACL rehabilitation: five physical therapists specialized in sports injury rehabilitation and one orthopedic surgeon specialized in knee surgery, ACL surgery in particular. The steering group consisted of ACL experts from different professions with 10 to 37 years of experience in ACL rehabilitation (three physical therapists, one sports physician, one orthopedic surgeon and one trauma surgeon).

Procedure

The first author (NvM) chaired the working group and was responsible for the systematic review steps (literature search, methodological quality assessment, data extraction, data analysis, description of the results and translation into practice guidelines) and for writing the Evidence Statement. The working group monitored each step in the systematic review process and assisted in methodological quality assessment of the included studies, the writing process and the translation into practice guidelines. The steering group (chairman REHvC) validated all steps made by the first author and the working group. The KNGF assisted in the administrative processes.

The working group contacted each other by email and every two months a consensus meeting was organized. Every other meeting, the steering group joined the working group.

The first meeting of the working and steering group together, started with the formulation of nine clinical topics important for ACLR rehabilitation. These topics were used to guide the systematic review process. These nine topics were: 1) preoperative predictors for postoperative outcome, 2) effectiveness of physical therapy, 3) open kinetic chain (OKC) versus closed kinetic chain (CKC) quadriceps exercises, 4) strength training and neuromuscular training, 5) electrostimulation and electromyographic feedback, 6) cryotherapy, 7) measurements of functional performance, 8) return to play, and 9) risk of re-injuries.

Articles found during the systematic review process were subdivided into the nine topics and every topic was given a level of evidence according to the EBRO (Dutch Evidence Based guideline development) criteria.[149] The recommendations were, if available, based on the latest scientific evidence, supplemented with best-practice when necessary. The results of the systematic review process (see Appendix 1) were used to formulate the Evidence Statement (see Appendix 2).

Search strategy

A systematic literature search was performed searching in Medline (Pubmed) and the Cochrane Library to identify relevant articles from January 1990 up to June 2015 using keywords specified for the database according to the nine topics mentioned above with PICO questions (Table 1). An academic librarian composed a syntax based on all the keywords. Meta-analyses, systematic reviews, randomized controlled trials (RCT's) and prospective cohort studies were included for study selection.

Table 1: *Search strategy 31 May 2015.*

	Citations Medline	**Citations Cochrane**
1: anterior cruciate ligament [Mesh]	10170	739
2: anterior cruciate ligament [tiab]	11970	1359
3: anterior cruciate ligaments [tiab]	331	-
4: ACL [tiab]	10402	853
5: 1 – 4 with OR	17340	1596
6: anterior cruciate ligament reconstruction [Mesh]	1794	179
7: anterior cruciate ligament reconstruction [tiab]	3903	968
8: anterior cruciate ligament/surgery [Mesh]	6451	-
9: reconstructive surgical procedures [Mesh]	143978	6051
10: reconstructive surgical procedures [tiab]	149	908
11: reconstructive surgical procedure [tiab]	32	-
12: reconstruction [tiab]	142371	3348
13: reconstructed [tiab]	39500	474
14: reconstructive [tiab]	25421	1187

	Citations Medline	Citations Cochrane
15: ligament surgery [tiab]	317	930
16: bone-patellar tendon-bone grafts [Mesh]	14	-
17: bone-patellar tendon-bone grafts [tiab]	67	-
18: bone-patellar tendon-bone graft [tiab]	212	94
19: tendon graft [tiab]	1357	247
20: tendon grafts [tiab]	699	-
21: tendon transfer [Mesh]	3540	62
22: tendon transfer [tiab]	1302	83
23: tendon transfers [tiab]	674	-
24: orthopedic procedures [Mesh]	213556	9925
25: orthopedic procedures [tiab]	680	1350
26: orthopedic procedure [tiab]	124	-
27: orthopaedic procedures [tiab]	523	-
28: orthopaedic procedure [tiab]	107	-
29: 6 – 28 with OR	444486	15852
30: physical therapy modalities [Mesh]	129118	16446
31: physical therapy [tiab]	11921	18473
32: physiotherapy [tiab]	12631	3939
33: kinesiotherapy [tiab]	114	850
34: exercise therapy [tiab]	2120	16047
35: postoperative care [Mesh]	52666	3903
36: postoperative care [tiab]	4852	13295
37: rehabilitation [Mesh]	154448	15806
38: rehabilitation [tiab]	110195	14259
39: rehabilitation [subheading]	168951	13952
40: instruction [tiab]	20681	3773
41: instructions [tiab]	21227	-
42: resistance training [Mesh]	3752	1255
43: resistance training [tiab]	4168	4113
44: strength training [tiab]	3137	4966
45: neuromuscular training [tiab]	227	631
46: exercise [Mesh]	124975	14346
47: exercise [tiab]	188673	42289
48: exercises [tiab]	25022	-
49: testing [tiab]	376479	23811
50: test [tiab]	1057291	101340
51: tests [tiab]	484232	-
52: 30 – 51 with OR	2266540	190016
53: 5 and 29 and 54	4252	580
54: inclusion publication date 1990-01-01 until 2015-05-31	4051	544
55: inclusion language English	3619	529

Study selection

All eligible articles were screened first by title and abstract independently by two reviewers (NvM and REHvC). When the two reviewers did not reach consensus, a third reviewer (CN) made the final decision. After this first inclusion, the full-text article was screened using the in- and exclusion criteria as listed in Table 2. In addition, a hand search was done on the reference lists of meta-analysis and systematic reviews for RCT's and prospective cohort studies that were not included in the primary search. A flowchart of the search strategy is presented in Figure 1.

Table 2: *Inclusion and exclusion criteria for literature search.*

Inclusion	Exclusion
• Date of publication: January 1990-June 2015 • English language • Meta-analyses, systematic reviews, RCT's and prospective cohort studies • Full text available • Articles about brace-free rehabilitation after arthroscopic ACLR with BPTB or HS autograft • Articles including information on one of the 9 clinical topics formulated by the experts	• Narrative reviews, retrospective cohort studies, case studies • Articles about non-operative treatment • Articles about allograft, synthetic graft or other autograft than BPTB or HS • Articles about ACL revision reconstruction • Articles with follow-up measurement, but no description of the rehabilitation protocol • Articles about operative techniques, timing of the operation or graft choice • Articles about bracing after ACLR • Articles about skeletally immature patients • Animal, cadaveric or in-vivo studies

ACLR=anterior cruciate ligament reconstruction, BPTB=bone-patellar tendon-bone, HS= hamstring, RCT=randomised controlled trial.

Methodological quality assessment

Quality assessment of the included articles was independently performed by two reviewers (NvM and REHvC). When the reviewers did not reach consensus a third reviewer made the final decision. All articles were individually graded for level of methodological quality (Table 3 and Appendix 1).

Methodological quality of meta-analyses and systematic reviews was assessed with the AMSTAR checklist. The assessment of risk of bias of the RCT's was

Table 3: *Grading of the level of methodological quality of individual studies (EBRO).*

Level of Evidence	Interventional studies	Diagnostic accuracy studies	Harm, side effects, etiology, prognosis
A1	Systematic review/meta-analysis of at least 2 independently conducted studies of A2 level.		
A2	Randomized, double blind trial with good study quality and an adequate number of study participants.	Index test compared to reference test (reference standard); cut-offs were defined a-priori; independent interpretation of test results; an adequate number of consecutive patients were enrolled; all patients received both tests.	Prospective cohort study of sufficient magnitude and follow-up, adequately controlled for "confounding" and no selective follow-up.
B	Clinical trial, but without all the features mentioned for level A2 (including case-control study, cohort study).	Index test compared to reference test, but without all the features mentioned for level A2.	Prospective cohort study, but without all the features mentioned for level A2 or retrospective cohort study or case-control study.
C	Non-comparative studies		
D	Expert opinion		

performed with the PEDro scale (www.pedro.org.au). The PEDro scale was scored on 10 items. Methodological quality was rated poor when an article had a score ≤4. Subsequently, the RCT's with poor quality were excluded.

The prospective cohort studies were assessed with an adapted Cochrane Library Checklist (Table 4), also used before in the KNGF guideline for urinary incontinence.[17] This checklist has a maximum score of 5. Prospective cohort studies were only used when no higher-level evidence was available or to support findings in the RCT's.

Table 4: *Adapted Cochrane Library Checklist.*

Item	Score: + or -
1. Are inclusion and exclusion criteria reproducible? 2. Are the applied measurements reproducible? 3. Follow-up of participants is at least 80%? 4. Is the analysis corrected for confounders? 5. Is outcome measure description reproducible?	
Level of methodological quality A2: all 5 items are scored positive B: 4 out of 5 items are scored positive C: 3 or less items are scored positive	

Data extraction

Data extraction was done by one reviewer (NvM). See Appendix 1 for the data extraction table. Results from the included studies were synthesised descriptively for the Evidence Statement. Based on the results of all articles selected in one topic, a final conclusion was made with a corresponding level of evidence (Table 5).[77,149] To correct for double evidence, RCT's that were also included in a meta-analysis or systematic review were not used separately to determine the level of evidence of the final conclusion.

Table 5: *Level of evidence of the conclusion (EBRO).*

Level	Conclusion based on
1	A1 study or at least 2 independent studies of level A2
2	1 study of level A2 or at least 2 independent studies of level B
3	1 study of level B or C
4	Expert opinion

Results

Study selection and methodological quality assessment

After removing doubles the systematic literature search in Medline and the Cochrane Library provided 3713 articles (Figure 1). After the first exclusion based on title and abstract 101 articles were included for full-text assessment. After reading, no study was excluded. After the hand-search in the reference lists of meta-analyses and systematic reviews, 8 articles were included additionally. After quality assessment 19 RCT's were excluded based on a PEDro score of ≤4. The

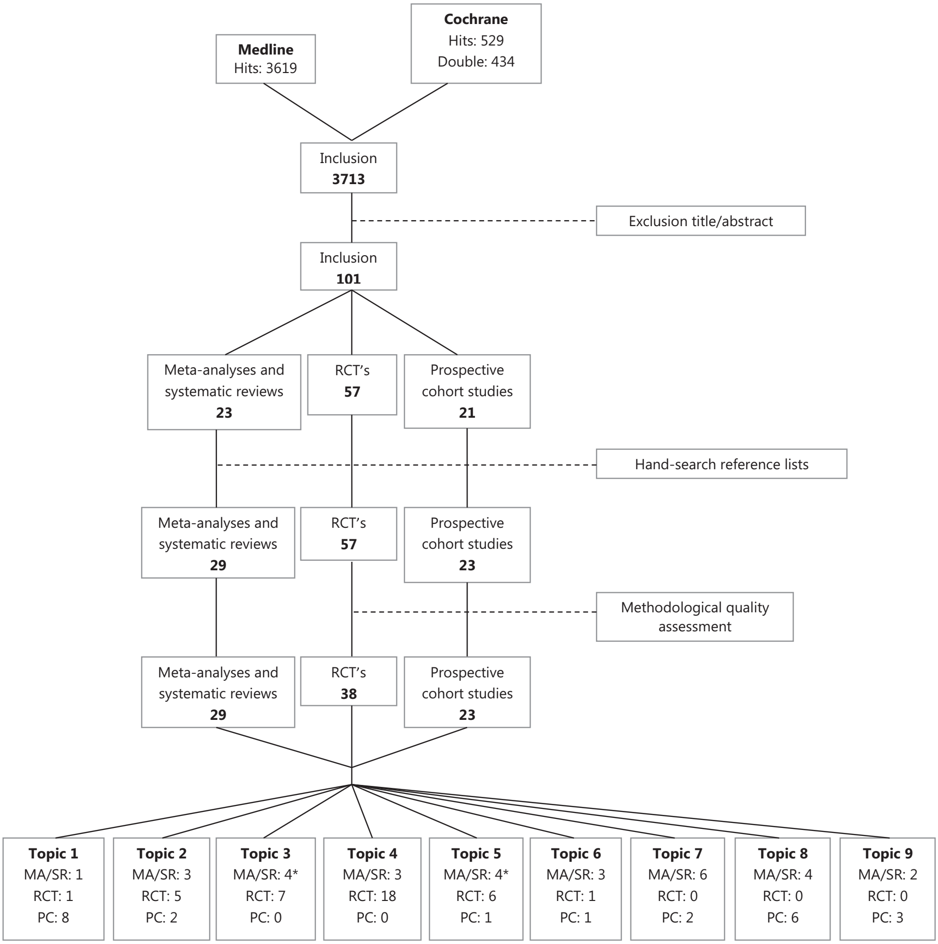

Figure 1: *Flowchart of search strategy 31 May 2015.*

**Topic 3 and 5 share one SR*

MA=meta-analysis, SR=systematic review, RCT=randomized controlled trial, PC=prospective cohort study

most common flaws were no blinding of participants, therapists or outcome assessors and an inadequate percentage of subjects eligible for follow-up.

All final included (n=90) articles were arranged by topic: 10 for preoperative predictors for postoperative outcome,[39,57,63,85,90,95,96,120,128,148] 10 for effectiveness of physical therapy,[14,19,20,30,36,56,59,69,105,155] 11 for OKC versus CKC quadriceps exercises,[4,24,48,52,64,88,98,101,118,147,156] 21 for strength training and neuromuscular training,[10,11,18,21,25,29,47,49-51,55,73,79,80,87,100,123,124,127,130,146] 11 for electrostimulation and electromyographic feedback,[27,37,44,45,72,78,86,115,137,150,156] 5 for cryotherapy,[38,53,70,91,121] 8 for measurements of functional performance,[12,13,32,41,61,104,108,143] 10 for return to play,[5,8,23,43,54,82,83,140,152,158] and 5 for risk of re-injuries[66,114,136,153,154] (topics 'open versus closed kinetic chain quadriceps exercises' and 'electrostimulation' share one systematic review).

Data extraction

Evidence for clinical practice at all nine topics is summarized below, according to Table 5. See also Appendix 1 for the data extraction table. Final recommendations were made according to the EBRO criteria in Table 5.

Preoperative predictors for postoperative outcome
Ten articles were found about preoperative predictors for postoperative outcome. These were one systematic review,[148] one RCT[128] and eight prospective cohort studies.[39,57,63,85,90,95,96,120]

The prospective cohort studies of Eitzen et al,[39] Heijne et al,[63] McHugh et al[96] and McHugh et al[95] were included in the systematic review of De Valk et al.[148] This level A2 systematic review documented that a) better functional outcomes after ACLR were achieved for men than for women at a minimum follow-up of one year after ACLR, no matter the graft choice; b) patients younger than 30 years of age had a higher postoperative Tegner activity level than older patients at a minimal follow-up of 22 months after ACLR; c) patients with ACLR within three months after injury and patients with a high preoperative Tegner activity level have a higher Tegner activity level at a minimal follow-up of two years after ACLR; d) smoking, high BMI (>30), quadriceps strength deficits and ROM deficits resulted in worse functional outcomes at a minimum of one year after ACLR.[148] The steering group found some prospective cohort studies that supported the conclusions of De Valk et al. Lepley and Palmieri-Smith[85] (level B) showed that preoperative quadriceps strength is positively related to postoperative quadriceps strength at the moment of return to play. Manson et al. [90] (level C) found that a higher preoperative Tegner activity level predicts a better outcome at a minimal follow-up of 22 months. Quelard et al.[120] (level B) described that a limited preoperative range of motion and female sex account for a limited range of motion three months postoperative.

Grindem et al.[57] (level C prospective cohort study) and Shaarani et al.[128] (level B RCT) investigated the effect of preoperative rehabilitation, so called prehabilitation on the outcome after ACLR. Grindem et al.[57] described that combined prehabilitation and postoperative rehabilitation had better self-reported knee function at two year follow-up compared to postoperative rehabilitation only. Shaarani et al.[128] had a follow-up of only 12 weeks after ACLR. They found no differences in quadriceps and hamstring strength between a prehabilitation group and a group with no prehabilitation, but the prehabiliation group scored better on self-reported knee function.[128]

From the above mentioned predictive factors the non-modifiable factors could be taken into account by the physical therapist to predict the outcome of treatment.

The conclusions about modifiable factors in this topic were:

- Level 2: A preoperative extension deficit (lack of full extension) is a major risk factor for an extension deficit after ACLR.[120,148]
- Level 2: A preoperative deficit in quadriceps strength of more than 20% has a significant negative consequence for the self-reported outcome two years after ACLR.[85,148]
- Level 3: Prehabilitation ensures better self-reported knee function up to two years after ACLR.[57,128]

Effectiveness of physical therapy
Ten articles were found about the effectiveness of postoperative physical therapy. These were three systematic reviews,[30,59,155] five RCT's[14,19,20,56,69] and two prospective cohort studies.[36,105]

The systematic review of Van Grinsven et al.[59] (level B) described a time-based rehabilitation protocol based on the available evidence supplemented with expert opinion.

The level A1 systematic review of Coppola and Collins[30] investigated the effect of physical therapy after knee surgery. Based on 10 RCT's they concluded that physical therapy is not more effective than a home exercise program in a young and healthy population following relatively simple knee surgery as arthroscopic meniscectomy. However, for rehabilitation after complicated knee surgery as ACLR, there is a lack of evidence.[30] The systematic review of Wright et al.[155] (level A1) concluded that it is reasonable that a minimally supervised rehabilitation can result in successful ACLR rehabilitation. In their study Coppola and Collins[30] included three RCT's about rehabilitation after ACLR. Wright et al.[155] included the same three RCT's plus the RCT of Beard and Dodd.[14] The level B RCT of Beard and Dodd[14] showed that physical therapy had minimal extra benefit in a, not explicitly described, young athletic population after ACLR. Their rehabilitation program was only administered from weeks 4 till 16 after ACLR. They found no differences in self-reported knee function and quadriceps and hamstring strength 24 weeks after ACLR.[14] Hohmann et al.[69] and Grant and Mothadi[56] (both level B) also investigated the difference between supervised physical therapy (Hohman: 19 sessions, Grant and Mothadi: 17 sessions) versus home-based rehabilitation (4 sessions). They both found no between group differences in range of motion, quadriceps and hamstring strength and hop tests at more than one year follow-up,[56,69] but Grant and Mothadi[56] found a better self-reported knee function in the home-based group. The level C prospective cohort study of Dragicevic-Cvjetjovic et al.[36] found a better self-reported knee function and greater improvement in thigh muscle circumference in a rehabilitation group (20 weeks) compared to a group with no rehabilitation at all at a one year follow-up.

Both studies of Beynnon et al.[19,20] (level B and A2) studied the difference between a 19-week and a 32-week rehabilitation program after ACLR. They concluded that there were no differences in self-reported knee function, laxity, range of motion, strength and hop tests at a two year follow-up.[19,20] The rehabilitation program of Muneta et al.[105] (level B) comprised a six month rehabilitation. Their results are comparable to both studies of Beynnon et al.[19,20,105]

The conclusions in this topic were:

- Level 2: Due to a lack of high quality studies and contradictory results it is unclear whether there is a benefit of supervised rehabilitation compared to home-based rehabilitation or no rehabilitation at all. A minimally supervised rehabilitation program may result in successful rehabilitation in specific groups of patients that are highly motivated and live far from a physical therapist.[30,56,69,155]
- Level 2: When comparing a 19-week with a 32-week rehabilitation program, there are no differences in terms of laxity, range of motion, self-reported knee function, single-leg hop test for distance or isokinetic concentric quadriceps and hamstring strength.[19,20,105]

OKC versus CKC quadriceps exercises

Concerning the OKC and CKC quadriceps exercises eleven articles were traced. These were four systematic reviews[4,52,88,156] and seven RCT's.[24,48,64,98,101,118,147]

Andersson et al.[4] conclude in their systematic review (level A1) that after ACLR with BTPB, CKC quadriceps exercises produce less pain, less risk of increased laxity and better self-reported knee function compared to OKC quadriceps exercises. They included the RCT's of Bynum et al,[24] Mikkelsen et al,[98] Morrissey et al[101] and Perry et al.[118] The recent RCT of Uçar et al.[147] found no differences between CKC and OKC exercises, but they investigated a group of patients after ACLR with a hamstring (HS) graft.

The systematic reviews of Glass et al.[52] (level A1) and Wright et al.[156] (level A1) both conclude that OKC quadriceps exercises should not be used in the first six weeks of rehabilitation after ACLR. Herewith, they confirmed the results of Andersson et al.[4] The RCT of Heijne et al.[64] (level B) investigated early (4 weeks) versus late (12 weeks) start of OKC quadriceps exercises and compared ACLR with BPTB and HS. They concluded that the HS group with an early start had more laxity after a follow-up period of 7 months than the other groups. Besides, an early start of OKC quadriceps exercises had no beneficial effect on quadriceps strength.[64] Fukuda et al.[48] (level B RCT) described that OKC quadriceps exercises can be started from week four after ACLR with HS, but in a limited range of motion between 45° and 90°.

The systematic review of Lobb et al.[88] concluded that there is limited evidence that a combination of OKC and CKC quadriceps exercises results in better strength and return to play than CKC exercises alone. They also included the systematic review of Andersson et al.[4,88]

The overall conclusions were:

- Level 1: Both CKC and OKC training can be used for regaining quadriceps strength.[52,88,147]
- Level 2: After ACLR OKC exercises can be performed from week 4 postoperative in a restricted range of motion (ROM) of 90-45°.[48,64,52,156]

Strength training and neuromuscular training

Concerning strength training and/or neuromuscular training 21 articles were found. Among them were three systematic reviews[10,55,80] and 18 RCT's.[11,18,21,25,29,47,49-51,73,79,87,100,123,124,127,130,146]

Both systematic reviews of Gokeler et al.[55] (level A1) and Kruse et al.[80] (level A1) concluded that eccentric quadriceps training can be safely incorporated three weeks after ACLR and may be the most effective way of restoring quadriceps strength. However, the level A1 systematic review of Augustsson et al.[10] concluded that the strength training programs after ACLR should be further developed because it is still unclear what is the best way to train the quadriceps. To optimize outcome after rehabilitation, neuromuscular training should be added to strength training according to Gokeler et al.[55] and Kruse et al.[80] Neuromuscular training is defined as training enhancing unconscious motor responses by stimulating both afferent signals and central mechanisms responsible for dynamic joint control.[125] These exercises are designed to induce compensatory changes in muscle activation patterns and facilitate dynamic joint stability.[125] Nine RCT's were included in the above mentioned systematic reviews: Cooper et al,[29] Gerber et al,[51] Gerber et al,[49] Risberg et al,[123] Risberg and Holm,[124] Sekir et al,[127] and Shaw et al.[130] The level B RCT's of Berschin et al.[18], Bieler et al.[21], Fu et al.[47], Gerber et al.[50] and Kinikli et al.[79] support the findings in those systematic reviews.

The level B RCT's of Isberg et al.[73] and Shaw et al.[130] concluded that isometric quadriceps exercises are safe in the first postoperative weeks, because there are no differences in laxity up to two years of follow-up.

Baltaci et al.[11] (level B RCT) and Cappellino et al.[25] (level B RCT) demonstrated that the use of Wii Fit respectively neurocognitive rehabilitation have no beneficial effect to a combined strength and neuromuscular rehabilitation at a short-term follow-up.

Tyler et al.[146] (level B RCT) concluded that immediate weight bearing had no detrimental effects for laxity and a positive effect on anterior knee pain at a one year follow-up.

The main conclusions were:

- Level 1: Starting eccentric quadriceps training (in CKC) from 3 weeks after ACLR is safe and contributes to a bigger improvement in quadriceps strength than concentric training.[21,50,55,79,80]
- Level 1: Neuromuscular training should be added to strength training to optimize self-reported outcome measurements.[18,47,55,80]
- Level 2: Isometric quadriceps exercises are safe from the first postoperative week.[73,130]
- Level 3: Immediate weight bearing does not affect knee laxity and results in decreased incidence of anterior knee pain.[146]

2

Electrostimulation and electromyographic feedback

Eleven articles about electrostimulation and electromyographic feedback were found. These were four systematic reviews,[72,78,150,156] six RCT's[27,37,44,45,115,137] and one prospective cohort study.[86]

Imoto et al.[72] and Kim et al.[78] (level A1 systematic reviews) both concluded that the addition of electrostimulation to conventional rehabilitation might be more effective in improving quadriceps strength up to two months after ACLR. The level A2 RCT of Paternostro-Sluga et al.[115] and the level B RCT of Fitzgerald et al.[45] were included in both systematic reviews. Ediz et al.[37] (level B RCT) and Lepley et al.[86] (level C prospective cohort study) found no differences in effusion, pain, range of motion and knee extension and flexion moments when electrostimulation was added to conventional rehabilitation. Feil et al.[44] and Taradaj et al.[137] (both level B RCT's) did examine quadriceps strength and found a higher increase in quadriceps strength when electrostimulation was added to conventional rehabilitation at a six month follow-up. Wright et al.[156] (level A1 systematic review) summarized that electrostimulation may help improve quadriceps strength in the early postoperative period, but that it is not a prerequisite for successful rehabilitation. All authors did not distinguish between regaining quadriceps motor control or increasing quadriceps strength.

Studies concerning electromyographic feedback are contradictory. The systematic review of Wasielewski et al.[150] (level A1) showed that electromyographic feedback improves short-term post-surgical pain after ACLR, but Christanell et al.[27] (level B RCT) described no differences in pain during the first six postoperative weeks with or without biofeedback.

The conclusions on this topic were:

- Level 1: Electrostimulation, in combination with conventional rehabilitation, might be more effective for improving muscle strength for up to two months after ACLR than conventional rehabilitation alone. However, its effect on long-term functional performance and self-reported knee function is inconclusive.[44,72,78,137,156]

- Level 2: Electromyographic feedback might improve short-term postsurgical pain after ACLR.[27,150]

Cryotherapy
Five articles were found about cryotherapy: two meta-analyses,[91,121] one systematic review,[70] one RCT[38] and one prospective cohort study.[53]

All three level A1 articles shared the conclusion that cryotherapy is effective in reducing postoperative pain until about one week post-surgery, but it has no effect on drainage or range of motion.[70,91,121] The level A2 RCT of Edwards et al.[38] was included in the meta-analyses of Martimbianco et al.[91] The prospective cohort study of Glenn et al. (level C) supports these findings.[53]

The conclusion on this topic was:

- Level 1: Cryotherapy is effective in decreasing pain immediately after application up to one week post-surgery after ACLR, but has no effect on postoperative drainage or range of motion.[53,70,91,121]

Measurements of functional performance
Eight articles about measurements of functional performance were traced: six systematic reviews[12,13,32,41,61,108] and two prospective cohort studies.[104,143]

Five systematic reviews (all level B) concluded that there is a lack of objective criteria to determine return to play.[12,13,41,61,108] Extensive test batteries for determining quantity and quality of movement are recommended, including strength tests, hop tests and video analysis for measuring quality of movement.[12,41]

There is weak evidence from a level A2 systematic review for factors that could be associated with a higher chance of return to play: less effusion, less pain, higher quadriceps strength, greater tibial rotation, higher Marx Scale score, higher athletic confidence, higher preoperative knee self-efficacy, lower kinesiophobia and higher preoperative self-motivation.[32] Müller et al.[104] (level B prospective cohort study) added better self-reported knee function and better hop test performance to this list.

Thomeé et al.[143] (level B prospective cohort study) described that there were poor results at two years after ACLR when testing leg muscle power and hop performance and applying a Limb Symmetry Index (LSI) of >90% to all six tests. Only 23% of patients passed when using these criteria and only 10% passed when an LSI of 95% was used.[143]

The overall conclusions were:

- Level 2: An extensive test battery should be used for determining the moment for return to play, but there are no tests or test batteries that have been tested for construct or predictive validity for return to play.[12,13,32,41,61,104,108]

- Level 3: It is not clear which cut-off point of the LSI should be used for strength and hop tests.[143]

Return to play

Ten articles were traced about return to play: two meta-analyses,[5,8] two systematic reviews[43,152] and six prospective cohort studies.[23,54,82,83,140,158]

The meta-analysis of Ardern et al.[5] (level A2) included their earlier meta-analysis[8] and the prospective cohort studies of Brophy et al,[23] Gobbi and Francisco[54] and Langford et al.[83] They found that 65% of patients after ACLR returned to preinjury competitive sport level within two years, but only 38% remained at the same level more than two years after ACLR. Men were 1.4 times more likely to return to their preinjury sport level than women, and BPTB was 1.2 times more likely than HS.[5,8,23,54,83] Laboute et al.[82] (level C prospective cohort study) reported 65.7% of athletes returning to preinjury sport level, while Zaffagnini et al.[158] reported a higher return to preinjury sport level of 71% in a group of professional soccer players four years after ACLR.

Several psychological factors have influence on the rehabilitation process and return to play. According to the systematic reviews of Everhart et al.[43] (level A2) and te Wierike et al.[152] (level B) a high self-efficacy, a high internal locus of control, and a low level of fear are associated with a higher chance of return to play. They included the prospective cohort studies of Gobbi and Francisco,[54] Langford et al[83] and Thomeé et al.[140]

The literature concluded that:

- Level 1: The rate of return to preinjury play level for (nonprofessional) pivoting athletes after ACLR is 65%.[5,82]
- Level 2: Psychological factors as self-efficacy, locus of control and fear of re-injury have influence on the rehabilitation process and return to play after ACLR.[43,152]

Risk of re-injuries

Five articles about risk of re-injuries were found. These were two systematic reviews[136,154] and three prospective cohort studies.[66,114,153]

The systematic reviews of Swärd et al.[136] and Wright et al.[154] (both level B) concluded that the risk of a contralateral ACL injury is higher than the risk of a first-time ACL rupture or an ACL graft re-rupture. The level B prospective cohort study of Wright et al.[153] was included in both systematic reviews.

The level B prospective cohort studies of Hewett et al[66] and Paterno et al[114] support the conclusions of the systematic review of Swärd et al.[136] that altered neuromuscular function and biomechanics could be responsible for the risk of second ACL rupture (both graft re-rupture or contralateral ACL). Factors contributing could be greater hip internal rotation, the occurrence of dynamic knee valgus, or less knee flexion when landing from a jump.[66,114,136]

Their conclusions were:

- Level 2: The risk of a contralateral ACL rupture (>10%) is higher than the risk of graft re-rupture (about 5%) (up to 10 years after ACLR) or first-time ACL rupture.[136,154]
- Level 2: Altered neuromuscular function and biomechanics (greater hip internal rotation, the occurrence of dynamic knee valgus, or less knee flexion during landing) after ACLR could be a risk factor for second ACL injury (graft re-rupture or contralateral rupture).[66,114,136]

Consensus conclusion

Although there are many articles published about ACL rehabilitation, there is limited evidence for parameters that influence or predict the final result of ACLR rehabilitation and return to play. The aim of this study was to describe the process in which the KNGF Evidence Statement for ACL rehabilitation was developed and to present this practice guideline (see Appendix 2). The goal of the Evidence Statement was to describe the rehabilitation after ACLR with bone-patellar tendon-bone (BPTB) or hamstring (HS) autograft and to encourage uniformity in physical therapy treatment and the use of measurements of functional performance. The Evidence Statement is aimed to fill a gap between evidence and clinical practice and describes a complete protocol to rehabilitate an athlete after ACLR. The multidisciplinary approval of this Evidence Statement underlines the importance of a close collaboration between different professions.

Despite the fact that our Evidence Statement is based on information from RCT's and systematic reviews from the two most important databases, the evidence is inconclusive. Due to this lack of scientific evidence, available background literature and a steering group consisting of ACL experts were used to develop a multidisciplinary consensus statement for an ACL rehabilitation protocol. This consensus statement was based on three formulated questions with the following conclusions.

What should be the content of the rehabilitation protocol after ACLR?

The description of the rehabilitation protocol is divided in preoperative and postoperative rehabilitation.

Preoperative rehabilitation

Preoperative rehabilitation, also known as prehabilitation, is not usually prescribed by orthopedic surgeons (or trauma surgeons) in the Netherlands. Previous studies showed that a preoperative full extension range of motion reduces the chance for postoperative complications as arthrofibrosis.[90,96] Moreover, a deficit in quadriceps strength of 20% or more predicts a significant strength deficit until two years after ACLR (*level 2*).[75,128] Therefore, the steering group recommends to measure the preoperative range of motion and quadriceps strength as part of the preoperative rehabilitation protocol. The steering group also advises to measure hamstring strength, although there is no recommendation for hamstring measurement in literature. Yet, there are studies that conclude that hamstring strength in the operated leg is still reduced compared to the non-operated leg until two years after ACLR.[75] For this examination and possible treatment the patient could be referred to a physical therapist in order to prevent a complicated or prolonged rehabilitation.

Preoperative information about walking with crutches, the early postoperative exercises and the rehabilitation process may improve a patients' self-efficacy, thus the steering group advises to discuss these topics with patients *(level 4).* See also Table 6 for a summary of conclusions and recommendations.

Postoperative rehabilitation

Good communication between the surgeon and physical therapist is of great importance. While the orthopedic surgeon is responsible for the surgery results and techniques the physical therapist should be leading in decision making in rehabilitation. Therefore, the steering group advises that the orthopedic surgeon (or trauma surgeon) informs the physical therapist about perioperative findings: graft type, menisectomy or meniscus repair, cartilage damage (location, size and grade), ligamentous injuries or complications during surgery. Also, when possible in his setting, the physical therapist should inform the surgeon about the current status of the patient preceding to every pre- or postoperative outpatient appointment, to ensure appropriate levels of stress are being applied to the healing tissues.[103]

During the first meeting of the working and steering group it was decided to define different phases during rehabilitation after ACLR. Current literature describes time-based rehabilitation protocols that are mainly based on the remodeling process of the graft.[59] Since there is still uncertainty about the time schedule of the human remodeling process it makes more sense to incorporate functional goal-based criteria to the rehabilitation protocol.[28,74,110,126] Besides, there are individual differences in neuromotor learning and -flexibility after ACLR. These underline the importance of a shift from time-based rehabilitation to goal-based rehabilitation with neuromuscular goals and criteria to manage the rehabilitation process. These goals for progression to the next phase and description of interventions during each phase are based on the International Classification of Functioning, Disability and Health (ICF) (WHO 2001). Our Evidence Statement consists of three phases (see Appendix 2) with a goal-based progression: the so-called traffic-light method of progression through phases. This is relatively new in rehabilitation, but it assures a more patient-tailored rehabilitation.[35,158] Patients can start with the next phase only if specific goals of the previous phase are achieved and these should be confirmed with objective tests (see Appendix 2 for criteria).

The steering group advises to start rehabilitation immediate after ACLR and continue rehabilitation for 9 to 12 months, depending on the final return-to-work or play goals of the patient.[58] This rehabilitation period is necessary to allow return to high-intensity sport or physically demanding work. This term differs from a previous ACLR rehabilitation protocol by Van Grinsven et al,[59], who presented a 22-week rehabilitation with four time-based phases. Recent evidence suggests longer rehabilitation periods are needed, because most patients are not able to reach the end-rehabilitation goals in 22 weeks.[16,68] Herbst et al.[65] presented a new functional performance test battery and concluded that most patients were not ready for return to play even at 8 months after ACLR. Others suggest that home-based rehabilitation is as effective as supervised rehabilitation.[14,56,69] These home-based rehabilitation programs are designed in countries where patients live too far from a physical therapist to schedule a visit a few times in a week. Important to mention is that these programs are not designed for patients that perform high-intensity sports. Still, there is no evidence which rehabilitation period or how many appointments per week works best for return to play.

During postoperative rehabilitation, a physical therapist can use several treatment modalities, of which some are proven to be effective in literature and some are not (Table 6). It is known that immediate weight bearing is safe (*level 3*).[146] The steering group recommends that immediate weight bearing should only be tolerated if there is a correct gait pattern (if necessary with crutches) and no pain, effusion or increase in temperature when walking or shortly after walking. Cryotherapy could eventually be applied in the first postoperative week to reduce pain (*level 1*).[38,53,70,91,121] The steering group suggests to start isometric quadriceps exercises in this first week for reactivating the quadriceps muscles when they provoke no pain (*level 2*).[73,130] In addition electrostimulation can be useful for reeducating voluntary contraction of the quadriceps muscles during the first postoperative weeks (*level 1*).[44,45,72,78,115,137,156] When the quadriceps is reactivated, concentric and subsequently eccentric exercises should be used to replace the isometric exercises, provided that the knee does not react with effusion or (an increase in) pain. Quadriceps strength training can be performed both in CKC and OKC. Concentric CKC exercises can be done from week 2 postoperative. For OKC exercises there should be a distinction between ACLR with a bone-patellar tendon-bone (BPTB) graft or a hamstrings (HS) graft. For BPTB OKC exercises can be started from 4 weeks postoperative in a restricted ROM of 90-45° and extra resistance is allowed, for example at a leg extension machine (*level 2*). For HS OKC exercises also can be started from 4 weeks postoperative in a restricted ROM of 90-45°, but no extra weight should be added in the first 12 weeks to prevent graft elongation (*level 2*).[48,64] ROM can be increased to 90-30° in week 5, to 90-20° in week 6, to 90-10° in week 7 and to full ROM in week 8 for both graft types.[59] The steering group strongly advises that neuromuscular training should be added to strength training to optimize outcome measurements (*level 1*).[18,29,47,55,80,87,123,124,127,130]

In literature about rehabilitation after ACLR there is a lack of focus on the evaluation and training of the quality of movement as measurement of neuromuscular recovery. The relevance to focus more on the quality of movement is underlined by the fact that altered neuromuscular function and biomechanics after ACLR could be a risk factor for a second ACL injury (*level 2*).[66,114,136] An improvement in quality of movement can be observed as an effect of motor learning. In the early phases of rehabilitation mostly explicit motor learning is necessary, but we advocate that in the late phase of rehabilitation more implicit motor learning strategies should be used.[93] This because implicit learning may produce more stable solutions under stress, anxiety-provoking conditions and fatigue states, especially necessary in sports.[16]

Which measurements and assessments can be applied to monitor progression during the rehabilitation program and to determine outcomes at the end of rehabilitation program?

There are no clear recommendations regarding the use of measurements for quantity (e.g. strength and hop performance) and quality of movement during the postoperative rehabilitation process. The criteria to progress from phase 1 to phase 2 or from phase 2 to phase 3 are based on expert opinion (see Appendix 2). Besides the quantity and quality of movement, it is important to evaluate psychological changes during rehabilitation with an objective instrument, for example with the Marx Scale, the Psychovitality Scale or the Knee Self Efficacy Scale (K-SES) (*level 2*).[32,43,54,83,140,152]

What criteria should be used to determine the moment of return to play?

All included systematic reviews about measurements of functional performance have the same conclusion: studies are lacking objective physiological criteria at what time after ACLR return to play is allowed.[12,13,32,41,61,108] There is also no conclusive evidence that any test or test battery can accurately identify athletes at high risk of re-injury. Therefore, the steering group recommends to perform an extensive test battery for both quantity and quality of movement (*level 2*).[12,13,32,41,61,104,108] This test battery should include at least a strength test battery and a hop test battery and measurement of quality of movement for determining the moment for return to play. A Limb Symmetry Index (LSI) of >90% could be used as a cut-off point. For pivoting/contact sports an LSI of ≥100% is recommended (see Appendix 2).[142] Qualitative scoring systems as the Jump Landing System (JLS) and Landing Error Scoring System (LESS) have been developed in the past few years, but it is still unclear in which manner quality of movement plays a role in the occurrence of ACL re-injuries.[1,15,22,111,134] Therefore, prospective studies are needed to evaluate whether these scoring systems are able to measure neuromotor control and to investigate the predictive validity of those qualitative scoring systems.

Table 6: *Summary of conclusions and recommendations.*

Conclusions and recommendations	Level of evidence
Preoperative rehabilitation	
A preoperative extension deficit (lack of full extension) is a major risk factor for an extension deficit after ACLR. *Recommendation: measure the preoperative range of motion.*	2
A preoperative deficit in quadriceps strength of more than 20% has a significant negative consequence for the self-reported outcome two years after ACLR. *Recommendation: measure quadriceps strength and also hamstring strength.*	2
Prehabilitation ensures better self-reported knee function up to two years after ACLR. *Recommendation: refer the patient to a physical therapist when necessary.*	3
Postoperative rehabilitation	
It is unclear whether there is a benefit of supervised rehabilitation compared to home-based rehabilitation or no rehabilitation at all. A minimally supervised rehabilitation program may result in successful rehabilitation in specific groups of patients that are highly motivated and live far from a physical therapist.	2
When comparing a 19-week with a 32-week rehabilitation program, there are no differences in terms of laxity, range of motion, self-reported knee function, single-leg hop test for distance or isokinetic concentric quadriceps and hamstring strength. *Recommendation: continue rehabilitation for 9 to 12 months, depending on the final return-to-work or play goals of the patient.*	2
Immediate weight bearing does not affect knee laxity and results in decreased incidence of anterior knee pain. *Recommendation: immediate weight bearing should only be tolerated if there is a correct gait pattern (if necessary with crutches) and no pain, effusion or increase in temperature when walking or shortly after walking.*	2
Cryotherapy is effective in decreasing pain immediately after application up to one week post-surgery after ACLR, but has no effect on postoperative drainage or range of motion. *Recommendation: cryotherapy could eventually be applied in the first postoperative week to reduce pain.*	1
Isometric quadriceps exercises are safe from the first postoperative week. *Recommendation: start isometric quadriceps exercises in this first week for reactivating the quadriceps muscles when they provoke no pain.*	2

Conclusions and recommendations	Level of evidence
Electrostimulation, in combination with conventional rehabilitation, might be more effective for improving muscle strength for up to two months after ACLR than conventional rehabilitation alone. However, its effect on long-term functional performance and self-reported knee function is inconclusive. *Recommendation: electrostimulation can be useful as an addition to isometric strength training for reeducating voluntary contraction of the quadriceps muscles during the first postoperative weeks.*	1
Both CKC and OKC training can be used for regaining quadriceps strength. After ACLR OKC exercises can be performed from week 4 postoperative in a restricted range of motion (ROM) of 90-45°. *Recommendation: When the quadriceps is reactivated, concentric and eccentric exercises should be used to replace the isometric exercises, provided that the knee does not react with effusion or (an increase in) pain. CKC exercises can be done from week 2 postoperative. For BPTB OKC exercises can be started from 4 weeks postoperative in a restricted ROM of 90-45° and extra resistance is allowed, for example at a leg extension machine. For HS OKC exercises also can be started from 4 weeks postoperative in a restricted ROM of 90-45°, but no extra weight should be added in the first 12 weeks to prevent graft elongation. ROM can be increased to 90-30° in week 5, to 90-20° in week 6, to 90-10° in week 7 and to full ROM in week 8 for both graft types.*	1 2
Neuromuscular training should be added to strength training to optimize self-reported outcome measurements. Altered neuromuscular function and biomechanics after ACLR could be a risk factor for second ACL injury (graft re-rupture or contralateral rupture). *Recommendation: neuromuscular training should be added to strength training. Pay attention to a correct quality of movement for prevention of reinjuries.*	1 2
Psychological factors as self-efficacy, locus of control and fear of re-injury have influence on the rehabilitation process and return to play after ACLR. *Recommendation: evaluate psychological changes during rehabilitation with an objective instrument.*	2
Criteria for return to play An extensive test battery should be used to determine the return to play moment, but there are no tests or test batteries that have been tested for construct or predictive validity for return to play. It is not clear which cut-off point of the LSI should be used for strength and hop tests. *Recommendation: perform an extensive test battery for both quantity and quality of movement. This test battery should include at least a strength test battery and a hop test battery and measurement of quality of movement. An LSI of >90% could be used as a cut-off point. For pivoting/contact sports an LSI of ≥100% is recommended.*	2 3

2

Limitations

Meta-analyses and systematic reviews were included in this study. A strength is the additional weight in evidence, but a limitation is that the included meta-analyses and systematic reviews may have used other inclusion and exclusion criteria than the ones used in this study. The main discrepancy is that they did not mention the graft choice or brace-free rehabilitation in their information. We accept this limitation because many meta-analyses and systematic reviews are written about rehabilitation after ACLR and they comprise the highest level of evidence. In most cases they give useful advise for day-to-day clinical practice and add value to the included RCT's and PC's.

Despite the extensive literature search, our recommendations are lacking a certain specificity regarding sets, repetitions and resistance used in exercises. This is because included studies are vague in describing these parameters. However, it is extremely difficult to describe this for a population of patients, because these parameters depend on pain, effusion, level of the patient (concerning type of sport and experience with strength training for example). We expect that every sports physical therapist is able to address the correct parameters to his individual patient, but suggest that more research is needed on this topic.

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Appendix 1

Author	Year	Design	Methods	Results	
			1) Preoperative predictors for postoperative outcome		
De Valk[148]	2013	SR	Reviewing articles about prognostic patient and injury factors for successful rehabilitation. *Included the following studies: 39,63,95,96.*	Better functional outcomes for men, patients younger than 30 years, patients with ACLR within 3 months after injury and high baseline activity level. Smoking, high BMI, quadriceps strength deficits and ROM deficits guaranteed worse functional outcomes.	A2
Shaarani[128]	2013	RCT	Six weeks of preoperative rehabilitation versus no preoperative rehabilitation before ACLR with BPTB. Follow-up until 12 weeks postoperative. N=39	No differences for isokinetic concentric quadriceps and hamstring strength. The preoperative rehabilitation group had a better self-reported knee function (Cincinnati Knee Score) and function (hop for distance).	B
Eitzen[39]	2009	PC	Identifying preoperative factors for knee function after ACLR with BPTB. Follow-up 2 years. N=73	Isokinetic quadriceps strength, meniscus injury and de SF-36 Bodily Pain subscore were identified as predictors for self-reported knee function (Cincinnati Knee Score) after ACL reconstruction. An isokinetic preoperative quadriceps strength deficit above 20% predicts persistent strength deficits after 2 years.	B
Grindem[57]	2015	PC	Investigating the difference between a combined preoperative and postoperative rehabilitation and a usual care rehabilitation after ACLR with BPTB or HS. Follow-up 2 years. N=84 resp. 2690	The combined group had better preoperative and postoperative self-reported knee function (KOOS).	C
Heijne[63]	2009	PC	Identifying preoperative factors for knee function after ACLR with BPTB or HS. Follow-up 12-16 months. N=64	A low degree of anterior knee pain is the most important predictor for good self-reported knee function (KOOS).	A2

Author	Year	Design	Methods	Results	
Lepley[85]	2015	PC	Identifying if preoperative quadriceps activation or strength predict postoperative quadriceps activation or strength after ACLR with BPTB. Follow-up 7.2 months (moment of return to sports). N=54	Preoperative quadriceps activation was positively related to postoperative quadriceps activation, but not to postoperative isometric quadriceps strength (90°). Preoperative isometric quadriceps strength was positively related to postoperative strength.	B
Månsson[90]	2013	PC	Identifying preoperative factors for knee function after ACLR with HS. Follow-up 22 to 36 months. N=73	Preoperative activity level (Tegner) is an important predictor of self-reported knee function (KOOS, SF-36).	C
McHugh[95]	1998	PC	Determining what degree of motion loss represents a risk for postoperative motion problems and if preoperative weakness affects return of strength following ACLR with BPTB. Follow-up 6 months. N=102	The magnitude of preoperative extension loss is no risk factor. It is the presence of absence of full extension (left=right) that predicts risk for postoperative extension problems. Preoperative concentric isokinetic strength was not a good predictor of residual weakness.	B
McHugh[96]	2002	PC	Determining if preoperative electromyographic analysis can predict residual muscle weakness after ACLR with BPTB. Follow-up 6 months. N=37	A combination of the preoperative median frequency deficit and the 5-week postoperative isometric strength deficit is the best predictor of residual weakness.	B
Quelard[120]	2010	PC	Determining preoperative factors associated with prolonged range of motion deficit after ACLR with BPTB. Follow-up 3 months. N=217	Preoperative limited range of motion and combined bone bruises of the lateral femoral condyle and tibia plateau are risk factors for a limited range of motion.	B
			2) Effectiveness of physical therapy		
Coppola[30]	2009	SR	Reviewing RCT's about recovery following knee surgery, comparing supervised physical therapy to an unsupervised home exercise program. *Included none of the studies below.*	Many studies had designs that biased the home exercise group, providing similar results to that provided by supervised physical therapy. There is a lack of evidence regarding complicated knee surgical procedures as ACLR.	A1

Author	Year	Design	Methods	Results	
van Grinsven[59]	2010	SR	Reviewing articles to develop an optimal evidence-based rehabilitation protocol after ACLR. *Included the following studies: 20,87,98,101,118,130.*	An accelerated rehabilitation protocol without postoperative bracing, in which reduction of pain, swelling and inflammation, regaining ROM, strength and neuromuscular control are the most important aims, has important advantages and does not lead to stability problems.	B
Wright[155]	2008	SR	Reviewing RCT's about home-based rehabilitation after ACLR. *Included the following study: 14*	A minimally supervised physical therapy program can result in successful ACL rehabilitation.	A1
Beard[14]	1998	RCT	Home program plus supervised rehabilitation versus home program alone from weeks 4-16 after ACLR with BPTB. Follow-up 24 weeks. N=26	No differences in self-reported knee function (Lysholm, IKDC), laxity and concentric isokinetic quadriceps and hamstring strength.	B
Beynnon[20]	2005	RCT	Accelerated (19 weeks) versus non-accelerated (32 weeks) rehabilitation after ACLR with BPTB. Follow-up 2 years. N= 22	No differences in self-reported knee function (IKDC, Tegner, KOOS), laxity, ROM, single-leg hop for distance or biomarkers of articular cartilage metabolism.	B
Beynnon[19]	2011	RCT	Accelerated (19 weeks) versus non-accelarated (32 weeks) rehabilitation after ACLR with BPTB. Follow-up 2 years. N=42	No differences between groups on laxity, self-reported knee function (IKDC, Tegner, KOOS), single-leg hop for distance, proprioception or isokinetic concentric quadriceps strength.	A2
Grant[56]	2010	RCT	Physical therapy supervised rehabilitation (17 sessions) versus home-based rehabilitation (4 sessions) during the first 3 months after ACLR with BPTB. Follow-up 2-4 years. N=88	Better self-reported knee function (ACL-QOL) for the home-based group. No differences in ROM, laxity and isokinetic concentric quadriceps and hamstring strength.	B

Author	Year	Design	Methods	Results	
Hohmann[69]	2011	RCT	Physical therapy supervised rehabilitation (19 sessions) versus home-based rehabilitation (4 sessions) after ACLR with BPTB. Follow-up 1 year. N=40	No differences in self-reported knee function (Lysholm, Tegner), function (hop for distance, timed hop and vertical jump) or isometric and isokinetic concentric and eccentric quadriceps and hamstring strength.	B
Dragicevic-Cvjetjovic[36]	2014	PC	Investigating the difference between postoperative rehabilitation for 20 weeks and no rehabilitation at all after ACLR with HS. Follow-up 1 year. N=70	The rehabilitation group had a greater improvement self-reported knee function (Tegner, Lysholm) and in thigh muscle circumference.	C
Muneta[105]	1998	PC	Determining the effect of aggressive early rehabilitation after ACLR with BPTB or HS. Mean follow-up 20 months. N=103	No differences between patients operated with BPTB or HS and between men and women for laxity, ROM, self-reported knee function (Lysholm, Tegner), patellofemoral grinding or isokinetic concentric quadriceps and hamstring strength.	B
			3) Open versus closed kinetic chain quadriceps exercises		
Andersson[4]	2009	SR	Reviewing RCT's about rehabilitations aspects after ACLR. *Included the following studies: 24,98,101,118.*	CKC exercises produce less pain, less risk of increased laxity and better self-reported knee function after ACL reconstruction with BPTB. Further studies are needed for ACLR with HS.	A1
Glass[52]	2010	SR	Reviewing RCT's about the effects of CKC and OKC quadriceps exercises on the knees of patients after ACLR. *Included the following studies: 98,101,118.*	Both CKC and OKC are beneficial for this patient population. An optimal time for initiation of OKC exercises is at least 6 weeks after ACL reconstruction.	A1

Author	Year	Design	Methods	Results	
Lobb[88]	2012	SR	Evaluating systematic reviews on interventions after ACLR. *Included the following study: 4.*	There is moderate evidence that there are no differences between CKC and OKC for pain, laxity and function. There is limited evidence that a combination of CKC and OKC results in better strength and return to sports than CKC alone.	A1
Wright[156]	2008	SR	Reviewing RCT's about the effects of CKC versus OKC exercises. *Included the following studies: 24,98,101*	Until further studies are performed, only CKC exercises should be used in the first 6 weeks after ACLR.	A1
Bynum[24]	1995	RCT	OKC versus CKC quadriceps exercises starting at week 1 after ACLR with BPTB. Follow-up 3 years. N=85	No differences in laxity, ROM, activity level (Tegner) or self-reported knee function (Lysholm).	B
Fukuda[48]	2013	RCT	OKC quadriceps exercises starting at 4 weeks in a restricted ROM versus OKC quadriceps exercises starting at 12 weeks after ACLR with HS. Follow-up 17 months. N=35	No differences in laxity, pain or function (hop for distance, crossover hop, Lysholm). Starting OKC exercises at 4 weeks results in a faster recovery of isometric quadriceps strength than starting OKC at 12 weeks.	B
Heijne[64]	2007	RCT	OKC quadriceps exercises starting 4 weeks after ACL reconstruction versus OKC quadriceps exercises starting 12 weeks after ACLR. Comparing BPTB with HS. Follow-up 7 months. N=52.	More laxity for HS starting at 4 weeks compared to HS starting at 12 weeks and BPTB starting at 4 or 12 weeks. Starting OKC at 4 weeks had no additional benefit for isokinetic concentric and eccentric quadriceps strength compared to starting OKC at 12 weeks.	B
Mikkelsen[98]	2000	RCT	CKC versus combined OKC and CKC quadriceps exercises starting 6 weeks after ACLR with BPTB. Follow-up at 6 months. N=44	The addition of OKC results in a higher isokinetic concentric and eccentric quadriceps strength and a higher number of athletes returning to their preinjury sport level. There are no differences on laxity or hamstring strength.	B

Author	Year	Design	Methods	Results	
Morrissey[101]	2002	RCT	CKC versus OKC quadriceps exercises from weeks 2-6 after ACLR with BPTB. Follow-up at week 6. N=43	No differences in anterior knee pain.	B
Perry[118]	2005	RCT	CKC versus OKC quadriceps exercises from weeks 8-14 after ACLR with BPTB or HS. Follow-up at week 14. N=49	No differences in laxity, self-reported knee function (VAS) or function (vertical hop, hop for distance, triple crossover hop).	B
Uçar[147]	2014	RCT	CKC versus OKC quadriceps exercises after ACLR with HS. Follow-up 6 months. N=58	Both groups improved in self-reported knee function (VAS, Lysholm) and knee flexion angle. There were no differences in thigh circumference. There were no differences between groups.	B
			4) Strength training and neuromuscular training		
Augustsson[10]	2012	SR	Reviewing RCT's about strength training during rehabilitation after ACLR. *Included the following studies: 29,87,98,101,124*	ACLR strength training protocols should be further developed, including documentation about training frequency, intensity, volume, progression and duration.	A1
Gokeler[55]	2013	SR	Reviewing RCT's about the most effective practices for quadriceps strengthening after ACLR. *Included the following studies: 49,51,64,87,123,124,127,130.*	Eccentric training may be most effective to restore quadriceps strength, but neuromuscular training should be added to optimize outcome measurements.	A1
Kruse[80]	2012	SR	Reviewing RCT's about strength training and neuromuscular training during rehabilitation after ACLR. *Included the following studies: 49-51,73,127,130.*	Eccentric quadriceps strengthening can be safely incorporated 3 weeks after ACLR. Neuromuscular exercises should be added to strengthening exercises.	A1

Author	Year	Design	Methods	Results	
Baltaci[11]	2013	RCT	Wii Fit versus conventional rehabilitation (combined strength and neuromuscular training) from weeks 1-12 after ACLR with HS. Follow-up at 12 weeks. N=30	No differences in isokinetic concentric quadriceps and hamstring strength, dynamic balance, proprioception or coordination.	B
Berschin[18]	2014	RCT	Strength training versus whole-body vibration during 10 weeks starting 2 weeks after ACLR with BPTB. Follow-up at week 11. N=40	The group with whole-body vibration training had better postural control. No differences in self-reported knee function (Lysholm), flexion and extension ROM, laxity, isometric quadriceps and hamstring strength.	B
Bieler[21]	2014	RCT	High-resistance training versus low-resistance training from week 8 after ACLR with BPTB or HS. Follow-up 20 weeks. N=38	The high-resistance training group had a higher increase in quadriceps power. No differences in laxity, self-reported knee function (KOOS) and function (hop for distance and triple hop for distance).	B
Cappellino[25]	2012	RCT	Neurocognitive rehabilitation versus conventional rehabilitation (strength) after ACLR with BPTB. Follow-up 6 months. N=14	No differences in static or dynamic baropodometry, pain, effusion, self-reported knee function (SF-36) and isometric quadriceps and hamstring strength.	B
Cooper[29]	2005	RCT	Strength training versus proprioceptive and balance training during 6 weeks starting 45-50 days after ACLR with BPTB or HS. Follow-up after 6 weeks of training. N=29	The strength training group has more improvement on self-reported knee function (Cincinnati Knee Score). No differences in ROM, pain or function (hop for distance, timed hop, triple crossover hop).	B

Author	Year	Design	Methods	Results	
Fu[47]	2013	RCT	Conventional rehabilitation versus conventional training plus whole-body vibration therapy during 8 weeks starting 1 month after ACLR. Follow-up 6 months. N = 48	The group with the whole-body vibration has better postural control, hop for distance, shuttle run test and isokinetic concentric quadriceps and hamstring strength. No differences in ROM, laxity, joint position sense, triple hop test and carioca test.	B
Gerber[51]	2007	RCT	Conventional training versus eccentric training during 12 weeks starting 3 weeks after ACLR with BPTB or HS. Follow-up 26 weeks. N=32	Isokinetic concentric quadriceps strength and hop for distance improved more and activity level decreased less in the eccentric training group. No differences in pain, effusion or laxity.	B
Gerber[50]	2007	RCT	Conventional training versus eccentric training during 12 weeks starting 3 weeks after ACLR with BPTB or HS. Follow-up after 12 weeks. N=40	The volume and cross-sectional area of the quadriceps and gluteus maximus improved more in the eccentric training group. Also concentric isokinetic quadriceps strength improved more in the eccentric training group. No differences in laxity, hop for distance, hamstring volume and cross-sectional area or self-reported knee function (Lysholm).	B
Gerber[49]	2009	RCT	Conventional training versus eccentric training during 12 weeks starting 3 weeks after ACLR with BPTB or HS. Follow-up 1 year. N=32 (exactly the same population as Gerber 2007-01)	The volume of the quadriceps and gluteus maximus, hop for distance and concentric isokinetic quadriceps strength improved more in the eccentric training group. No differences in laxity, hamstring volume or self-reported knee function (Lysholm, Tegner).	B

Author	Year	Design	Methods	Results	
Isberg[73]	2006	RCT	Active knee extension versus no active knee extension during the first 4 post-operative weeks after ACLR with BPTB. Follow-up 2 years. N=22	No differences in laxity, ROM, self-reported knee function (Lysholm, Tegner, IKDC) or single-leg hop for distance.	B
Kinikli[79]	2014	RCT	Conventional training versus conventional training plus progressive eccentric and concentric quadriceps and hamstring training during 12 weeks starting 3 weeks after ACLR with HS. Follow-up 16 weeks. N=33	The progressive training group had higher increases in self-reported knee function (Lysholm, ACL-QOL) and function (vertical jump and hop for distance). No differences in isokinetic quadriceps and hamstring strength.	B
Liu-Ambrose[87]	2003	RCT	Strength training versus proprioceptive training during 12 weeks after ACLR with HS. Follow-up after 12 weeks. N=10	The proprioceptive training group had more improvement on concentric isokinetic quadriceps and eccentric isokinetic hamstring strength. No differences in self-reported knee function (Lysholm), hop for distance and timed hop.	B
Moezy[100]	2008	RCT	Conventional training versus whole body vibration training during 1 month starting 12 weeks after ACLR with BPTB. Follow-up after 1 month of training. N=20	Postural stability and joint reposition sense improved more in the whole body vibration group.	B
Risberg[124]	2007	RCT	Neuromuscular training versus traditional strength training during 6 months after ACLR with BPTB. Follow-up 6 months. N=65	The neuromuscular group had a better self-reported knee function (Cincinnati Knee Score and VAS for global knee function). No differences in pain, concentric isokinetic quadriceps and hamstring strength, static and dynamic balance, proprioception and hop performance (hop for distance, triple hop, stair hop).	B

Author	Year	Design	Methods	Results	
Risberg[123]	2009	RCT	Neuromuscular training versus traditional strength training during 6 months after ACLR with BPTB. Follow-up 2 years. N=60	The neuromuscular group had less pain and a better VAS for global knee function. The strength group improved more on concentric isokinetic hamstring strength. No differences in Cincinnati Knee Score, hop performance (hop for distance, triple hop, stair hop) or concentric isokinetic quadriceps strength.	B
Sekir[127]	2010	RCT	Early (3 weeks) versus late (9 weeks) start of isokinetic hamstring strengthening exercise after ACLR with BPTB. Follow-up 1 year. N=26	The early group had a better Cincinnati Knee Score and a more improved isokinetic concentric hamstring strength. No differences in IKDC or isokinetic concentric quadriceps strength.	B
Shaw[130]	2005	RCT	Isometric quadriceps exercises versus no quadriceps exercises during the first 2 weeks after ACLR with BPTB or HS. Follow-up 6 months. N=91	No differences in pain, laxity, self-reported knee function (Cincinnati Knee Score), concentric and eccentric isokinetic quadriceps strength or hop performance (hop for distance, triple hop).	B
Tyler[146]	1998	RCT	Immediate weight bearing versus non-weight bearing during the first 2 post-operative weeks after ACLR with BPTB. Follow-up 1 year. N=49	The immediate weight bearing group had less anterior knee pain. No differences in laxity, ROM and isometric vastus medialis EMG.	B
			5) Electrostimulation and electromyographic feedback		
Imoto[72]	2011	SR	Reviewing RCT's about electrostimulation of the quadriceps after soft tissue injuries of the knee. *Included the following studies: 45,115.*	Electrostimulation, in combination with conventional rehabilitation, might be more effective for improving muscle strength and function for up to 2 months after ACLR than conventional rehabilitation alone.	A1

Author	Year	Design	Methods	Results	
Kim[78]	2010	SR	Reviewing RCT's about electrostimulation of the quadriceps after ACLR. *Included the following studies: 45,115.*	Electrostimulation combined with exercise may be more effective in improving quadriceps strength than exercise alone, but its effect on functional performance and self-reported knee function is inconclusive.	A1
Wasielewski[150]	2011	SR	Reviewing RCT's about electromyographic biofeedback of the quadriceps after various knee conditions. *Included none of the studies below.*	Electromyographic feedback appeared to benefit short-term postsurgical pain and quadriceps strength after ACLR.	A1
Wright[156]	2008	SR	Reviewing RCT's about the effect of electrostimulation after ACLR. *Included the following studies: 45,115.*	Electrostimulation must be applied in a high-intensity setting early in the postoperative period. It may help achieve improved quadriceps strength but does not appear to be a requirement for successful rehabilitation.	A1
Christanell[27]	2012	RCT	Conventional rehabilitation versus conventional rehabilitation added with electromyographic biofeedback during the first 6 postoperative weeks after ACLR with BPTB. Follow-up 6 weeks. N=16	The biofeedback group had a better passive knee extension and a higher integrated EMG of the vastus medialis. There were no differences in passive knee flexion, pain, effusion or giving way.	B

Author	Year	Design	Methods	Results	
Ediz[37]	2012	RCT	Conventional rehabilitation versus conventional rehabilitation added with electrostimulation of the quadriceps, hamstrings, tibialis anterior and triceps surae from the 4th postoperative day during 6 weeks after ACLR with HS. Follow-up 6 months. N=26 Electrostimulation: Intelect Advanced Therapy Stim, 30 Hz, 65-100 mA, puls width 300 µs, duty cycle 10s on and 20s off, 20 minutes per session, 5 days a week.	There are no differences between groups on effusion or pain.	B
Feil[44]	2011	RCT	Conventional rehabilitation versus conventional rehabilitation added with 2 different kinds of electrostimulation of the quadriceps with voluntary active contraction during 12 weeks after ACLR with HS. Follow-up 6 months. N=96 Electrostimulation: Polystim, 50 Hz, max 70 mA, duty cycle 10s on and 20s off, 1.5s ramp-up and 1s ramp-down; Kneehab, 50 Hz, max 70 mA, duty cycle 5s on and 10s off, 2s ramp-up and 1s ramp-down. 20 minutes per session, 3 times a day , 5 days a week.	The Kneehab group had a higher increase in self-reported knee function (Lysholm), isokinetic concentric quadriceps strength and hop performance (hop for distance) than both the control group and the Polystim group. There were no differences in activity level (Tegner).	B

Author	Year	Design	Methods	Results	
Fitzgerald[45]	2003	RCT	Conventional rehabilitation versus conventional rehabilitation added with electrostimulation of the quadriceps without voluntary active contraction after ACLR. Follow-up 16 weeks. N=43 Electrostimulation: VeraStim, 2500 Hz (alternating current), duty cycle 10s on and 50s off, 2s ramp-up and 2s ramp-down, 10 minutes per session, 2 times a week.	A greater proportion of the electrostimulation group achieved clinical criteria for advancing to agility training.	B
Paternostro-Sluga[115]	1999	RCT	Conventional rehabilitation versus conventional rehabilitation added with electrostimulation of the quadriceps and hamstrings during 6 weeks after ACLR with BPTB. Follow-up 1 year. N=49 Electrostimulation: Stiwell, 4 times set 1 (30 Hz, 5s on and 15s off, 12 reps) and 2 times set 2 (50 Hz, 10s on and 50s off, 12 reps), 30 minutes per session, 7 times a week.	There were no differences on isometric quadriceps strength and isokinetic concentric quadriceps and hamstring strength.	A2

Author	Year	Design	Methods	Results	
Taradaj[137]	2013	RCT	Conventional rehabilitation versus conventional training added with electrostimulation of the quadriceps during 1 month after ACLR with HS. Follow-up 3 months. N=80 Electrostimulation: Ionoson, 2500 Hz, max 67mA, duty cycle 10s on and 50s off, 30 minutes per session, 3 times a day, 5 times a week.	The electrostimulation group had a higher increase in thigh circumference and isometric quadriceps strength.	B
Lepley[86]	2015	PC	Electrostimulation plus eccentric training versus electrostimulation or eccentric training alone during 12 weeks after ACLR with BPTB or HS. Follow-up >3 months. N=36 Electrostimulation: Intelect Legend XT, 2500 Hz, duty cycle 10s on and 50s off, 2s ramp-up, 10 minutes per session, 2 times a week.	No differences in ROM and knee extension and flexion moments.	C
			6) Cryotherapy		
Martimbianco[91]	2014	MA	Reviewing RCT's about cryotherapy after ACLR. N=573 *Included the following study: 38.*	Cryotherapy reduced postoperative pain up to 48 hours after surgery and did not increase the risk of adverse events.	A1
Raynor[121]	2005	MA	Reviewing RCT's about cryotherapy after ACLR. N=551 *Included none of the studies below.*	Cryotherapy is associated with lower postoperative pain, but has no effect on postoperative drainage or range of motion.	A1

Author	Year	Design	Methods	Results	
Hubbard[70]	2004	SR	Reviewing RCT's about cryotherapy in patients recovering from acute soft tissue or orthopedic surgical interventions. *Included none of the studies below.*	Cryotherapy seems to be effective in decreasing pain immediately after application to 1 week post-surgery after ACL reconstruction.	A1
Edwards[38]	1996	RCT	Ice water cryotherapy versus room temperature water cryotherapy versus no cryotherapy during the first 36 postoperative hours after ACLR with BPTB. Follow-up 48 hours postoperative. N=71	No differences in pain or ROM between the 3 groups.	A2
Glenn[53]	2004	PC	Determining the effect cryotherapy in the first postoperative hour versus cryotherapy in the second postoperative hour on intraarticular temperature after ACLR with BPTB. Follow-up 2 hours postoperative. N= 16	Both groups had a decline in intraarticular temperature in the suprapatellar pouch but not in the lateral gutter.	C
			7) Measurements of functional performance		
Barber-Westin[13]	2011	SR	Reviewing articles about objective criteria used to determine the moment of return to sports and re-injury rates (>2 years) after ACLR. *Included the following study: 73.*	Few objective criteria are used to determine return to sports. A more extensive test battery for quantity of movement is recommended. Graft re-rupture ranged from 0%-24%. Contralateral ACL injury ranged from 2%-15%.	B
Barber-Westin[12]	2011	SR	Reviewing articles about objective criteria used to determine the moment of return to sports (>1 years) after ACLR. *Included none of the studies below.*	There is a lack of objective criteria to determine return to sports. A more extensive test battery for quantity of movement is recommended.	B

Author	Year	Design	Methods	Results	
Czuppon[32]	2014	SR	Reviewing articles about parameters associated with return to sports (>6 months) after ACLR. *Included the following studies: 54,63,94,98.*	There is only weak evidence for several factors associated with a higher chance of return to sport: less effusion, less pain, higher quadriceps strength, greater tibial rotation, higher Marx Scale score, higher athletic confidence, higher preoperative knee self-efficacy, lower kinesiophobia and higher preoperative self-motivation.	A2
Engelen-van Melick[41]	2013	SR	Reviewing articles about clinimetrics for long-term follow-up (> 2 years) of functional performance after ACLR. *Included none of the studies below.*	Only concentric strength measurements and a single-leg hop for distance were used as clinimetrics. There were no measurements of quality of movement. An extensive test battery for quantity and quality of movement is recommended.	B
Harris[61]	2014	SR	Reviewing RCT's about self-reported and objective criteria used to determine the moment of return to sports after ACLR. *Included none of the studies below.*	90% of included studies failed to use objective criteria for determining the moment of return to sports.	
Narducci[108]	2011	SR	Reviewing articles about clinimetrics used prior to return to sports (<1 year) after ACL reconstruction. *Included none of the studies below.*	No study identified a single test or test battery that has construct or predictive validity for return to sports.	B
Müller[104]	2015	PC	Defining parameters that can predict successful return to preinjury sport 6 months after ACLR with HS. Follow-up 6 months. N=40	Patients that return to sport had better scores on the ACL-RSI and IKDC self-reported knee evaluation form and better function (hop for distance, triple hop and crossover hop). No differences in isometric quadriceps and hamstring strength or TSK-11.	B

Author	Year	Design	Methods	Results	
Thomeé[143]	2012	PC	Describing leg muscle power and hop performance after ACL reconstruction with BPTB or HS. Follow-up 2 years. N=82	The non-operated leg had a better hop performance (vertical jump, hop for distance, side hop) than the operated leg. No differences in quadriceps and hamstring power between the operated and non-operated leg. When using an LSI of >90%, >95% or >100% on all 6 tests as a criterion, results are poor, because respectively 23%, 10% and 0% passes this criterion.	B
			8) Return to play		
Ardern[5]	2014	MA	Reviewing articles about return to play outcomes after ACLR. N=7556 *Included the following studies: 5,34,54,94,98.*	The rate of return to preinjury sport level was 65%. Men were 1.4 times more likely to return to their preinjury sport level than women. BPTB was 1.2 times more likely to return to preinjury sport level than HS.	A2
Ardern[8]	2011	MA	Reviewing articles about return to play outcomes after ACLR. N=5770 *Included the following studies: 54,94,98.*	The rate of return to preinjury sport level was 62% for studies with a follow-up of more than 2 years. Fear of re-injury was the most common reason for a reduction in or cessation of sports participation.	A2
Everhart[43]	2015	SR	Reviewing articles about psychological factors that affect return to play after ACLR. *Included the following studies: 54,94.*	A higher self-efficacy is positively associated with return to sports, while stress is negatively associated.	A2

Author	Year	Design	Methods	Results	
te Wierike[152]	2013	SR	Reviewing articles about psychosocial factors that affect recovery after ACL injury and reconstruction. *Included the following studies: 54,94,140.*	There were several psychosocial factors that facilitated the rehabilitation process: high internal locus of control, high self-efficacy, and low level of fear of re-injury.	B
Brophy[23]	2012	PC	Determining the rate of return to soccer and the risk for future ACL injury after ACLR with BPTB. Mean follow-up 7.2 years. N=100	After 12.2 months 72% returned to soccer, of whom 85% played at the same or a higher level. After 7.2 years only 36% were still playing soccer, of whom 46% at the same or a higher level. There were 9% contralateral ACL injuries and 3% graft re-ruptures. ACLR on the nondominant limb potentially places the dominant limb at risk for future ACL injury.	A2
Gobbi[54]	2006	PC	Determining the rate of return to play and contributing factors after ACLR with BPTB or HS. Follow-up 2 years. N=100	65% returned to the preinjury sport level, 24% returned to the same sport at a lower level and 11% were unable to return to their preinjury sport. There are no differences between BPTB and HS. Athletes returning to preinjury sport obtrained better scores with the Marx Scale and the Psychovitality Scale. There were no differences between athletes who returned to their preinjury sport and those who did not return when using the IKDC, Lysholm, Noyes and Tegner questionnaires.	B

Author	Year	Design	Methods	Results	
Laboute[82]	2010	PC	Determining the rate of return to play and contributing factors and the risk for future ACL injury after ACLR with BPTB or HS. Mean follow-up 3.5 years. N=298	65.7% returned to the preinjury sportlevel. There were no differences between BPTB and HS in terms of graft rerupture (6.1% and 12.7% respectively). Soccer had the highest re-injury rate (20.8%). Athletes returning to competition within 7 months of surgery had a greater risk of re-injury than those returning after this time point (15.3% and 5.2% respectively).	C
Langford[83]	2009	PC	Determining the influence of psychological changes on the rate of return to play after ACLR with HS. Follow-up 1 year. N=87	51% returned to competitive sport. Athletes who did return scored higher on the ACL-RSI scale.	C
Thomeé[140]	2007	PC	Determining patients' self-efficacy after ACLR. Follow-up 1 year. N=33	The K-SES had good responsiveness and there was increased self-efficacy during the rehabilitation. Young athletes with male gender and a high physical activity level scored higher on the K-SES.	B
Zaffagnini[158]	2014	PC	Determining the rate of return to play for professional soccer players after ACLR with HS. Follow-up 4 years. N=21	The mean duration of rehabilitation was 157 days and return to the first match was 186 days. One soccer player achieved a re-injury. After 4 years 71% was still playing soccer. Those that did not, the main reason was not related to knee status.	B

Author	Year	Design	Methods	Results	
			9) Risk of reinjuries		
Swärd[136]	2010	SR	Reviewing articles about the risk factors associated with a contralateral ACL injury (>2 years) after ACLR. *Included the following study: 46.*	The risk of sustaining a contralateral ACL injury was greater than the risk of a first time ACL injury. Return to a high activity level after ACLR was the most important risk factor of a contralateral ACL injury. There was no inconclusive evidence of the relevance of factors such as gender, family history and narrow intercondylar notch. It was most likely that risk factors acquired secondary to the ACL injury (altered neuromuscular function and biomechanics) increase the risk of a contralateral ACL injury.	B
Wright[154]	2011	SR	Reviewing articles about re-rupture of the graft or contralateral ACL injury (>5 years) after ACLR. *Included none of the studies below.*	The risk of a contralateral ACL injury was double the risk of re-rupture of the graft: 11.8% versus 5.8%.	B
Hewett[66]	2005	PC	Determining risk factors for ACL injury in healthy female athletes. Follow-up 2 seasons. N=205	There were 9 ACL injuries (4.4%). Predictors of an ACL injury were increased dynamic knee valgus and high abduction loads when landing.	B

Author	Year	Design	Methods	Results	
Paterno[114]	2010	PC	Determining risk factors for graft re-rupture or contralateral ACL injury after ACLR with BPTB or HS. Follow-up 1 year. N=56	There were 10 contralateral (17.8%) ACL injuries and 3 graft re-ruptures (5.3%). Predictors of a second ACL injury were less hip external rotator moment, an increase in knee valgus movement, greater asymmetry in internal knee extensor moment at initial contact and a deficit in single-leg postural stability of the involved limb.	B
Wright[153]	2007	PC	Determining the risk of graft re-rupture and contralateral rupture after ACLR with BPTB or STG. Follow-up 2 years. N=235	The risk of a contralateral ACL injury was similar (7 patients; 3.0%) to the risk of graft re-rupture (7 patients; 3.0%).	B

ACL-QOL=ACL Quality Of Life, ACLR=anterior cruciate ligament reconstruction, ACL-RSI=ACL Return to Sport after Injury, BMI=Body Mass Index, BPTB=bone-patellar tendon-bone graft, CKC=closed kinetic chain, HS=hamstring graft, IKDC=International Knee Documentation Committee, K-SES=Knee Self-Efficacy Scale, KOOS=Knee Injury and Osteoarthritis Outcome Score, MA=meta-analysis, OKC=open kinetic chain, PC=prospective cohort study, RCT=randomized controlled trial, ROM=range of motion, SF-36=Short-Form 36, SR=systematic review, VAS=visual analogue scale.

Appendix 2: KNGF Evidence Statement for anterior cruciate ligament reconstruction rehabilitation

Inclusion and exclusion criteria for rehabilitation according to the Evidence Statement

Inclusion of patients that:

- had an anterior cruciate ligament reconstruction (ACLR) with an autologous bone-patellar tendon-bone (BPTB) or hamstring (HS) graft;
- are 16 years old or above;
- are athletes or perform physically demanding work;
- have other ligamentous injury grade A or B according to the IKDC classification;
- had a partial meniscectomy previous to or simultaneously with ACLR;
- have cartilage damage grade I or II according to the ICRS classification.

Exclusion of patients that:

- are younger than 16 years old;
- had ACLR with an allograft or synthetic graft;
- had ACL revision surgery;
- have other ligamentous injury grade C or D according to the IKDC classification;
- had meniscal repair simultaneously with ACLR;
- have cartilage damage grade III or IV according to the ICRS classification.

IKDC classification of ligamentous injury

Grade	ACL, PCL, MCL or LCL	PMC or PLC
A	0-2 mm	<5°
B	3-5 mm	6-10°
C	6-10 mm	11-19°
D	>10 mm	>20°

ACL=anterior cruciate ligament, PCL=posterior cruciate ligament, MCL=medial/tibial collateral ligament, LCL=lateral/fibular collateral ligament, PMC=posteromedial corner, PLC=posterolateral corner

ICRS classification of cartilage damage

Grade	Classification	Description
0	normal	-
1	nearly normal	Superficial lesions. Soft indentation and/or superficial fissures and cracks.
2	abnormal	Lesions extending down to <50% of cartilage depth.
3	severely abnormal	Cartilage defects extending down to >50% of cartilage depth as well as down to calcified layer and down to but not through the subchondral bone. Blisters are included in this grade.
4	severely abnormal	Osteochondral defects. Lesions extending down through the subchondral bone.

Preoperative rehabilitation

An ACLR should only be done on the condition that:

- the patient has a functional instability with complaints of giving way. In an acute situation, it is difficult to say if there is a functional instability. Therefore, we recommend to avoid ACLR in the acute situation, in order to minimize the chance of operating asymptomatic patients.[2,97]
- the knee has a minimal synovial reaction, the knee has a full extension (0 degrees), there is good patellofemoral mobility (left=right), the patient can actively control the quadriceps and there is a correct gait pattern in order to prevent arthrofibrosis.[33,92,95,99,120,131]
- there is a quadriceps strength deficit compared with the healthy leg of maximum 20%. A strength deficit of 20% or more predicts a significant strength deficit until two years after ACLR.[39,75]

We advise the subsequent preoperative treatment:

- The physical therapist should give information about walking with crutches, about the first postoperative exercises and about the complete rehabilitation process. This increases self-efficacy and the subjective and objective outcome at the end of the rehabilitation.[89,139-141]
- When the knee has a limited patellofemoral or tibiofemoral mobility, use mobilization techniques to reach the goals mentioned above.[99,131]
- When there is a quadriceps strength deficit of more than 20%, use closed and open kinetic chain exercise to improve strength.[39,75]

Preoperative measurements of functional performance:

- Stroke test[135]
- Passive range of motion, both patellofemoral and tibiofemoral[99]

- Visual Analogue Scale (VAS), IKDC Subjective knee evaluation form and/or KOOS[97]
- A psychological questionnaire (TSK-11, ACL-RSI, K-SES)
- Strength measurement of the quadriceps and hamstrings.[39,75]

Postoperative rehabilitation

Phase 1

Goal: minimal synovitis/effusion, extension 0°, voluntary quadriceps control, active dynamic gait pattern.[97,131]

2

1. Level of body functions and structures
    a. Mobility
        - Passive mobilization of the patella (both medial-lateral and inferior-superior translations) when there is a mobility deficit.[109]
        - Aim at a good patella mobility (left=right) in four to six weeks.
        - Active and/or passive knee extension exercises, when there is an extension deficit. If the extension deficit is more than 10°, use heel props.[33,109]
        - Aim at an extension of 0° in two to four weeks.[33,99,109,131]
        - Heel-slides to improve knee flexion.[33]
        - Aim at 120-130° of flexion in four to six weeks.[33,99,109,131]

        N.B. In case of increasing knee temperature, effusion or pain as a reaction to mobilizations, evaluate treatment and re-adjust it by enhancing rest periods, using cryotherapy and/or NSAID's (after consultation of a doctor).[92] Cryotherapy only influences pain, not effusion.[38,53,70,91,121]

    b. Strength training
        - Reactivation of the quadriceps: active knee extensions when seated with the legs straightened.[33,73,130] Use manual facilitation techniques or electrostimulation when voluntary contraction of the quadriceps is not possible.[44,45,72,78,115,137,156]
        - Progress from isometric quadriceps exercise (active straight leg raises, ASLR), to concentric and eccentric exercises provided that the knee does not react with increasing temperature, effusion and/or pain.[10,49-51]
        - Closed kinetic chain quadriceps training (ROM 0-60°), for instance with the leg press, squat or step-up.[33,69,64,124,131]
        - BPTB-graft: open kinetic chain quadriceps exercises (for instance leg extension) can be performed with resistance from week 4 in ROM 90-45°.[42,48,64]

        HS-graft: open kinetic chain quadriceps exercises can be per-

formed without resistance from week 4 in ROM 90-45°.[48,64]
For both BPTB-graft and HS-graft, increase ROM with 10° every week from week 5: week 5 ROM 90-30°, week 6 ROM 90-20°, week 7 ROM 90-10° to full-ROM in week 8.[4,33,42,59]

- Concentric and eccentric strength training of the gluteal muscles, hamstrings and calf muscles.[124]

2. Level of activities and participation
   a. Neuromuscular training
      - Neuromuscular training on two legs, for instance on a wobble-board (only forward-backward movements). Gradually increase difficulty by:
        - adding perturbation, without the patient being able to see what the physical therapist is doing,
        - training on one leg,
        - training on an increasingly difficult board,
        - training with eyes closed,
        - adding tasks: for example catch and throw a ball or answer a difficult arithmetical problem.[124]
      - Encourage a correct quality of performance (e.g. trunk lateroflexion, hip- and knee flexion, dynamic knee valgus and knee-over-toe) during strength training and walking.[59,124,145] Use implicit learning techniques instead of explicit learning techniques.[16,65]

   a. Walking and bicycling
      - Load the operated leg, if necessary with crutches.[33,132,146] Keep using crutches as long as there is a deviation in the gait pattern. Practice gait in different speeds and on various surfaces.[33]
      - Start cycling on a hometrainer when knee flexion reaches 100°.[33,124] Use cycling as a warm-up and mobilization exercise.

Criteria to start phase 2:

- Closed wound
- No knee pain with phase 1 exercises (VAS)[109]
- Minimal synovitis or effusion,[109]
- Normal mobility (left=right) of the patellofemoral joint[109]
- Knee extension of at least 0° and a 120-130° flexion[59,97,109,131]
- Voluntary control of the quadriceps[33,59,131]
- Active dynamic gait pattern without crutches
- Correct qualitative performance of phase 1 exercises.

Abnormal progress if:

- the wound doesn't close or if there is an infection: refer the patient to the surgeon.
- there is still a considerable amount of mobility loss in the patella after 6 to 8 weeks. Consult the surgeon because of the risk on infrapatellar contracture syndrome.[62,116,117]
- the (loaded) extension is less than 0° after 6 to 8 weeks or decreases. Consult the surgeon because of the risk on arthrofibrosis or cyclops.[99,133]
- there is still no voluntary quadriceps control after 6 to 8 weeks.
- there is still no dynamic gait pattern.

2

Phase 2

Goal: performing sport specific tasks and physically demanding work without restrictions.[97]

1. Level of body functions and structures
   a. Mobility
      - Maintain full patellofemoral and tibiofemoral range of motion.[59]

   b. Strength training
      - Increase closed kinetic chain quadriceps exercises in range of motion, to full ROM in week 8 and add one-legged exercises (for instance lunges or single-leg squats).[59]
      - Increase open kinetic chain quadriceps exercises in range of motion, to full ROM in week 8.[33,59,64]
      - Note that patients with HS-grafts are allowed to perform open kinetic chain exercises with resistance only from week 12.[4,52,64,156]
      - Intensify strength training of the gluteal muscles, hamstrings and calf muscles.
      - Decrease repetitions and increase resistance for all strength exercises.[33,59]

2. Level of activities and participation
   a. Neuromuscular training
      - Increase difficulty of neuromuscular and perturbation training:
        - by altering from static to dynamic training,
        - by altering from forward-backward movements to side-ward movements,
        - by changing predictability, speed, direction and amplitude of the disturbance, for example on a moving platform,
        - with two-legged jumps, including rotations.[124]
      - Keep paying attention to a correct quality of performance during strength training, walking and jogging.

b. Walking and bicycling
   - Start bicycling outdoors at the start of phase 2.[59]
   - Add cyclic training to the program, for example cross-trainer or rowing machine.
   - Start jogging in week 10 to 12, but only if it is performed symmetrically and the knee does not react with increasing temperature, effusion or pain.[33,132]
   - Aggravate cardiovascular training (mainly aerobic).

c. Sport specific training
   - Start agility training under supervision of a physical therapist.[124]
   - Pay attention to a correct quality of performance.

Criteria to start phase 3:

- Correct qualitative performance of phase 2 exercises
- Limb Symmetry Index (LSI) >80% for quadriceps and hamstring strength[59]
- LSI >80% for a hop test battery,[59] with preference towards the hop test battery of Gustavsson[60]
- Complete the IKDC Subjective knee evaluation form and/or KOOS.
- Complete a psychological questionnaire (TSK-11, ACL-RSI, K-SES)

Phase 3

Goal: return to sport or physically demanding work.

1. Level of body functions and structures
   a. Mobility
      - Maintain full patellofemoral and tibiofemoral range of motion.[59]

   b. Strength training
      - Intensify (sport) specific strength training.[59,109,124]

2. Level of activities and participation
   a. Neuromuscular training
      - Increase difficulty of neuromuscular and perturbation training:
        - with single-legged jumps,
        - with emphasis on sport specific movements.[59,124]
      - Keep paying attention to a correct quality of performance during strength training, walking, jogging, and sport specific exercises.

   b. Walking and bicycling
      - Enhance bicycling or jogging in intensity and duration. Built sport specific load concerning energy expenditure (anaerobic lactic, anaerobic alactic, aerobic) and surface (for example soccer field, road, forest or sports hall).

c. Sport specific training
    - Increase and intensify agility training.[124]
    - Restart training at the patient's own sports club.

Criteria for return to play:

- No knee pain at sport specific activities.
- No giving way or fear of giving way during sport specific activities.
- Active dynamic gait pattern, symmetrical jogging pattern[99], and correct quality of performance with all sport specific activities.
- LSI >90% for quadriceps and hamstring strength (to exclude quadriceps dominance and leg dominance).[59,106]
- LSI >90% for a hop test battery[59], with preference towards the hop test battery of Gustavsson[60], with the single-leg hop-and-hold test added (to exclude quadriceps dominance and leg dominance).[106]
- Drop jump test with observation or video-analysis of the quality of movement, at least measuring trunk lateroflexion, dynamic knee valgus (to exclude ligament dominance) and the knee flexion angle when landing.[40,41,60]
- Complete the IKDC Subjective knee evaluation form and/or KOOS.
- Complete a psychological questionnaire (TSK-11, ACL-RSI, K-SES).

Chapter 3

ACL reconstruction with hamstring tendon autograft and accelerated brace-free rehabilitation: a systematic review of clinical outcomes

Rob P.A. Janssen
Nicky van Melick
Jan B.A. van Mourik
Max Reijman
Lodewijk W. van Rhijn

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Abstract

Objective: To investigate the clinical outcomes after hamstring tendon autograft ACL reconstruction (ACLR) with accelerated, brace-free rehabilitation.

Design: Systematic review according to Preferred Reporting Items for Systematic Reviews and Meta-Analysis guidelines.

Data sources: Embase, MEDLINE Ovid, Web of Science, Cochrane CENTRAL and Google scholar from 1 January 1974 to 31 January 2017.

Eligibility criteria for selecting studies: Study designs reporting outcomes in adults after arthroscopic, primary ACLR with hamstring autograft and accelerated, brace-free rehabilitation.

Results: Twenty-four studies were included in the review. The clinical outcomes after hamstring tendon autograft ACLR with accelerated brace-free rehabilitation were the following: (1) early start of open kinetic exercises at 4 weeks in a limited range of motion (ROM 90°-45°) and progressive concentric and eccentric exercises from 12 weeks did not alter outcomes (2) gender and age did not influence clinical outcomes, (3) anatomical reconstructions showed better results than non-anatomical reconstructions, (4) there was no difference between single-bundle and double-bundle reconstructions, (5) femoral and tibial tunnel widening occurred, (6) hamstring tendons regenerated after harvest and (7) biological knowledge did not support return to sports at 4–6 months.

Conclusions: After hamstring tendon autograft ACLR with accelerated brace-free rehabilitation, clinical outcome is similar after single-bundle and double-bundle ACLR. Early start of open kinetic exercises at 4 weeks in a limited ROM (90°-45°) and progressive concentric and eccentric exercises from 12 weeks postsurgery do not alter clinical outcome. Further research should focus on achievement of best balance between graft loading and graft healing in the various rehabilitation phases after ACLR as well as on validated, criterion-based assessments for safe return to sports.

Introduction

Rehabilitation after ACL reconstruction (ACLR) could be described as adaptations to a complex biological system.[36] Outcomes after ACLR are influenced by both surgical and rehabilitation factors. ACL surgery requires the understanding of several factors: anatomical graft placement, mechanical properties of the selected graft tissue, mechanical behaviour and fixation strength of fixation materials as well as the biological processes that occur during graft remodelling, maturation and incorporation.[24,36,38,39,54] These factors influence directly the mechanical properties of the knee joint after ACLR and should, in combination with rehabilitation progress, dictate the time course until normal function of the knee joint can be expected.[44,38]

After surgery, graft healing is characterised by a remodelling process.[38,39,41,52,54] During this period, the graft will undergo changes, becoming morphologically similar to intact ligament tissue.[27,38,39,41,65] Contemporary rehabilitation - defined as early-unrestricted motion, immediate weight-bearing and eliminating the use of immobilising braces - is appropriate after ACLR with patellar tendon grafts.[12,14,16,17,23,61,67-69] However, conclusions are unclear when evaluating the effects of this type of rehabilitation after hamstring autograft ACLR.[36] This is important because the hamstring tendons are a popular graft source for ACLR.[63] Advantages of accelerated, brace-free rehabilitation protocols after ACLR are earlier normal function of the knee, weight-bearing and alleged ability to return to even most strenuous activities after primary ACLR at 6 months.[4,12,27,30,35,38,39,51,66,80] A major challenge in postoperative rehabilitation after ACLR is optimising the balance between muscular strengthening exercises and loading of the graft to stimulate graft cells to produce cellular and extracellular components for the preservation of graft stability, without compromising graft integrity, which might result into an early elongation of the ACLR.[12,38,39,49,65,79]

The purpose of this systematic review is to present the current knowledge on outcomes after hamstring tendon autograft ACLR with accelerated, brace-free rehabilitation in adults. The primary aim was to examine the influence of different rehabilitation protocols, patient characteristics and surgical techniques on clinical outcomes after hamstring tendon autograft ACLR. The secondary aim was to examine the influence of contemporary rehabilitation on tunnel widening, tendon regeneration and time to return to sports after hamstring tendon autograft ACLR.

Methods

This systematic review was performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA).[50] We had six key review questions:

1. How do differences in rehabilitation protocols affect clinical outcomes?
2. How do different patient characteristics affect clinical outcomes?
3. How do different non-anatomical and anatomical surgical techniques affect clinical outcomes?
4. Does accelerated, brace-free rehabilitation influence tunnel widening?
5. Do hamstring tendons regenerate after harvest?
6. Does the current biological knowledge on hamstring tendon autografts support early return to sports?

Eligibility criteria

The inclusion and exclusion criteria for the systematic review are presented in Box 1.

Box 1: *Inclusion and exclusion criteria.*

Inclusion criteria

- Studies (meta-analysis, randomised, non-randomised, systematic reviews, case series, prospective or retrospective design) evaluating outcome in adult patients undergoing isolated ACL reconstruction (ACLR)
- Studies must have included an accelerated rehabilitation protocol. Accelerated rehabilitation is characterized by immediate post-operative weight-bearing, without restriction in motion and brace-free rehabilitation. Return to sports is allowed after 4-6 months
- Any arthroscopic surgical method of primary intra-articular ACLR
- Hamstring tendon autograft
- Human in vivo studies with reported outcome
- English language
- Abstract and full text available

Exclusion criteria

- Concomitant surgery limiting an accelerated rehabilitation protocol (meniscal repair or transplant, osteotomy, microfracture, autologous cartilage implantation or matrix autologous chondrocyte implantation)
- Revision surgery
- Allografts, bone-patellar-tendon graft, quadriceps tendon or synthetic grafts
- Multiligament reconstructions
- Posterolateral, medial or posterior cruciate ligament instability
- Non-defined rehabilitation protocol
- Children and adolescents
- Animal or cadaveric (in vitro) studies
- Non-arthroscopic ACLR
- Non-English language
- Abstract or full-text not available

Electronic search

A systematic electronic search was performed using specific search terms in the following databases: Embase, MEDLINE Ovid, Web of Science, Cochrane CENTRAL and Google scholar from 1 January 1974 to 31 January 2017 (Appendix 1).

Study selection

All potentially eligible articles were screened by title, abstract and full text by two teams of reviewers (RPAJ and NvM, and RPAJ and JBAvM). When two reviewers did not reach consensus, a third reviewer (NvM or JBAvM) made the final decision. We screened the reference lists of excluded and included articles for potentially eligible articles that may have been missed in the electronic database search.

Data extraction

Data were extracted by two independent reviewers (RPAJ and NvM), and disagreements were resolved by consensus.

We extracted data on key variables regarding surgical techniques, graft type, patient demographics, details of rehabilitation, patient-reported outcome, clinical outcome measures and radiological evaluation.

Synthesis of results

Due to substantial heterogeneity with regard to surgical techniques, populations, outcome and study design, it was not possible to pool data for statistical analysis. Instead, we used a best-evidence synthesis[70,76] with the following ranking of levels of evidence:

1. Strong evidence is provided by two or more studies with good quality (low risk of bias) and by generally consistent findings in all studies (≥75% of the studies reported consistent findings).
2. Moderate evidence is provided by one good quality (low-risk of bias) study and two or more questionable quality (higher risk of bias) studies and by generally consistent findings in all studies (≥75%).
3. Limited evidence is provided by one or more questionable quality (higher risk of bias) studies or one good quality (low-risk of bias) study and by generally consistent findings (≥75%).
4. Conflicting evidence is provided by conflicting findings (<75% of the studies reported consistent findings).[76]

Risk of bias assessment

Two reviewers (RPAJ and NvM) assessed the risk of bias of the articles independently. If the two reviewers did not reach consensus, a third reviewer (JBAvM) made the final decision. The reviewers were not blinded for author, journal or publication. The assessment of risk of bias of all articles was performed by standardised checklists of the Dutch Cochrane Library (www.netherlands.cochrane.org/beoordelingsformulieren-en-andere-downloads), namely for therapy and prevention (intervention, randomised controlled trials (RCTs)) and for prognosis (cohort studies).

The assessment of risk of bias for RCTs used nine criteria, displayed in Table 1. These nine items could be rated 'yes'(+), 'no'(-) or 'do not know'(?). The same list was used for assessing clinical controlled trials, but these scored a'no'for items 1 and 2.

The assessment of risk of bias for cohort studies described eight items, displayed in table 1. All eight items could be rated positive (+), negative (-) or 'do not know' (?). The same list was used for cross-sectional studies, but these scored a '-' for item 2 because the study design could cause a selection bias.

We also evaluated two additional items due to their influence on outcome after ACLR and contemporary rehabilitation: (1) accurate description of the rehabilitation protocol and (2) ratio of men and women participating in the study. A final judgement of 'good', 'questionable' or 'poor' was given to every article. A 'good' was assigned to articles scoring positive for more than 50% of all items (low risk of bias); a 'questionable' if the positive score was between 30% and 50% (questionable risk of bias) and a 'poor' was assigned to articles with a positive score inferior to 30% (high risk of bias). The articles with a total score of 'good' and 'questionable' were included in the review.

Table 1: *Cochrane criteria for the assessment of RCTs and cohort studies.*

RCT	Cohort studies
1. Is a method of randomisation applied?	1. Are study groups clearly defined?
2. Is randomization blinded?	2. Is there any selection bias?
3. Are the patients blinded?	3. Is the exposure clearly defined?
4. Is the therapist blinded?	4. Is the outcome clearly defined?
5. Is the outcome assessor blinded?	5. Is the outcome assessment blinded?
6. Are the groups comparable?	6. Is the follow-up accurate?
7. Is there an acceptable lost-to-follow-up?	7. Is there an acceptable loss-to-follow-up?
8. Is there an intention-to-treat?	8. Are confounders described and/or eliminated?
9. Are treatments comparable?	

RCT=randomised controlled trial

Results

Study selection

The PRISMA flow chart of the systematic review is presented in figure 1. A total of 29 studies were selected for the risk of bias assessment: 6 RCTs,[7,17,27,45,64,77] 4 clinical controlled trials,[47,53,62,74] 12 prospective cohort studies,[13,15,21,22,33,35,40,42,43,46,71,83] 4 cross-sectional studies,[3,19,41,48] and 3 retrospective cohort studies.[2,72,75]

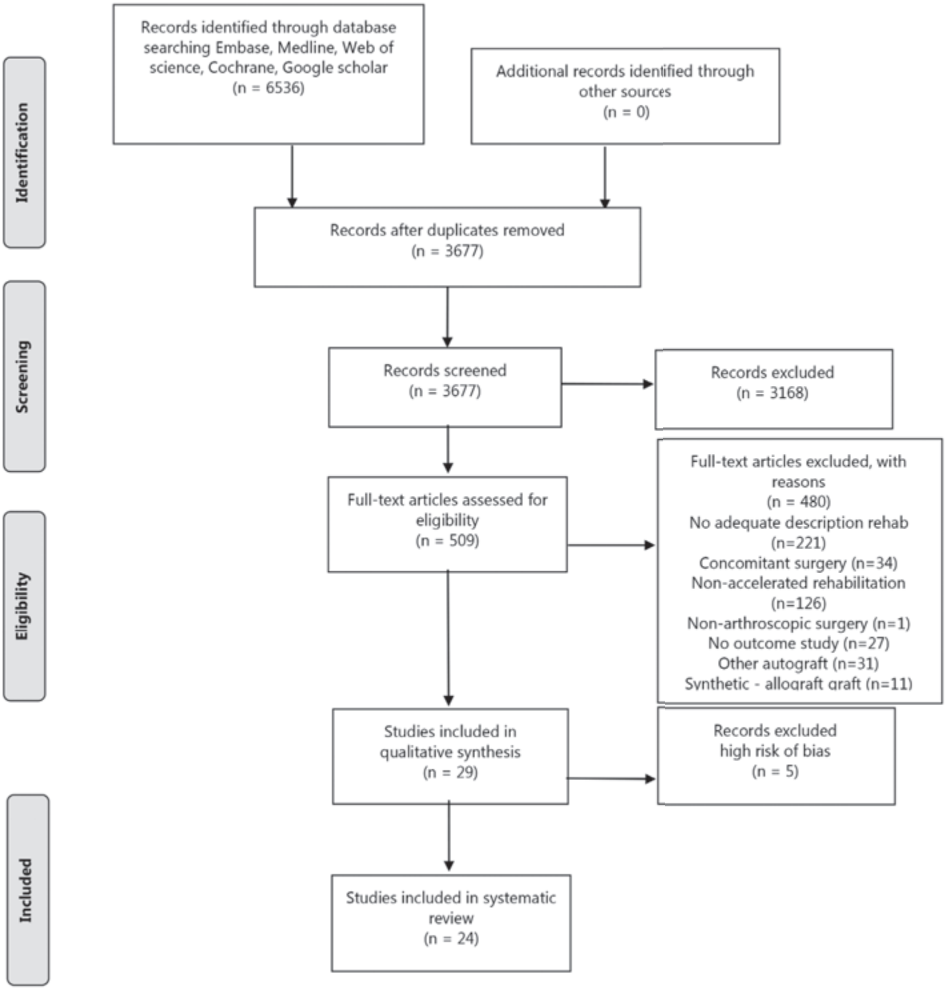

Figure 1: *Preferred Reporting Items for Systematic reviews and Meta-Analysis flow diagram. From: Moher D, Liberati A,Tetzlaff J, Altman DG. The PRISMA Group. Preferred items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med 2009;6(6):e1000097. doi:10.1371/journal.pmed1000097.*

Risk of bias assessment

The results of the risk of bias assessment for the included studies are presented in Tables 2 and 3. Five articles were discarded because of the total score 'poor' after quality appraisal. Twenty-four articles were included in the systematic review.

Details of studies and rehabilitation

The details of the included studies are presented in Table 4. The details of accelerated rehabilitation of the 24 included studies are presented in Table 5.

Results of individual studies and answers to research questions

How do differences in rehabilitation protocols affect clinical outcomes after hamstring tendon autograft ACLR with accelerated, brace-free rehabilitation?

Czaplicki et al[22] prospectively evaluated serial changes in isokinetic muscle strength preoperatively and postoperatively. They found significant differences between extension peak torques for the injured and healthy limbs at all stages of accelerated rehabilitation. At 1 year, there was still a deficit in muscle strength of the operated leg.[22]

The effects of accelerated brace-free free rehabilitation versus rehabilitation with brace and limited ROM for 4 weeks postsurgery were examined by Christensen et al.[17] No differences were found between the two groups for IKDC, range of motion (ROM) and peak isometric force at 12 weeks postsurgery.[17]

Fukuda et al[27] evaluated the outcome of early start of open kinetic chain exercises in a restricted ROM at 1 year after non-anatomical, four-strand hamstring ACLR. A start of open kinetic chain quadriceps exercises at 4 weeks postoperatively in a restricted ROM (90°-45°) did not differ from a start at 12 weeks in terms of anterior knee laxity, pain and functional improvement. The early start group showed a faster recovery for quadriceps strength (19 weeks vs 17 months).[27]

The effect of progressive eccentric and concentric training at 12 weeks on functional performance after four-strand hamstring ACLR was investigated by Kinikli et al.[45] Outcome measures were isokinetic muscle strength, single and vertical hop tests, Lysholm score and ACL Quality of Life Questionnaire. There was a significant improvement of all outcome measures except for isokinetic strength of knee extensors and flexors.[45]

Baltaci et al[7] compared a 12-week Nintendo Wii Fit versus a conventional accelerated, brace-free rehabilitation after hamstring ACLR. The two different 12-week

Table 2: *Risk of bias assessment of RCTs and CCTs.*

Article	Study design	1	2	3	4	5	6	7	8	9	Accurate description rehabilitation	Men-women ratio	Total score
Baltaci et al[7]	RCT	+	+	-	?	-	+	+	+	+	+	+	Good
Christensen et al[17]	RCT	+	+	?	-	-	-	+	+	+	+	+	Good
Fukuda et al[27]	RCT	+	+	?	?	+	+	-	+	+	+	-	Good
Kinikli et al[45]	RCT	+	?	+	-	-	+	?	?	+	+	-	Questionable
Koutras et al[47]	CCT	-	-	+	+	+	+	+	-	+	+	-	Good
Melikoglu et al[53]	CCT	-	-	?	?	?	+	?	?	+	+	-	Poor
Salmon et al[62]	CCT	-	-	?	?	?	?	-	?	+	+	+	Questionable
Sastre et al[64]	RCT	+	+	?	?	?	+	+	+	+	+	+	Good
Treacy et al[74]	CCT	-	-	?	?	?	+	?	?	+	+	-	Poor
Vadalà et al[77]	RCT	+	+	?	?	?	+	+	?	+	+	-	Good

CCT=clinical controlled trial, RCT=randomised controlled trial

Table 3: *Risk of bias assessment of cohort and cross-sectional studies.*

Article	Study design	1	2	3	4	5	6	7	8	Accurate description rehabilitation	Men-women ratio	Total score
Ahlen et al[2]	RC	+	-	+	+	?	+	+	-	+	+	Good
Ali et al[3]	CS	+	-	+	+	?	?	-	?	+	-	Questionable
Biernat et al[13]	PC	-	-	-	-	?	?	?	-	+	+	Poor
Boszotta et al[15]	PC	-	-	+	+	?	?	?	-	-	?	Poor
Clark et al[19]	CS	+	-	+	+	?	+	?	?	-	+	Questionable
Czamara et al[21]	PC	+	-	+	+	?	+	+	?	+	+	Good
Czaplicki et al[22]	PC	+	-	+	+	?	+	?	-	-	-	Questionable
Hill et al[33]	PC	-	-	+	+	?	+	-	?	-	-	Poor
Howell et al[35]	PC	+	-	+	+	?	+	+	?	+	-	Good
Janssen et al[41]	CS	+	-	+	+	?	+	+	+	+	?	Good
Janssen et al[40]	PC	-	+	+	+	?	+	+	+	+	-	Good
Jenny et al[42]	PC	-	+	+	+	?	+	+	-	-	+	Good
Karikis et al[43]	PC	+	-	+	+	?	+	+	-	-	+	Good
Koutras et al[46]	PC	+	-	+	+	-	+	+	-	-	-	Questionable
Krolikowska et al[48]	CS	+	-	+	+	?	-	+	-	+	-	Questionable
Srinivas et al[71]	PC	+	-	+	+	?	+	+	-	-	-	Questionable
Toanen et al[72]	RC	+	-	+	+	?	+	+	-	-	+	Questionable
Trojani et al[75]	RC	+	+	+	+	?	+	+	?	+	-	Good
Zaffagnini et al[83]	PC	+	-	+	+	-	+	+	+	-	+	Good

Table 4: *Details of the included studies.*

Rehabilitation	N	Gender (M to F)	Participant groups	Follow-up	Outcomes
Ahlen et al[2]	19	10 to 9	Operated versus contralateral leg	8.5 (6-11) years	Significant increase Tegner, Lysholm and hop test postoperative versus preoperative. ST and G regenerated in resp 89% and 95% of patients with almost normal insertion pes anserinus. Regenerated tendons had similar cross sectional area compared to contralateral leg. Strength deficit in deep flexion but not in internal rotation.
Ali et al[3]	78	69 to 5	NA	64 (48-84) months	Detachment of tibia insertion is unnecessary and an accelerated rehabilitation can be followed without brace use.
Baltaci et al[7]	30	All males	Wii Fit (15) versus conv rehab (15)	12 weeks	Both rehabilitation programs have same effect on muscle strength, dynamic balance and functional performance. Practice of Wii Fit activities could address physical therapy goals.
Christensen et al[17]	36	53% male (aggressive rehab) versus 88% male (non-aggressive rehab)	Aggressive (19) versus nonaggressive rehab (!17)	24 weeks	No difference between aggressive and non-aggressive rehabilitation in AP laxity, subjective IKDC scores, ROM and muscle strength.
Clark et al[19]	82	27 to 14 in each group	41 ACLR versus 41 controls	12 months	Significant increases in asymmetry in ACLR group for all outcome measures except symmetry index relative to operated limb. Weight bearing asymmetry can be assessed with Wii balance board.
Czamara et al[21]	30	All males	SB ACLR (15) versus DB ACLR (15)	24 weeks	No differences between SB versus DB ACLR in AP laxity, pivot shift test, ROM, joint circumference, pain scores, peak torque muscles tibial rotation and run test.
Czaplicki et al[22]	29	All males	NA	12 months	One year after anterior cruciate ligament reconstruction may be too early to return to full physical fitness for males who are physically active.

Rehabilitation	N	Gender (M to F)	Participant groups	Follow-up	Outcomes
Fukuda et al[27]	49	Early start (16 to 7) versus late start (13 to 9)	Early start (25) versus late start (24)	17 (13-24) months	Faster recovery quadriceps strength in early group. No difference between early and late start of open kinetic chain exercises in pain and functional improvement.
Howell et al[35]	41	28 to 13	NA	26 (24-32) months	Absent pivot shift in 82% patients and 88% < 3 mm laxity difference with KT-1000. Stability, girth of thigh, Lysholm and Gillquist scores were identical at 4 months and 2 years.
Janssen et al[41]	67	6-12 ms (9 to 6), 1-2 years (10 to 6), > 2 years post-ACLR (7 to 10)	Group 1 (15), Group 2 (16), Group 3 (11)	117 months	Human hamstring autografts remain viable after ACLR and showed 3 typical stages of graft remodelling. Remodelling in humans takes longer compared to animal studies and is not complete up to 2 years after ACLR.
Janssen et al[40]	22	17 to 5	MRI operated and contrlateral leg	12 months	Gracilis regenerated in all patients, ST in 14/21 patients. There was no relation between isokinetic flexion strength and tendon regeneration.
Jenny et al[42]	72	57 to 15	NA	4.3 years	Patient-based decision to return to work and sport was possible without compromising functional outcome. The post-operative restrictions implemented by orthopedic surgeons following ACLRs may be relaxed and more patient based.
Karikis et al[43]	94	DB (32 to 13) versus SB (31 to 18)	DB (45) versus SB (49) ACLR	26 (22-34) months	Anatomic DB ACLR did not result in better rotational or AP stability compared to anatomic SB ACLR
Kinikli et al[45]	33	33 to 2	Study group (16) versus control (17)	16 weeks	Adding progressive eccentric and concentric exercises may improve the functional results after ACLR with autograft hamstring tendons.
Krolikowska et al[48]	40	All males	ST group (20) versus ST-G group (20)	6 months	Generally no difference between ST and ST-G groups. There is an influence of gracilis tendon harvest on internal shin rotation isometric torque at deep internal rotation angle.
Koutras et al[46,47]	42	39 to 3	NA	9 months	Measuring knee flexion strength in prone demonstrates higher deficits than in conventional seated position.

Rehabilitation	N	Gender (M to F)	Participant groups	Follow-up	Outcomes
Salmon et al[62]	200	100 to 100	Men versus women	7 years	Significant greater laxity in women compared to men without effect on activity level, graft failure, subjective and functional assessment.
Sastre et al[64]	40	DB (70% male) versus SB (70% male) ACLR	DB (20) versus SB (20) ACLR	2 years	No significant differences DB versus SB ACLR In IKDC objective and subjective results.
Srinivas et al[71]	63	58 to 5	Various fiaxtion systems femur and tibia	1 year	Femoral and tibial tunnel widening varies with different methods and was maximum with suture disc method compared to others after ACLR with hamstring autograft.
Toanen et al[72]	12	5 to 7	NA	49.6 (24) months	Older patients (>60 years) and active patients with non-arthritic ACL-deficient knees showed good results on functional recovery without risk of midterm OA.
Trojani et al[75]	18	6 to 12	NA	30 (12-59) months	Age >50 years is not a contraindication to select hamstring tendon autograft for ACLR. ACLR restores knee stability but does not modify pain in case of previous medial meniscectomy.
Vadalà et al[77]	45	33 to 12	Acc rehab (20) versus conv rehab (25)	10 (9-11) months	Bone tunnel enlargement can be increased by accelerated rehab after ACLR with hamstring tendon autografts.
Zaffagnini et al[83]	21	All males	NA	48.1 (46-50) months	Return to sports was 95% after 1 year and 64% after 4 years in professional soccer players after nonanatomical quadruple hamstring tendon autograft ACLR. 71% still played competitive soccer at final follow-up. Clinical scores were restored after 6 months.

ACLR=ACL reconstruction, AP=anterioposterior, conv=conventional, DB=double bundle, F=female, G=gracilis tendon, IKDC=International Knee Documentation Committee, M=male, NA=not applicable, OA=osteoarthritis, rehab=rehabilitation, ROM=range of motion, ST=semitendinosus tendon, ST-G=semitendinosus/gracilis.

Table 5: *Details rehabilitation.*

Rehabilitation	Preoperative rehabilitation	ACL graft	Brace	Full weight-bearing allowed	FROM allowed	CKC exercises	OKC exercises	Concentric exercises	Eccentric exercises	Running	Return to light sports	Unrestricted return to sports	Criteria for return to sports
Ahlen et al[2]	?	HS	No	Immediate	Immediate	Immediate	6 weeks	?	?	3 months	?	6 months	Subjective functional stability compared to contralateral leg
Ali et al[3]	?	HS	No	Immediate (Programme Shelbourne)	Immediate	Programme Shelbourne	Programme Shelbourne	Programme Shelbourne	Programme Shelbourne	?	6 months	9 months	Stable knee (Lachman and pivot test) and asymptomatic knee
Baltaci et al[7]	?	HS	No	Immediate	Immediate	Immediate	6-8 weeks	3-4 weeks	6-8 weeks?	3 months	6-8 months	6-8 months	?
Christensen et al[17]	?	HS	Brace versus no brace	Immediate (Programme Biggs)	Immediate	Program Biggs	Program Biggs	?	?	8-12 weeks	?	?	?
Clark et al[19]	?	HS	No	Immediate	Immediate	?	?	?	?	3-4 months	?	?	?
Czamara et al[21]	?	HS	No	Immediate	Immediate	Immediate	6-12 weeks?	6 weeks	6-12 weeks	4 months	?	?	?
Czaplicki et al[22]	Yes	HS	No	Immediate (Programme Shelbourne)	Immediate	Programme Shelbourne	Programme Shelbourne	Programme Shelbourne	Programme Shelbourne	?	?	?	?
Fukuda et al[27]	?	HS	No	Immediate	Immediate	2 weeks	4 versus 12 weeks	?	?	10 weeks	?	?	?

Rehabilitation	Preoperative rehabilitation	ACL graft	Brace	Full weight-bearing allowed	FROM allowed	CKC exercises	OKC exercises	Concentric exercises	Eccentric exercises	Running	Return to light sports	Unrestricted return to sports	Criteria for return to sports
Howell et al35	?	HS	No	Immediate	Immediate	4 weeks	4 weeks	?	?	8-10 weeks	?	4 months	?
Janssen et al[40,41]	Yes	HS	No	Immediate	Immediate	Immediate	6 weeks	6 weeks (start 90°-40°) 10 weeks (FROM)	6 weeks (start 90°-40°) 10 weeks (FROM)	10 weeks	4 months	4-6 months	?
Jenny et al[42]	?	HS	No	Immediate	Immediate	?	?	?	?	4 months	4 months	4-6 months	Patient-based decision
Karikis et al[43]	?	HS	No	Immediate ('accelerated' programme)	Immediate	Immediate	?	?	?	3 months	?	6 months	Full functional stability in muscle strength, coordination, balance compared to uninvolved leg
Kinikli et al[45]	?	HS	No	Immediate (Programme Wilk/Majima)	Immediate	Immediate	6-8 weeks	3 weeks (study group)	3 weeks (study group)	?	?	?	?
Krolikowska et al[48]	?	HS	No	Immediate	Immediate	1-5 weeks	?	6-12 weeks	6-12 weeks	13-20 weeks	21 weeks	6 months	?
Koutras et al[46,47]	Yes	HS	No	Immediate (Programme Shelbourne)	Immediate	Programme Shelbourne	Programme Shelbourne	Programme Shelbourne	Programme Shelbourne	?	?	?	?
Salmon et al[62]	?	HS	No	Immediate	Immediate	Immediate	?	?	?	6 weeks	?	6 months	Rehabilitation goals met

Rehabilitation	Preoperative rehabilitation	ACL graft	Brace	Full weight-bearing allowed	FROM allowed	CKC exercises	OKC exercises	Concentric exercises	Eccentric exercises	Running	Return to light sports	Unrestricted return to sports	Criteria for return to sports
Sastre et al[64]	?	HS	No	Immediate	Immediate	?	?	?	?	12 weeks	?	6-9 months	?
Srinivas et al[71]	?	HS	No	Immediate	Immediate	Second day	?	?	?	?	?	6 months	?
Toanen et al[72]	?	HS	No	?	?	?	?	?	?	6-12 weeks	3-6 months	6 months	?
Trojani et al[75]	?	HS	No	Immediate	Immediate	Immediate	?	?	?	8 weeks	?	6 months	?
Vadalà et al[77]	?	HS	Brace versus no brace	Immediate	Immediate versus 2 weeks	Immediate	?	?	?	3 months	?	?	?
Zaffagnini et al[83]	?	HS	No	Immediate	Immediate	Immediate	?	?	?	2 months	?	4 months	Criteria for on field rehabilitation, not for return to unrestricted sports

CKC=closed kinetic chain, FROM=full range of motion, HS=hamstring autograft, OKC=open kinetic chain physiotherapy programme had the same effect on muscle strength, dynamic balance and functional performance values.[7] Clark et al[19] used the Nintendo Wii Fit Balance Board to assess weight-bearing asymmetry during squatting as outcome after hamstring autograft ACLR with accelerated rehabilitation. The authors found significant increases in asymmetry after ACLR compared with a matched control group.[19]

Jenny et al[42] assessed functional outcome (sport activity, Tegner, Lysholm and IKDC subjective score) and rerupture rate after patient-based decision to return to work and sports. Return to work was possible for 96% of patients after a mean delay of 2.3 months. Return to sports was 92%, 6.1 months for pivoting sports and 6.6 months for contact sports. A 6% rerupture rate occurred after a new significant knee injury.[42] Assessing time to return to sports based on muscle strength may also be influenced by testing technique. Koutras et al[46] compared knee flexion isokinetic strength deficits between seated and prone positions after hamstring autograft ACLR with accelerated rehabilitation. Peak torque knee flexion deficits were higher in the prone position compared with the conventional seated position by an average of 6.5% at 60°/s and 9.1% at 180°/s ($p<0.001$). At 9 months after hamstring ACLR, most athletes would not be cleared to return to sports if tested in prone position.[46]

Brace-free accelerated rehabilitation after hamstring tendon autograft ACLR, early start of open kinetic chain quadriceps exercises at 4 weeks in a limited knee ROM (90°-45°) and progressive concentric and eccentric exercises from 12 weeks do not alter clinical outcomes ('moderate' level of evidence).

Isokinetic extension peak torque deficit is still present at 1 year after accelerated rehabilitation. The use of Nintendo Wii Fit activities could address weight-bearing asymmetry and physical therapy goals ('limited' level of evidence).

Patient-based decision to return to work and sports is possible without compromising functional outcome ('limited' level of evidence).

Measuring knee flexion strength in prone position shows larger knee flexion isokinetic deficits compared with the conventional seated position ('limited' level of evidence).

How do different patient characteristics affect clinical outcomes after hamstring tendon autograft ACLR with accelerated, brace-free rehabilitation?

Gender

Salmon et al[62] did not find significant gender differences for graft rupture, activity level, self-reported or functional assessment or radiological outcome. Women did have significantly greater laxity than men on the Lachman test, pivot shift test and KT-1000 mean manual maximum testing at all time points. The higher laxity measurements did not influence the self-reported and functional outcome assessments.[62]

Gender does not influence clinical outcomes after hamstring tendon autograft ACLR with accelerated, brace-free, rehabilitation ('limited' level of evidence).

Age
Trojani et al[75] retrospectively analysed the same ACLR technique as Salmon et al[62] in patients >50 years. Surgery restored knee stability but did not modify pain in patients with previous medial meniscectomy. Graft failure did not occur. The authors concluded that age over 50 years is not a contraindication to select a hamstring autograft for ACLR.[75] Toanen et al[72] demonstrated that older and active patients >60 years without osteoarthritis showed good results after single-bundle hamstring autograft ACLR. The majority of patients (83%) returned to sports activities with 50% returning to their preinjury level of activity.[72]

Age >50 years does not influence clinical outcome after hamstring tendon autograft ACLR with accelerated, brace-free rehabilitation ('limited' level of evidence).

How do different non-anatomical and anatomical surgical techniques of hamstring tendon autograft ACLR affect clinical outcomes after accelerated, brace-free rehabilitation?

Non-anatomical single tunnel four-strand hamstring tendon autograft ACLR
Three studies have examined this surgical technique.[3,35,83]

Howell et al[35] presented a single surgeon prospective cohort series of transtibial ACLR technique with special attention to intercondylar roof impingement. Patients returned to unrestricted sports and work activities after 4 months. The authors justified the early return to vigorous activities at 4 months by unchanged knee stability, girth of the thigh, knee extension as well as Lysholm and Gillquist scores at 2-year follow-up.[35]

Ali et al[3] presented the outcomes of a single surgeon, cross-sectional study of transtibial non-anatomical ACLR using a hamstring graft without detachment of its tibial insertion. Follow-up was 64 (range 48–84) months. All patients achieved full ROM with a mean KT-1000 side-to-side difference of 1.43 (SD 3.86) and negative pivot shift test. The authors concluded that their technique showed satisfactory and comparable results to studies with conventional detachment of hamstring tendons from their tibial insertion.[3]

Zaffagnini et al[83] analysed return to sports in a homogeneous group of male professional soccer players after ACLR. Follow-up was 4 years. The authors used a non-anatomical, four-strand hamstring technique with additional extra-articular fixation of the graft. After 12 months, 95% of patients returned to the preoperative professional soccer level. Mean time from surgery to first official match was 186 (range 107–282) days. The Knee injury and Osteoarthritis Outcome Scores reached the plateau level at 6 months postoperatively. At 4 years, 71% still played professional soccer, 62% at the same preoperative level and 9% in a lower division. Five per cent of patients experienced rerupture of the ACLR.[83]

Non-anatomical transtibial four-strand hamstring ACLR with accelerated, brace-free rehabilitation is associated with good clinical results. Return to sports was possible at 4–6 months postsurgery ('moderate' level of evidence).

Non-anatomical versus anatomical hamstring tendon autograft ACLR
Koutras et al[47] compared the short-term functional and clinical outcomes between a non-Anatomical transtibial Versus an anatomical anteromedial ACL technique. The anteromedial approach group had better Lysholm scores at 3 months and better performance in the timed lateral movement functional tests at 3 and 6 months. All other comparisons were non-significant.[47]

Anatomical ACLR shows better short-term results than non-anatomical ACLR after accelerated, brace-free rehabilitation ('limited' level of evidence).

Single-bundle versus double-bundle hamstring tendon autograft ACLR
Sastre et al[64] compared anatomical four-strand single bundle and double-bundle hamstring ACLR in a randomised prospective study. The authors did not find any difference between the two groups with respect to anterior laxity, pivot shift test, IKDC subjective and objective scores.[64] In a similar study, Czamara et al[21] found no differences between the two groups for anterior tibial translation, pivot shift test, ROM and joint circumference, subjective assessment of pain and knee joint stability, peak torque for internal and external rotation and run test with maximal speed and change of direction manoeuvres.[21] Karikis et al found that anatomical double-bundle ACLR did not result in better rotational or anteroposterior stability measurements than anteromedial portal non-anatomical single-bundle reconstruction at 2-year follow-up.[43]

There is no difference in clinical results between single-bundle and double-bundle hamstring tendon autograft ACLR with accelerated, brace-free rehabilitation ('strong' level of evidence).

Semitendinosus versus combined semitendinosus/gracilis autograft ACLR
Krolikowska et al[48] assessed isometric and peak torque of muscles responsible for internal and external rotation of the lower leg post-ACLR after a 6-month accelerated brace-free rehabilitation programme. There was no difference between patients reconstructed with only the semitendinosus autograft (ST) compared with patients reconstructed with a combined semitendinosus/gracilis autograft (STGR). There was, however, a significant difference in isometric internal rotation strength in the operated knee compared with the uninvolved knee at 25°of internal rotation in the STGR group.[48]

There is an influence of additional gracilis harvest in internal rotation strength at a deep internal rotation angle ('limited' level of evidence).

Does accelerated, brace-free rehabilitation after hamstring tendon autograft ACLR influence tunnel widening?
Vadalà et al[77] analysed tunnel widening after four-strand hamstring tendon ACLR by means of CT scan comparing accelerated brace-free rehabilitation versus non-accelerated rehabilitation with brace. Mean follow-up was 10 months. There was a significant increase in femoral and tibial tunnel diameter after accelerated, brace-free rehabilitation.[77] The extend of tunnel widening with hamstring autograft and accelerated brace-free rehabilitation was measured by Srinivas et al[71] with CT at 1-year follow-up: femoral and tibial tunnel widening varied with different methods of fixation and was maximal in the tibia with suture disc method compared with interference screw fixation.[71]

Accelerated, brace-free, rehabilitation after hamstring tendon autograft ACLR causes increased tunnel widening on both the femur and tibia ('limited' level of evidence).

Do hamstring tendons regenerate after harvest for ACLR with accelerated, brace-free rehabilitation?
Regeneration of hamstring tendons in the upper leg after harvest for ACLR with accelerated, brace-free rehabilitation was examined in two studies.[2,40]

Ahlen et al[2] performed a retrospective MRI study with 6-year follow-up after hamstring tendon harvest. The gracilis tendon regenerated in 18 of 19 patients, the ST tendon in 17 of 19 patients.[2] Janssen et al[40] performed a prospective MRI study in 22 patients with follow-up at 6 and 12 months. Regeneration of the gracilis tendon occurred in all patients, the ST tendon regenerated in 14 of 22 patients. The majority of tendons regenerated distal to the joint line of the knee. The authors did not find a significant relationship between isokinetic flexion strength and tendon regeneration.[40]

Hamstring tendons regenerate after harvest for ACLR. There is no evidence to support a relationship between increased isokinetic flexion strength and tendon regeneration ('strong' level of evidence).

Does the current biological knowledge of the hamstring graft support early return to sports after ACLR with accelerated, brace-free rehabilitation?
Janssen et al[41] examined 67 midsubstance biopsies after clinically successful four-strand hamstring autograft ACLR with a standardised accelerated rehabilitation programme. Cellular density and vascular density were increased up to 24 months after ACLR. Especially the strong increase in myofibroblast density, from 13 to 24 months, indicated an active remodelling process from 1 to 2 years. Furthermore, vessel density increased over 24 months, whereas cell and myofibroblast density decreased but stayed higher than native hamstring and ACL controls. Collagen

orientation did not return to normal in the study period. The authors question whether early return to sports (4–6 months) after accelerated rehabilitation is to be recommended after hamstring ACLR.[41]

Intra-articular hamstring graft remodelling is still active at 2 years after ACLR with an accelerated, brace-free rehabilitation. Based on the current evidence, the early return to sports after 4–6 months may be questionable ('limited' level of evidence).

Discussion

A significant body of literature has shown that accelerated rehabilitation - defined as early-unrestricted motion, immediate weight-bearing and eliminating the use of immobilising braces - is appropriate after ACLR with patellar tendon grafts.[12,14,16,17,23,61,67-69] However, conclusions are unclear when evaluating the effects of this type of rehabilitation after hamstring autograft ACLR. There are several factors that need to be considered. First, hamstring autografts require fixation of soft tissue (tendon) to bone.[56] A period of 8–12 weeks is necessary for proper incorporation of hamstring grafts in the bone tunnels.[26] Fixation of this soft tissue graft is considered the 'weak link' early on after ACLR.[26,31] In a systematic review, Han et al concluded that both intratunnel and extratunnel fixation methods of hamstring ACL autografts displayed comparable outcomes based on objective IKDC, Lysholm and Tegner scores, anterior knee laxity and return to sports timing.[31]

Second, the intra-articular remodelling of the ACL hamstring autograft requires an optimal equilibrium between muscle strength training and graft loading to prevent stretch out of the ACL graft.[10,12,27,39,79] Finally, early after ACLR, relative protection of the autograft donor site must be considered. Therefore, force generation from the hamstrings should be minimised when a hamstring autograft is employed.[26] In summary, accelerated, brace-free rehabilitation needs to restore knee function and at the same time stimulate optimal graft healing.[57]

Accelerated rehabilitation

This review presented a 'moderate' level of evidence that accelerated rehabilitation after hamstring ACLR does not alter clinical outcome compared with non-accelerated rehabilitation with knee brace.[17] The rationale of using a knee brace is to protect the healing graft during the early phases of rehabilitation.[4] Various systematic reviews could not substantiate this hypothesis based on clinical results.[4,30,49,81] Furthermore, full weight-bearing without crutches within 10 days (with a normal gait pattern) improves quadriceps function, prevents patellofemoral pain and does not affect knee stability.[30,81]

This review showed that start of open kinetic chain quadriceps exercises with 90°-45° ROM at 4 weeks postsurgery does not alter the clinical outcome after hamstring autograft ACLR ('moderate' level of evidence). The combination of closed and open kinetic chain exercises protects the healing graft as a result of better dynamic lower extremity stability and neuromuscular control.[57] Beynnon et al[11] found similar maximum ACL strain values produced by active flexion–extension (an open kinetic chain exercise) and squatting (a closed kinetic chain exercise). They also demonstrated that increasing resistance during the squat exercise did not produce a significant increase in native ACL strain values, unlike increased resistance during active flexion–extension exercise.[11] Escamilla et al[26] showed that non-weight-bearing exercises generally loaded the ACL graft more than weight-bearing exercises and that, for both exercises, the ACL was loaded to a greater extent between 10° and 50° compared with 50° and 100° of knee flexion.[26] These biomechanical findings are in agreement with the good clinical results presented in this review with the early start of open kinetic exercises in a limited ROM.[27,37] Majima et al[51] demonstrated that accelerated rehabilitation with open kinetic exercises started at 7–10 days after hamstring ACLR could rapidly restore muscle strength without significantly compromising graft stability. However, the incidence of synovitis of the knee was significantly increased after accelerated rehabilitation.[51] Van Grinsven et al concluded in their systematic review on evidence-based rehabilitation after ACLR that there is increasing consensus that open kinetic chain exercises did not increase graft laxity (in and exceeding the safe range with a focus on endurance). Additionally, these exercises had a favourable effect on quadriceps strength.[30]

This review also demonstrated that start of eccentric and concentric muscle training at 12 weeks after surgery did not influence clinical outcome after hamstring autograft ACLR ('moderate' level of evidence). Therapeutic exercises that emphasise eccentric gluteus maximus, quadriceps femoris and gastrocnemius–soleus activation can improve lower extremity muscular shock absorption, prevent knee re-injury, enhance athletic performance, help heal lower extremity musculotendinous injuries, increase bone mineral density and decrease fall risk.[57] Further research is warranted to determine the best timing of introducing open kinetic exercises and safe amount of progressive resistance training after ACLR with hamstring autografts.[1,30]

A critical remark is necessary when accelerated rehabilitation is discussed. There is little consensus in the literature about what composes an accelerated rehabilitation programme because few papers have described their protocol adequately.[30] In this review, almost all included studies on accelerated, brace-free rehabilitation agreed that immediate weight-bearing, full ROM and closed kinetic exercises were permitted after hamstring autograft ACLR. However, if even specified at all, the programme varied in their timing and details of open kinetic chain exercises, frequency of concentric and eccentric training and neuromuscular training (Table 4). Few studies described full details of the accelerated rehabilitation after hamstring ACLR. The rehabilitation programme by Shelbourne and Nitz was most often cited. This programme emphasised specific presurgical rehabilitation goals.[4,11,22,30,51,57,81] Remarkably, only five studies in this review provided specific details of this prehabilitation.[22,40,41,46,47] Furthermore, although referring to the aforementioned rehabilitation protocols, the timing of return to activities such as running or unrestricted sports varied widely among studies, often without specific criteria (Table 4). The lack of details of accelerated rehabilitation programme after hamstring autograft ACLR makes it difficult to evaluate the potential disadvantages of accelerated rehabilitation such as tunnel widening[20,77] and increased synovitis.[51] Postoperative rehabilitation is a major factor contributing to the success of ACLR and needs to be defined in detail for adequate research on clinical outcome and safe return to sports.

Return to sports

3

Return to sports is often used as short-term to midterm outcome measure for ACLR and rehabilitation.[80] In their meta-analysis of 69 articles, Ardern et al[5] have shown that after ACLR, the overall return to some kind of sports activity is 81%. Sixty-five per cent of patients returned to their preinjury level and 55% to competitive sports at final follow-up. Younger age, male gender and a positive psychological response all favoured returning to the preinjury level sport. Elite athletes had more than twice the odds of returning to competitive sports compared with non-elite athletes.[5] This is supported by the evidence in the present review with 95% return to sports 1 year after with accelerated, brace-free rehabilitation.[83] Elite male UEFA soccer league players needed 7 months to return to the first training after ACLR, 10 months to return to regular practice and 12 months to return to match play.[60,78] Grindem et al have shown that the return to play after 9 months postsurgery substantially reduces ACL graft rerupture rate. Leading ACL experts generally let their patients return to sports at 6 months in average and involvement in active competition at 8 months postsurgery.[29] However, a recent study by Herbst et al[34] showed that most patients, in terms of neuromuscular abilities and compared with healthy controls, were most likely not ready for a safe return to sports, even 8 months postoperatively. The most limiting factor was a poor Limb symmetry index (LSI) value of <90% if the dominant leg was involved and <80% if the non-dominant leg was involved.[34] Gokeler et al[28] found that the majority of patients who are 6 months after ACLR require additional rehabilitation to pass return to sports criteria. Further studies identifying sport-specific differences in ACLR outcomes in athletes could further enhance accelerated rehabilitation programme for athletes after ACLR.[28,83]

Graft failure after ACLR is not uncommon even with improved ACLR techniques.[39,54] Evidence-based evaluations did not prove a 4–6 months return to sports to be safe due to the fact that biological healing is not complete.[18,39,41,59,60,73] This is also demonstrated in the current review: intra-articular hamstring graft remodelling was still active at 2 years after ACLR with an accelerated, brace-free rehabilitation.[41] This may provide biological support for the findings by Paterno et al that in the 24 months after ACLR and return to sports, patients are at greater risk to suffer a subsequent ACL injury compared with young athletes without a history of ACL injuries.[58] Considering the fact that rehabilitation protocols were extrapolated from animal in vivo studies, studies on human in vivo graft healing suggest a need for new postoperative rehabilitation schedules after ACLR with hamstring autografts.[39] No final conclusions can be drawn on the mechanical strength of the healing ACL grafts in humans without any available technique for in vivo measurements of their mechanical properties.[18,39]

In this systematic review, only 20% of studies reported assessment criteria for return to sports after hamstring autograft ACLR. These criteria, however, lacked specific details for use in clinical practice or comparative scientific research. This is in agreement with previous reviews on return to sports after ACLR.[8,32,49] Furthermore, commonly used muscle functional tests are not demanding or sensitive enough to identify differences between injured and non-injured sides.[9,60] Large meta-analysis have shown that despite 90% of patients having normal validated outcome scores, only 44% of patients returned to competitive sports.[6,32] Currently, there are no concrete guidelines that allow for a safe return to unrestricted activity.[32,82] Further research is necessary to develop a validated set of criteria to determine safe return to sport-specific training and unrestricted activity.[5,8,25,57,60]

One of the strengths of this systematic review is that it presents all available knowledge on outcomes after hamstring tendon autograft ACLR with accelerated rehabilitation. This extensive search strategy was performed in several databases, for all relevant papers to be included. Furthermore, the PRISMA standard was applied to study selection, data collection, risk of bias assessment and reporting of results. This led to an extensive and complete overview of the current evidence on this topic with defined levels of evidence. As such, it is a useful paper for ACL experts in various fields of healthcare (eg, orthopaedic surgeons, physical therapists) and may facilitate interprofessional patient care. This systematic review also has limitations. Studies of different evidence levels were included in the search for all available knowledge on clinical outcome after accelerated, brace-free rehabilitation after ACLR. It must be noticed that the type of rehabilitation was not a primary intervention in all of the included studies. Some conclusions of the 'best-evidence synthesis' may therefore not be primarily related to accelerated rehabilitation. Another limitation is the inclusion of studies with limited number of patients. Furthermore, the 'best-evidence synthesis' by van Tulder et al[76] for this review may have limited the level of evidence due to the quality and limited number of studies for specific research questions. Although strict and adapted for various study types, the risk of bias assessment of the Cochrane Library may limit the strength of evidence. It may be argued that a 'low' risk of bias RCT study is of higher level of evidence than a 'low' risk of bias prospective cohort study.

The inclusion of merely publications in English is another limitation.

Conclusions

After hamstring tendon autograft ACLR with accelerated brace-free rehabilitation, clinical outcome is similar after single-bundle and double-bundle ACLR. Early start of open kinetic exercises at 4 weeks in a limited ROM (90°-45°) and progressive concentric and eccentric exercises from 12 weeks postsurgery do not alter clinical outcome. Further research should focus on achievement of best balance between graft loading and graft healing in the various rehabilitation phases after ACLR as well as on validated, criterion-based assessments for safe return to sports.

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Appendix 1: Search strategy systematic review

Embase.com	2529	2502
Medline Ovid	1916	432
Web of science	1632	619
Cochrane CENTRAL	259	45
Google scholar	200	79
Total	**6536**	**3677**

Embase.com 2529

('anterior cruciate ligament'/exp OR 'knee cruciate ligament'/de OR 'anterior cruciate ligament rupture'/exp OR 'anterior cruciate ligament injury'/exp OR 'anterior cruciate ligament reconstruction'/exp OR (((anterior*) NEAR/6 (cruciate* OR crutiat*) NEAR/6 ligament*) OR acl OR acls OR aclr OR (anterior* NEAR/6 cruciate* NEAR/6 deficien*)):ab,ti) AND ('knee surgery'/exp OR 'tendon graft'/exp OR 'tendon transfer'/exp OR 'orthopedic surgery'/exp OR (surg* OR reconstruct* OR repair* OR (tendon* NEAR/6 (graft* OR transfer*)) OR orthoped* OR orthopaed*):ab,ti) AND (physiotherapy/exp OR kinesiotherapy/exp OR exercise/exp OR 'postoperative care'/de OR 'rehabilitation'/de OR 'acceleration'/de OR 'post-operative care'/de OR 'resistance training'/de OR 'rehabilitation'/exp OR (physiotherap* OR kinesiotherap* OR kinesitherap* OR exercise* OR ((phys*) NEAR/6 therap*) OR ((postoperative* OR post-operative*) NEAR/3 care) OR rehabilitat* OR Instruction* OR ((resistan* OR Strength) NEAR/3 train*) OR Accelerated OR (accelerat* NEAR/6 rehab*) OR Brace-free* OR (postoperative NEAR/3 care) OR rehabilitat* OR Instruction* OR ((resistance OR Strength) NEAR/3 training)):ab,ti) NOT ([Conference Abstract]/lim OR [Letter]/lim OR [Note]/lim OR [Editorial]/lim) NOT ([animals]/lim NOT [humans]/lim) AND [english]/lim AND ('treatment outcome'/exp OR 'clinical effectiveness'/de OR 'program effectiveness'/de OR 'questionnaire'/exp OR 'assessment of humans'/de OR 'muscle strength'/de OR sport/de OR 'physical activity, capacity and performance'/de OR 'physical activity'/de OR 'osteoarthritis'/de OR 'knee osteoarthritis'/de OR 'range of motion'/de OR 'knee instability'/de OR 'daily life activity'/exp OR 'work resumption'/de OR 'return to work'/de OR (outcome* OR effectiv* OR efficac* OR questionnaire* OR assessment* OR strength* OR ((hop* OR function*) NEAR/3 test*) OR sport OR sports OR (physical* NEAR/3 activ*) OR osteoarthrit* OR (Knee* NEAR/3 (stabil* OR stable* OR instab*)) OR (Tunnel* NEAR/3 enlarge*) OR (range NEAR/3 motion) OR (daily NEAR/6 (life OR living) NEAR/6 activ*) OR (work NEAR/3 (return* OR resum*))):ab,ti)

Medline Ovid 1916

(“Anterior Cruciate Ligament”/ OR “Anterior Cruciate Ligament Injuries”/ OR “Anterior Cruciate Ligament Reconstruction”/ OR (((anterior*) ADJ6 (cruciate* OR crutiat*) ADJ6 ligament*) OR acl OR acls OR aclr OR (anterior* ADJ6 cruciate* ADJ6 deficien*)).ab,ti,kf.) AND (knee/su OR “Bone-Patellar Tendon-Bone Grafts”/ OR “Tendon Transfer”/ OR “Orthopedics”/ OR “Orthopedic Procedures”/ OR “Reconstructive Surgical Procedures”/ OR “Anterior Cruciate Ligament Reconstruction”/ OR surgery.xs. OR (surg* OR reconstruct* OR repair* OR (tendon* ADJ6 (graft* OR transfer*)) OR orthoped* OR orthopaed*).ab,ti,kf.) AND (Physical Therapy Modalities/ OR exp “Exercise Therapy”/ OR “Exercise Movement Techniques”/ OR exp “Musculoskeletal Manipulations”/ OR exp exercise/ OR “Postoperative Care”/ OR “Rehabilitation”/ OR “acceleration”/ OR “Resistance Training”/ OR (physiotherap* OR kinesiotherap* OR kinesitherap* OR exercise* OR ((phys*) ADJ6 therap*) OR ((postoperative* OR post-operative*) ADJ3 care) OR rehabilitat* OR Instruction* OR ((resistan* OR Strength) ADJ3 train*) OR Accelerated OR (accelerat* ADJ6 rehab*) OR Brace-free* OR (postoperative ADJ3 care) OR rehabilitat* OR Instruction* OR ((resistance OR Strength) ADJ3 training)).ab,ti,kf.) NOT (letter OR news OR comment OR editorial OR congresses OR abstracts).pt. NOT (exp animals/ NOT humans/) AND english.la. AND (exp “Treatment Outcome”/ OR “Program Evaluation”/ OR “questionnaires”/ OR “muscle strength”/ OR sports/ OR “Physical Fitness”/ OR “osteoarthritis”/ OR “osteoarthritis, knee”/ OR “Range of Motion, Articular”/ OR “Activities of Daily Living”/ OR “Return to Work”/ OR (outcome* OR effectiv* OR efficac* OR questionnaire* OR assessment* OR strength* OR ((hop* OR function*) ADJ3 test*) OR sport OR sports OR (physical* ADJ3 activ*) OR osteoarthrit* OR (Knee* ADJ3 (stabil* OR stable* OR instab*)) OR (Tunnel* ADJ3 enlarge*) OR (range ADJ3 motion) OR (daily ADJ6 (life OR living) ADJ6 activ*) OR (work ADJ3 (return* OR resum*))).ab,ti,kf.)

Cochrane CENTRAL 259

((((anterior*) NEAR/6 (cruciate* OR crutiat*) NEAR/6 ligament*) OR acl OR acls OR aclr OR (anterior* NEAR/6 cruciate* NEAR/6 deficien*)):ab,ti) AND ((surg* OR reconstruct* OR repair* OR (tendon* NEAR/6 (graft* OR transfer*)) OR orthoped* OR orthopaed*):ab,ti) AND ((physiotherap* OR kinesiotherap* OR kinesitherap* OR exercise* OR ((phys*) NEAR/6 therap*) OR ((postoperative* OR post-operative*) NEAR/3 care) OR rehabilitat* OR Instruction* OR ((resistan* OR Strength) NEAR/3 train*) OR Accelerated OR (accelerat* NEAR/6 rehab*) OR Brace-free* OR (postoperative NEAR/3 care) OR rehabilitat* OR Instruction* OR ((resistance OR Strength) NEAR/3 training)):ab,ti) AND ((outcome* OR effectiv* OR efficac* OR questionnaire* OR assessment* OR strength* OR ((hop* OR function*) NEAR/3 test*) OR sport OR sports OR (physical* NEAR/3 activ*) OR osteoarthrit* OR (Knee* NEAR/3 (stabil* OR stable* OR instab*)) OR (Tunnel* NEAR/3 enlarge*) OR (range NEAR/3 motion) OR (daily NEAR/6 (life OR living) NEAR/6 activ*) OR (work NEAR/3 (return* OR resum*))):ab,ti)

Web of science 1632

TS=(((((anterior*) NEAR/5 (cruciate* OR crutiat*) NEAR/5 ligament*) OR acl OR acls OR aclr OR (anterior* NEAR/5 cruciate* NEAR/5 deficien*))) AND ((surg* OR reconstruct* OR repair* OR (tendon* NEAR/5 (graft* OR transfer*)) OR orthoped* OR orthopaed*)) AND ((physiotherap* OR kinesiotherap* OR kinesitherap* OR exercise* OR ((phys*) NEAR/5 therap*) OR ((postoperative* OR post-operative*) NEAR/2 care) OR rehabilitat* OR Instruction* OR ((resistan* OR Strength) NEAR/2 train*) OR Accelerated OR (accelerat* NEAR/5 rehab*) OR Brace-free* OR (postoperative NEAR/2 care) OR rehabilitat* OR Instruction* OR ((resistance OR Strength) NEAR/2 training))) AND ((outcome* OR effectiv* OR efficac* OR questionnaire* OR assessment* OR strength* OR ((hop* OR function*) NEAR/2 test*) OR sport OR sports OR (physical* NEAR/2 activ*) OR osteoarthrit* OR (Knee* NEAR/2 (stabil* OR stable* OR instab*)) OR (Tunnel* NEAR/2 enlarge*) OR (range NEAR/2 motion) OR (daily NEAR/5 (life OR living) NEAR/5 activ*) OR (work NEAR/2 (return* OR resum*))))) AND DT=(article) AND LA=(english)

Google scholar 200

“anterior cruciate ligament|ligaments”|acl surgery|reconstruction|repair|”tendon graft|transfer” “Accelerated rehabilitation”|”Brace-free”

3

Part II

Playing with return to play criteria

Chapter 4

Assessment of functional performance after anterior cruciate ligament reconstruction: a systematic review of measurement procedures

Nicky Engelen-van Melick
Robert E.H. van Cingel
Marsha P.W. Tijssen
Maria W.G. Nijhuis-van der Sanden

Knee Surgery, Sports Traumatology, Arthroscopy 2013;21(4):869-879

Abstract

Purpose: The purpose of this systematic review was to identify the measurements that are used in clinical practice to assess the quantity and quality of functional performance in men and women more than 2 years after ACL reconstruction with bone patellar-tendon bone (BPTB) or semitendinosus/gracilis (STG) graft.

Methods: A systematic literature search was performed in Medline (Pubmed), EMBASE (OVID), the Cochrane Library and PEDro to identify relevant articles from 1990 up to 2010. Articles were included if they described functional performance after BPTB or STG reconstruction and had a follow-up of more than 2 years. Two authors screened the selected articles for title, abstract and full-text in accordance with predefined inclusion and exclusion criteria. The methodological quality of all articles was assessed by checklists of the Cochrane Library by two authors. Only the articles with good methodological quality were considered for further analysis.

Results: A total of 27 studies were included by full-text. According to their methodological quality six were rated as good. Different authors used different study designs for muscle testing which led to different outcomes that could not be compared. Besides strength, a single-leg hop for distance was used as a measurement for quantity of functional performance. No measurements for quality of functional performance were reported.

Conclusions: Measurement of functional performance more than 2 years after ACL reconstruction consists of concentric or isometric strength, the single-leg hop for distance or a combination. The Limb Symmetry Index is used as the main outcome parameter to compare the involved leg with the uninvolved. In all studies the results of men and woman are combined. Based on our findings and previous studies that discussed additional important parameters a more extensive test battery to assess functional performance is suggested.

Introduction

Anterior cruciate ligament (ACL) reconstruction is a worldwide accepted treatment for ACL deficiency in athletes participating in jumping and pivoting sports.[58] For ACL reconstruction autologous material like the bone-patellar tendon-bone (BPTB) and the semitendinosus and gracilis tendons (STG) are the most common methods.[23,58] The BPTB has a lower rate of graft failure, less objective knee laxity and fewer loss of flexion compared to the STG. The STG has a lower incidence of patellofemoral crepitance, less kneeling pain and fewer loss of extension.[23,58] These advantages only refer to pain or loss of function but do not cover functional performance which is of great importance for return to sports.

Evidence based rehabilitation after ACL reconstruction without complications (e.g. arthrofibrosis) takes about 22 weeks and neuromuscular training is shown to be an effective method to prepare athletes for their return to sports.[26,34] Neuromuscular training is described as a combination of balance, weight, plyometric, agility and sport-specific exercises.[31]

Functional performance can be defined as the result of neuromuscular training and consists of two components. The first component is the quantity of movement, like muscle strength measurements (concentric and eccentric) and hop tests.[1] The second component is the quality of movement, for instance the occurrence of dynamic knee valgus or the amount of knee flexion when landing from a jump.[17,56] Both components are important in rehabilitation and prevention of ACL (re)injuries.[1,53,59,68,73] Despite intensive rehabilitation protocols ambiguity exists whether an athlete can restore functional performance to his preinjury level.[2,18,30,41,42,45,48,75] Ardern et al.[4] showed that for a follow-up of 2 years or more the rate of return to preinjury level was 62%. Moreover, up to 12% of ACL reconstructed patients suffered an ACL re-injury within 5 years, with the highest incidence in the first 2 years.[62,77]

Most studies describing the functional performance after ACL reconstruction are limited to quantitative measurements in a follow-up period of maximally 2 years combining the results of BPTB and STG.[20,30,45,75]

Results of functional performance longer than2 years after ACL reconstruction are lacking. Especially the selection of measurement instruments is unknown. Therefore, the aim of this systematic review is to identify which measurements are used in clinical practice to assess both aspects of functional performance in men and women more than 2 years after ACL reconstruction with BPTB or STG. The results may contribute to the development of a protocol to measure functional performance in all ACL reconstructed patients and to predict whether they are at risk if they return to sports.

Materials and methods

Search strategy

A systematic literature search was performed searching in Medline (Pubmed), EMBASE (OVID), the Cochrane Library and PEDro to identify relevant articles from January 1990 up to December 2010 using keywords specified for the database. Randomised controlled trials (RCTs), controlled clinical trials (CCTs), cohort studies and cross-sectional studies could be included for study selection.

Study selection

All eligible articles were screened first by title and abstract by two reviewers (NM and MT). The applied inclusion and exclusion criteria are listed in Table 1. When the reviewers did not reach consensus, a third reviewer (RC) made the final decision. After the first inclusion, the full-text article was assessed. If the full-text article did not meet the inclusion criteria it was excluded. In addition, a hand search was done on the reference lists of the included articles and of the excluded review articles.

Finally the reviewers assessed the articles for methodology and outcomes with the checklists of the Cochrane Library (www.cochrane.nl). The reviewers were not blinded for author or journal of publication. An overview of the selection procedure is presented in Figure 1.

Table 1: *Inclusion and exclusion criteria.*

Inclusion criteria	Exclusion criteria
Article is published in English and available as full-text article	Animal or cadaveric studies
Article describes functional performance after BPTB and/or STG autograft reconstruction	Articles comparing BPTB or STG with allografts or synthetic grafts
Follow-up of more than 2 years	Articles combining test results for BPTB and STG
	Articles comparing different rehabilitation programs or surgical techniques
	Arthrotomy instead of arthroscopic reconstruction
	Review or meta-analysis

BPTB=bone-patellar tendon-bone, STG=semitendinosus/gracilis

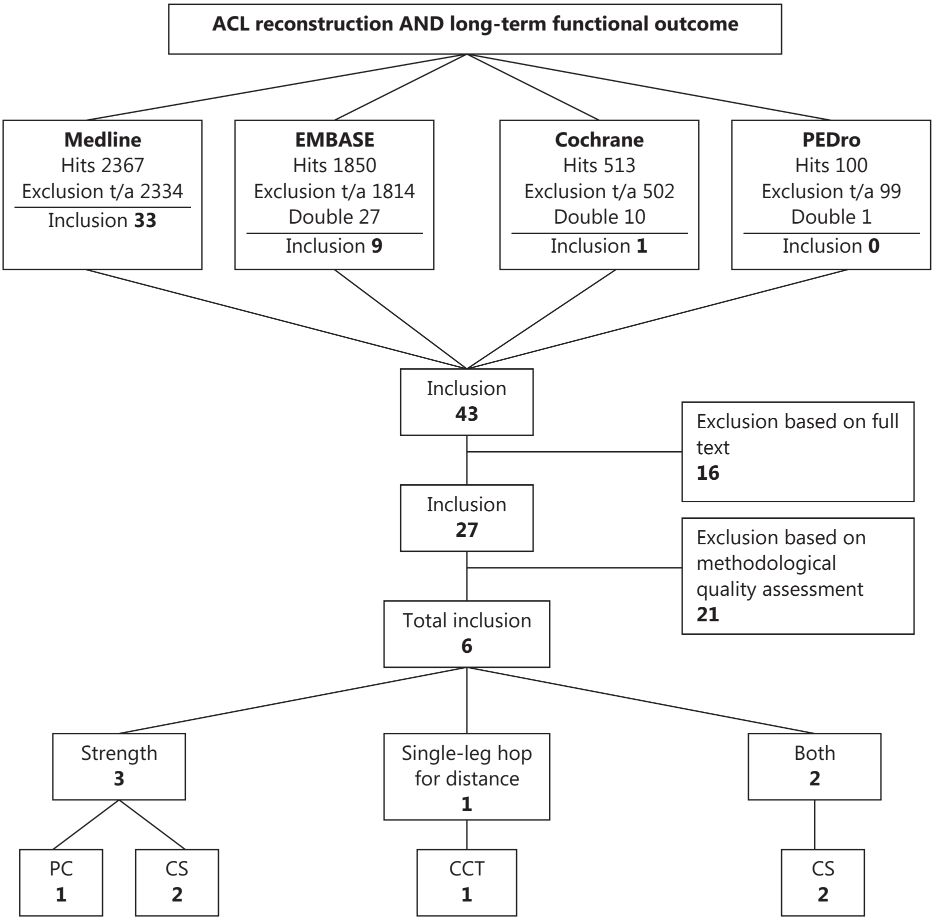

Figure 1: *flow-chart of search strategy.*
t/a=title/abstract, CCT=clinical controlled trial, PC=prospective cohort study, CS=cross-sectional study

Quality assessment

The assessment of risk of bias of all articles was assessed by standard checklists of the Cochrane Library (www.cochrane.nl) and by two assessors (NM and MT).

The assessment list for randomised controlled trials (RCTs) used the 9 criteria, displayed in Table 2. These 9 items could be rated ''yes'' (?), ''no'' (-) or ''do not know'' (?). The same list was also used for assessing controlled clinical trials (CCTs), but these scored a ''no'' for items 1 and 2 (Table 3).

The assessment list for cohort studies described 8 items, displayed in Table 2. All 8 items could be rated positive (?), negative (-) or ''do not know'' (?). The same list was used for assessing cross-sectional studies, but these scored a ''no'' for item 2 because the study design could cause selection bias (Table 4).

Based on the research question two additional items were evaluated (Tables 3, 4). The first item considered accurate description of tests. The second item considered the proportion men and women participating in a study.

A total score was calculated by counting up all positive items. A final judgment of good, questionable or poor was given to every article. A good was assigned to articles scoring positive for more than 50% of all items; a poor for scoring positive for less than 30% of all items; a questionable was assigned for a positive score between 30 and 50%.

The articles scoring a good for methodological quality were used for further data collection. Data were extracted for loss-to-follow-up, graft choice, mean follow-up, mean age of participants, proportion of men and women participating, description of the population in terms of level of activity, tests used to assess functional performance.

Table 2: *Cochrane criteria for assessment of randomised controlled trials and cohort studies.*

Randomised controlled trials	Cohort studies
1. Is a method of randomisation applied?	Are study groups clearly defined?
2. Is randomisation blinded?	Is there any selection bias?
3. Are the patients blinded?	Is the exposure clearly defined?
4. Is the therapist blinded?	Is the outcome clearly defined?
5. Is the outcome assessor blinded?	Is the outcome assessment blinded?
6. Are groups comparable?	Is the follow-up accurate?
7. Is there an acceptable loss-to-follow-up?	Is there an acceptable loss-to-follow-up?
8. Is there an intention-to-treat?	Are confounders described and/or eliminated?
9. Are treatments comparable?	

Table 3: *Quality assessment of RCTs and CCTs.*

Article	Study design	1	2	3	4	5	6	7	8	9	Accurate description of test? [a]	Proportion men and women? [a]	Total score
Barenius et al.[8]	RCT	+	?	?	?	-	+	+	?	+	+	-	Questionable
Beynnon et al.[11]	RCT	+	?	?	?	?	+	?	?	+	-	-	Poor
Eriksson et al.[19]	RCT	+	?	?	?	?	?	+	?	+	-	-	Poor
Harilainen et al.[29]	RCT	± (quasi-random)	-	?	?	?	?	+	-	+	-	?	Poor
Lidén et al.[43]	RCT	+	?	?	?	?	+	-	?	+	+	-	Questionable
Sajovic et al.[61]	RCT	+	-	?	?	?	+	+	?	+	-	+	Questionable
Taylor et al.[70]	RCT	± (quasi-random)	?	?	?	?	+	-	?	+	-	-	Poor
Brandsson et al.[13]	CCT	-	-	?	?	?	+	+	?	+	+	-	Questionable
Hiemstra et al.[33]	CCT	-	-	-	-	-	-	+	?	+	-	-	Poor
Keays et al.[36]	CCT	-	-	?	?	?	?	+	?	+	+	-	Poor
Laxdal et al.[42]	CCT	-	-	?	?	-	+	+	+	+	+	+	Good
Pinczewski et al.[55]	CCT	-	-	?	?	?	+	-	-	+	-	-	Poor
Svensson et al.[67]	CCT	-	-	?	?	-	+	+	?	+	+	+	Questionable
Zaccherotti et al.[80]	CCT	-	-	?	?	?	+	+	?	+	+	-	Questionable

RCT=randomised controlled trial, CCT=clinical controlled trial

[a] *Additional item because of research question*

Table 4: *Quality assessment of cohort studies and cross-sectional studies.*

Article	Study design	1	2	3	4	5	6	7	8	Accurate de-scription of test?[a]	Proportion men and women?[a]	Total score
Asik et al.[5]	PC	+	+	+	-	?	+	+	-	-	-	Good
Gobbi et al.[22]	PC	-	+	+	-	?	+	?	-	-	-	Questionable
Goradia et al.[24]	PC	+	+	+	-	?	+	-	-	-	-	Questionable
Nyberg et al.[52]	PC	-	-	-	+	?	+	-	-	+	-	Questionable
Salmon et al.[63]	PC	+	-	+	-	?	-	-	-	-	-	Poor
Sernert et al.[64]	PC	+	-	-	-	?	+	+	-	-	-	Questionable
Toritsuka et al.[74]	PC	+	+	+	-	?	+	-	-	-	-	Questionable
Weninger et al.[78]	PC	-	-	-	-	?	-	+	-	+	-	Poor
Ageberg et al.[2]	CS	+	-	+	+	+	+	+	-	+	-	Good
Lautamies et al.[41]	CS	+	-	+	+	?	+	+	-	+	-	Good
Moisala et al.[48]	CS	+	-	-	+	?	+	+	-	+	-	Good
Novak et al.[51]	CS	-	-	+	-	?	+	-	-	-	+	Questionable
Tadokoro et al.[69]	CS	+	-	+	+	?	+	+	-	+	-	Good

PC=prospective cohort study, CS=cross-sectional study

[a] *Additional item because of research question*

Results

Study selection and methodological quality assessment

After the first exclusion based on title and abstract 43 articles were eligible for inclusion and were assessed (Figure 1). Based on the full-text assessment 16 studies were excluded (Table 1); 27 studies were included based on full text. All studies used quantitative outcome parameters. Tables 2, 3 and 4 show the results of the methodological quality and risk of bias assessment. More than half of the 21 excluded articles had a loss-to follow-up of more than 15% without mentioning a reason for drop-outs, which could have led to selection-bias.[11,22,24,29,51,52,55,61,63,70,74,78] The study characteristics of the six articles rated as good are listed in Table 5. All studies use the LSI (Limb Symmetry Index) as an outcome parameter, calculated as the value of the operate leg divided by the value of the healthy leg and multiplied by 100.[6]

Study description

Strength measurement

Five studies reported outcomes of strength measurement and combined results of men and women. No RCT was included and average follow-up after ACL reconstruction was 3–7 years (36–82 months). Different authors used different study designs for muscle testing which led to different outcomes that could not be compared (Table 5).[2,5,41,48,69]

Three out of five studies compared BPTB with STG.[2,41,48] Moisala et al.[48] reported no significant differences between groups. Ageberg et al.[2] found a lower LSI for flexion power in the STG group (p=0.001). Lautamies et al.[41] found a lower LSI for extension peak torque in the BPTB group (p=0.01).

Single-leg hop tests

Three studies described a single-leg hop for distance.[41,42,48] Lautamies et al.[41] and Moisala et al.[42] combined strength measurement with a single-leg hop for distance (Table 5).

Besides reporting the LSI, all three studies compared BPTB with STG.[41,42,48] Only Lautamies et al.[41] reported a significant difference between groups and showed that the LSI for the STG group was lower (p=0.040).

Table 5: *Study characteristics of the six included articles with good methodological quality.*

Study	Study design	n (% follow-up)	Graft (BPTB/ST(G)	Mean follow-up in months (range)	Mean age in years (range)	Sex (men/women)	Population	Test results
Ageberg et al.[2]	Cross-sectional	36 (100)	20/16	36 (24-60)	30 (20-39)	27-9	Moderate to high preinjury physical activity level (Tegner 5-9)	Strength tests according to Neeter, power BPTB LSI extension 94%; flexion 106% STG LSI extension 94%; flexion 88%
Asik et al.[5]	Prospective cohort	323 (84)	0/271	82 (48-108)	25.7 (17-52)	198/73	Moderate to high post-operative physical activity level (Tegner 4-10)	Cybex II, concentric strength PT 240°/s 7% LSI < 80%
Lautamies et al.[41]	Cross-sectional	288 (100)	175/113	60 (41-75)	BPTB 28 (14-54) STG 29 (13-56)	BPTB 84/91 STG 48/65	Moderate preinjury physical activity level (median Tegner 7)	Single-leg hop for distance BPTB 72% LSI > 90% STG 68% LSI > 90% Lido multijoint II, concentric strength PT 60°/s BPTB LSI quadriceps 90.3%; hamstrings 98.5% STG LSI quadriceps 94.2%; hamstrings 96.5% 180°/s BPTB LSI quadriceps 91.5%; hamstrings 97.5% STG LSI quadriceps 94.7%; hamstrings 95.0%

Study	Study design	n (% follow-up)	Graft (BPTB/ ST(G)	Mean follow-up in months (range)	Mean age in years (range)	Sex (men/ women)	Population	Test results
Laxdal et al.[42]	CCT	126 (98)	45/78	BPTB 25 (23-31) STG 25 (23-33)	BPTB 26 (14-49) STG 28 (17-61)	123/0	High preinjury physical activity level (median Tegner 9)	Single-leg hop for distance BPTB LSI 94% STG LSI 96%
Moisala et al.[48]	Cross-sectional	48 (92)	16/32	69 (44-89)	?	39/9	Moderate post-operative physical activity level (mean Tegner 5 for BPTB and 6 fot STG)	Single-leg hop for distance BPTB 56% LSI > 90% STG 82% LSI > 90% Dynacom, concentric strength PT 60°/s BPTB LSI quadriceps 90%; hamstrings 99% STG LSI quadriceps 93%; hamstrings 97% 180°/s BPTB LSI quadriceps 95%; hamstrings 101% STG LSI quadriceps 98%; hamstrings 100%
Tadokoro et al.[69]	Cross-sectional	28 (100)	0/28	67.2 (24-84)	22.2 (15-39)	10/18	Recreational or competitive athlete prior to injury	Cybex, isometric strength Seated 90° flexion LSI 86.2% Prone 90° flexion LSI 54.6% Prone 110° flexion LSI 49.1%

PT=Peak Torque

Discussion

The most important finding of the present study was that all included articles used limited quantitative measurements to determine functional performance more than 2 years after ACL reconstruction with BPTB or STG. Qualitative tests were not executed.

Concerning methodological quality six out of 27 articles were rated as good and were included. These six articles described concentric or isometric strength measurement, single-leg hop for distance or both. The Limb Symmetry Index was used as the main outcome parameter to compare the involved leg with the uninvolved leg. In all studies the results of men and woman were combined. These important findings will be discussed separately.

Strength measurement

This review shows that four out of five included articles performed concentric or isometric strength measurements using different isokinetic dynamometers. Isokinetic strength testing is a reliable method to measure peak torque of knee extensors and flexors.[14,35,37,44,66] However, there are many different isokinetic devices and the intermachine reliability is low.[27] As a result, comparing outcomes (i.e. peak torque) of various devices is difficult. Concentric strength measurement showed strength deficits up to 12%.[2,41,48]

Tadokoro et al.[69] performed isometric strength measurements in two positions (seated and prone) with flexion angles of 90 and 110 and showed large strength deficits expressed in LSI (49–86%).

The fifth article used concentric power measurements in an open kinetic chain as described by Neeter et al. which have a high ability to discriminate between the leg power performance on the injured and uninjured side in patients who have undergone ACL reconstruction.[2,49]

None of the studies measured eccentric strength. This is in contrast with previous studies in healthy populations showing that eccentric contractions are important in sports. During running 80% of hamstring activity is eccentric.[12,15,16,65] Landing after a jump requires eccentric contractions of quadriceps femoris.[10] Also, pivoting sports like soccer, handball or basketball require frequent accelerating and decelerating movement patterns, putting high demands on eccentric activity of leg muscles.[25,40] Therefore, it is questionable whether only concentric measurements should be used to measure muscle strength.

Moreover, no included study described endurance (15–25 repetitions) muscle strength for quadriceps femoris and hamstrings. This is an important parameter since fatigue may reduce dynamic knee stability in healthy persons and therefore could be a causal factor in ACL (re)injuries.[21,32,47,71,76,79,81]

Single-leg hop tests

The included articles reported the use of a single-leg hop for distance. Most studies used this test as the gold standard for measuring functional performance after ACL reconstruction, because the reliability of this test is high (ICC ranging from 0.86 to 0.95).[28,57] However, several studies showed that the sensitivity increases when two or more different hop tests are performed.[6,7,50,57] By using a variety of hop tests, different hop qualities can be evaluated and thereby the opportunity to detect discrepancies in hop performance increases.[28]

Noyes et al. introduced in 1991 four hop tests to determine alterations in lower limb function in ACL deficient knees. Besides the single-leg hop for distance they also described the timed hop test, the triple hop for distance and the cross-over hop for distance, all measurements in a forward or diagonal direction.[50] In this test battery an endurance and sideward component is lacking.

In 2006 Gustavsson et al. presented a sensitive and accurate test battery consisting of three hop tests that had a high ability to discriminate between the hop performance of the injured and uninjured leg for patients who have undergone ACL reconstruction. They concluded that a combination of the vertical hop, the single-leg hop for distance and the side hop discriminated the best between the injured and the uninjured leg. The side hop test is a sideward endurance test for 30 s. During that kind of hop test muscle fatigue is induced, and there is a high demand on dynamic knee stability. It appeared that the side hop test discriminated the best between the injured and the uninjured leg.[28] None of the included studies used the test battery of Gustavsson.

Limb symmetry Index

All included studies used an LSI as their main outcome parameter, comparing the involved with the noninvolved leg. Noyes et al. described that an LSI of 85% or more would allow an athlete to return to his preinjury level. This was based on the findings that 93% of a healthy population scored an LSI of 85% or more.[6] Most researchers prefer to use an LSI of 90% or more as normal.[2,41,42,48,69] On the contrary, Asik et al.[5] describe an LSI of 80% or more as normal. Most studies use the LSI as an important outcome parameter but the cutoff points for return to sports differ. Recently Thomeé and coworkers discussed differences in LSI between pivoting/contact sports and non-pivoting/non-contact sports They suggested an LSI of more than 100% is required for knee extensor and knee flexor strength in pivoting/contact sports.[73] However, using the LSI is debatable because recent studies show that ACL injury could lead to a cross-over effect in the uninvolved leg resulting in strength and functional loss based on biomechanical and neuromuscular changes.[60,68] A small flexion angle when landing from a jump may also be present in the contralateral leg after ACL injury.[59] Landry et al.[38] suggest that a loss of afferent input from mechanoreceptors in the ACL injured or reconstructed knee will probably induce proprioceptive deficits in the contralateral leg.

Gender differences

Except for Laxdal et al.[42] who measured men, all studies examined both men and women and combined the results. No study described the differences between genders. Combining test results could lead to bias because previous studies show gender differences regarding biomechanical and functional performance. It is known that males are significantly stronger than females for knee extension and flexion strength.[14] During sport-specific movements in soccer Bencke et al.[9] described a lower pre-activation of the hamstrings prior to ground contact for females compares to males. Landry et al. showed an increased and imbalanced gastrocnemius muscle activity, combined with altered rectus femoris and hamstring muscle activity and reduced hip flexion angles and moments in female athletes during an unanticipated cutting maneuver. The differences suggest that the activation patterns observed in females might not be providing adequate joint protection and stability.[38,39] The extensive review of Renstrom et al.[59] supported these findings.

An important finding of this systematic review is the limited use of measurements to assess functional performance 2–7 years after ACL reconstruction and the fact that results of men and women were combined. Furthermore, all included studies reported quantitative data like distance in centimetres and peak torque in Newton-meter but none of them described the quality of movement (e.g. dynamic knee valgus or knee flexion angle). This is of great importance since it is known that landing from a jump with a higher extension moment leads to increased anterior directed shear forces and places the knee at risk for ACL injury.[59] Also landing with dynamic knee valgus is associated with a higher ACL injury risk.[17,53,59,73] Studies focussing on prevention showed that the risk for ACL injuries reduced when training the quality of performance.[3,31,46,54] For ACL injury screening Ekegren et al. examined dynamic knee valgus during a drop-jump task. The drop jump turned out to be a reliable and valid instrument in observing dynamic knee valgus.[17] Von Porat et al. investigated video-taped functional performance tests in ACL injured subjects. They concluded that observation of the single-leg hop for distance is a reliable and valid instrument for assessing knee flexion angles.[56]

Considering an ACL re-injury rate up to 12% within 2 years and a return to preinjury sport level of only 62%, it is still questionable whether men and women with BPTB or STG graft are fully recovered more than 2 years after their reconstruction.[41,62,77]

This review shows that there is no conclusive evidence for one test or method to measure functional performance after 2 years or even in an earlier stage of ACL rehabilitation. In addition, it is known that a battery of muscle strength tests as well as a battery of functional performance tests are reliable and superior to a single strength or functional test when it comes to discriminating between the operated and healthy leg.[28,49,72]

In accordance with these findings we postulate that in clinical practice a more extensive test battery should be used to assess both components of functional performance after ACL reconstruction. Based on the high demanding motor activities in sports the following items should be included:

- Concentric and eccentric (isokinetic) strength measurement of quadriceps femoris and hamstrings including an endurance test.
- At least 2 hop tests with preference for the test battery of Gustavsson et al.[28]
- Videotaping or observation of hop tests and the drop jump test to assess the quality of movement (i.e. knee flexion angles and dynamic knee valgus during landing).
- The LSI as a main outcome parameter should be used with caution and comparing the results with healthy controls is recommended.
- Not combining the results of men and women.
- Optimising methodological quality by blinding outcome assessors. This can be accomplished by using Tubigrip stockings covering both knees to disguise scars from reconstructive surgery.[2]

This test battery consists of quantitative and qualitative measurements and could be used in clinical practice to monitor the rehabilitation process and to predict whether athletes are still at risk if they return to sports. Further study should focus on the validity of this test protocol.

Limitations of the study

In this review there could be publication bias because of unpublished and/or ongoing research.

The data from the included studies alone did not allow any conclusions to be made for a test battery measuring functional performance. Therefore other studies, with unknown quality were used to complete the suggested test battery.

Conclusion

This review shows that in follow-up studies of more than 2 years after ACL reconstruction concentric and isometric strength measurements of quadriceps femoris and hamstrings were used and that the LSI was a main outcome parameter. No extensive research was carried out for endurance or eccentric strength. Concerning functional tests the single-leg hop for distance was used in all studies. No study described a combination of hop tests including a sideward or endurance component. Furthermore, no differences between men and women were described and no observation or videotaping was used to assess the quality of the single-leg hop test performance.

Because previous studies discuss additional important parameters a more extensive test battery is suggested to measure both the quantitative and qualitative aspects of functional performance after ACL reconstruction.

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Chapter 5

Functional performance 2–9 years after ACL reconstruction: cross-sectional comparison between athletes with bone–patellar tendon–bone, semitendinosus/gracilis and healthy controls

Nicky Engelen-van Melick
Robert E.H. van Cingel
Tony G. van Tienen
Maria W.G. Nijhuis-van der Sanden

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Abstract

Purpose: The purpose of this cross-sectional study was to provide descriptive data on functional performance in men and women with ACLR, to compare bone–patellar tendon– bone (BPTB) with semitendinosus/gracilis (STG) within the same sex and to compare the ACLR subjects with healthy controls.

Methods: Eligible participants comprised 100 men (43% BPTB) and 84 women (41% BPTB) after ACLR, of whom 30 men (STG n=19; BPTB n=11) and 18 women (STG n=12; BPTB n=6) were untraceable/not willing and 15 men (STG n=9; BPTB n=6) 15 women (STG n=12; BPTB n=3) were not able to take part in the measurements because of injury. Besides men BPTB (n=24), women STG (n=24), men STG (n=27), women BPTB (n=23) and women STG (n=23), healthy men (n=22) and women (n=22) participated. Measurements consisted of questionnaires, isokinetic peak torque and endurance tests, a hop test battery and drop jump including video analysis.

Results: Only the occurrence of dynamic knee valgus differed between ACLR and healthy subjects.

Conclusion: Two to nine years after ACLR, 16% of athletes could not participate because of a lower extremity injury. In the remaining group, this study showed similar results for males and females with BPTB compared with STG. Also, similar results are found for quantity of movement comparing operated and healthy subjects. For quality of movement, only the occurrence of dynamic knee valgus in landing from a jump is higher in operated subjects compared with healthy controls. This supports the relevance of a focus on quality of movement as part of ACLR rehabilitation programmes and return to sports criteria.

Introduction

For most athletes, rehabilitation after anterior cruciate ligament reconstruction (ACLR) is only successful if they return to their previous level of sports. Recent research, however, shows that 35% of athletes do not return to this level within 2 years.[4,48] After 3 or more years, this number even increases to 50%.[5,31,32] Half of these athletes report their ACL injury as the primary reason for a lower activity level.[4,5,12,32] Moreover, athletes who do return to their previous level have a considerable risk of tearing the graft or the contralateral ACL within the first 2 years; 3–22% of athletes re-rupture the reconstructed ligament, and 3–24% rupture the contralateral ACL.[3,8,12,43,47,51,59]

It is still unclear which measurements should be used to determine whether athletes are able to return to (pivoting) sports safely or whether they are still at risk after finishing rehabilitation.[8,9,19] In view of the above numbers, it is necessary to evaluate the functional performance of athletes before they return to their previous level of sports. Functional performance has both quantitative and qualitative components.[19] The quantity of movement can be determined by, for example, muscle strength or distance hopped on one leg.[2] The quality of movement can, for instance, be defined by the occurrence of dynamic knee valgus, the amount of knee flexion or (lateral) flexion of the trunk when an athlete is landing from a jump.[18,19,57] Previous research showed that the presence of dynamic knee valgus in landing from a jump and deficits in neuromuscular control of the trunk can predict ACL injury in healthy athletes.[24,60] Recently, Paterno et al.[42] analysed landing techniques of athletes returning to sport after ACLR. They found that the occurrence of dynamic knee valgus and an asymmetric internal knee extensor moment when landing are predictive for ACL re-rupture. It can be concluded that both the quantitative and qualitative components of functional performance are important in rehabilitation after ACLR and prevention of (re)injuries.[24,42,46,53]

The majority of follow-up studies on functional performance after ACLR last up to 2 years; long-term follow-up results on functional performance are scarce and limited to quantitative measurements. In most short-term follow-up studies, the results for men and women or different types of autografts are combined and comparisons are made with the contralateral leg instead of healthy controls. Considering this lack of the literature about both quantitative and qualitative components of functional performance more than 2 years after ACLR, the purpose of this study was to provide descriptive data for both components of functional performance in men and women with ACLR and healthy controls and to compare: (1) men who underwent ACLR using bone–patellar tendon–bone graft (BPTB) with men who underwent ACLR using semitendinosus/gracilis graft (STG), (2) women BPTB with women STG, (3) operated men with healthy men and (4) operated women with healthy women. To our knowledge, this is the first study to investigate these four operated groups separately in comparison with healthy controls more than 2 years after ACLR. The results of this study could be relevant for rehabilitation of athletes with ACLR.

Materials and methods

All subjects (n=184) who underwent rehabilitation at Sports Medical Center Papendal (Arnhem, the Netherlands) after a unilateral ACLR with BPTB or STG technique between January 2002 and August 2008 were approached for this cross-sectional study. Subjects underwent surgery in two different hospitals (Rijnstate Arnhem and Sint Maartenskliniek Nijmegen, the Netherlands) and followed a standardised rehabilitation protocol.[56]

Subjects with traumatic cartilage damage in the operated knee or a lower extremity injury at the time of the measurements were excluded from the study, but subjects with concomitant meniscectomy or collateral ligament tears at the time of surgery were included.

Of the 184 operated subjects, 30 subjects (16%) were not able to participate in this study because of lower extremity injuries that prevented them from performing the measurements. These injuries were: re-injuries to the operated knee (n=7: one recent notch plasty, two focal cartilage damage, one posteromedial instability, two osteoarthritis and one patella luxation), other injuries to the operated leg (n=9: two ankle distortion, one fracture of the femur, four patellofemoral dysfunction, one Sudeck's dystrophy and one shin splint), injuries to the contralateral ACL (n=4: four recent ACL ruptures) or other injuries to the contralateral leg (distortions, two shin splints and one patellofemoral n=10: five meniscectomies, two ankle dysfunction).

Another 31 were untraceable, and 17 had no time to participate in the study.

Finally, 97 operated subjects were able and willing to participate in the study (Figures 1, 2; Table 1). These operated subjects were divided into four groups: men with BPTB (n=24), men with STG (n=27), women with BPTB (n=23) and women with STG (n=23). Measurements were taken between December 2009 and October 2010.

In addition, 22 healthy men and 22 healthy women, matched for age, height and weight to the operated groups, participated as controls (Table 1). The exclusion criteria for healthy controls were a lower extremity or back injury in the past 6 months, lower extremity or back operation in the past 3 years or ACL injury or reconstruction in the past. Healthy controls were measured between March and August 2011. All subjects gave their written informed consent to their inclusion in this study. The study was approved by the CMO Arnhem/ Nijmegen (no. 2011/186).

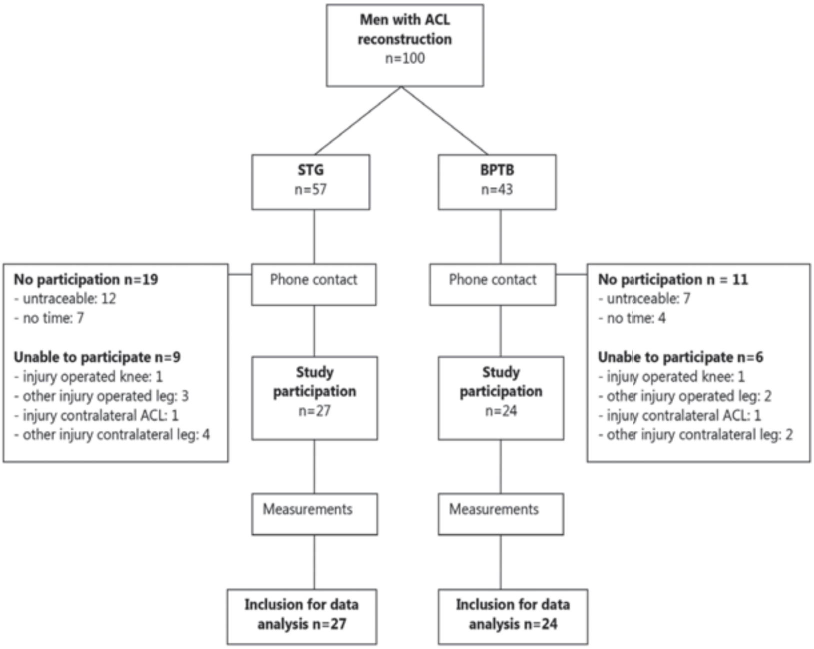

Figure 1: *Flow chart of men BPTB and STG.*

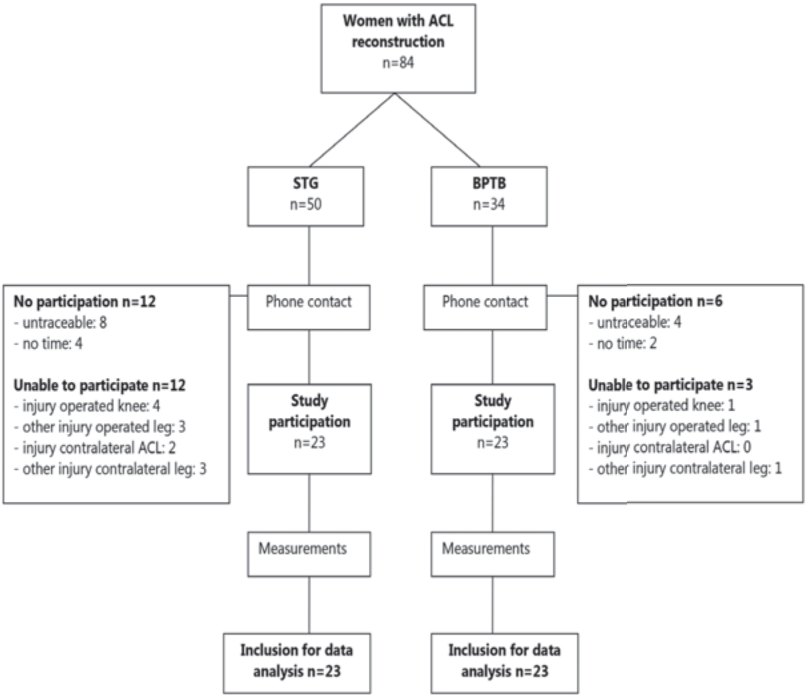

Figure 2: *Flow chart of women BPTB and STG.*

Table 1: *Demographic variables of study groups.*

	MEN				WOMEN			
	BPTB	**STG**	**Healthy**	**p-value‡**	**BPTB**	**STG**	**Healthy**	**p-value‡**
N	24	27	22	-	23	23	22	-
Follow-up in months mean(sd); range	63.5(23.3); 27.0-106.0	41.1 ± 13.5; 25.0-79.0	-	0.000	64.8 ± 25.3; 25.0-100.0	52.0 ± 20.6; 25.0-88.0	-	0.066
Age in years mean (sd); range	36.9 (8.9); 22.0-53.0	37.6 ± 9.8; 19.0-64.0	35.5 ± 10.6; 21.0-52.0	0.748	36.0 ± 11.0; 19.0-53.0	33.5 ± 10.0; 18.0-51.0	31.5 ± 11.9; 19.0-58.0	0.386
Height in meters mean (sd); range	1.83 (0.08); 1.68-1.97	1.83 ± 0.08; 1.67-1.99	1.81 ± 0.06; 1.65-1.90	0.515	1.72 ± 0.08; 1.58-1.85	1.71 ± 0.07; 1.60-1.85	1.70 ± 0.05; 1.60-1.80	0.566
Weight in kilograms (mean ± sd; range)	85.3 (11.3); 70.0-110.0	87.4 ± 12.5; 69.0-127.0	79.6 ± 9.5; 61.0-95.0	0.053	68.7 ± 14.5; 50.0-112.0	68.8 ± 15.3; 50.0-132.0	67.2 ± 11.1; 54.0-96.0	0.912
BMI in kg/m^2 (mean ± sd; range)	25.4 ± 2.4; 20.9-31.0	25.9 ± 2.7; 20.8-34.5	24.3 ± 2.42; 18.9-29.0	0.062	23.2 ± 4.3; 19.1-36.6	23.1 ± 4.1; 17.5-38.6	23.3 ± 3.2; 18.7-30.0	0.994
IKDC in % (mean ± sd; range)	87.7 ± 11.1; 49.4-100.0*	86.6 ± 8.7; 66.6-100.0*	97.3 ± 4.7; 83.9-100.0	0.000	89.2 ± 10.2; 51.7-100.0	90.4 ± 6.0; 77.0-100.0	94.9 ± 10.4; 66.7-100.0	0.091
Tegner (mean ± sd; 95%CI)	5.7 ± 1.1; 5.3-6.2	5.3 ± 2.0; 4.5-6.1	5.2 ± 1.5; 4.5-5.9	0.520	4.9 ± 1.5; 4.2-5.5	4.9 ± 1.7; 4.2-5.6	4.8 ± 1.2; 4.3-5.3	0.967

BPTB=bone-patellar tendon-bone graft, STG=semitendinosus/gracilis graft, sd=standard deviation, CI=confidence interval
** differs significantly from healthy controls*
‡ p-value from between group comparisons (ANOVA)

Assessments and questionnaires

All follow-up assessments were performed by the same physical therapist. First, subjects completed the International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form and the Tegner Activity Scale (TAS) (Table 1). Before the assessment of the quantity and quality of movement, reflectorised tape was placed on both legs of the subjects on the following bony landmarks: the lateral malleolus, the lateral femoral condyle, the greater trochanter, the midpoint of the patella and the distal phalange of the hallux. Then, subjects were given a 10-min warm-up session on a bicycle ergometer (75 W, 70–80 rpm). The quantity and quality of movement were assessed with an extensive test battery previously described.[19]

Assessment of quantity of movement

Participants accomplished single-leg hop tests and isokinetic strength tests for knee extensors and flexors. The first leg to be tested was randomly assigned.

Single-leg vertical jump, single-leg hop for distance and single-leg side hop
The three single-leg hop tests were performed according to Gustavsson et al.[23] Their hop test battery has a sensitivity of 91%. The vertical jump was performed on a ProJump contact mat (Biometrics, the Netherlands). For the vertical jump and hop for distance, subjects performed two submaximal practice sessions and three maximal test sessions for both legs. For the side hop, subjects were allowed to perform a few practice jumps to familiarise themselves with the jumping distance, before they performed the test session.

Between different hop test, subjects had a 5-minute rest period; between practice and test sessions, the rest period was 2 minutes.

Strength measurement
To measure isokinetic strength of the knee extensors and flexors, a Humac (Cybex) Norm dynamometer (CSMi, Stoughton, MA, USA) was used with machine settings as described before.[16,27,45,55] Three concentric tests and two eccentric tests were performed. To become familiar with the apparatus and to exclude any change as a result of practice-based improvement, subjects performed a specific warm-up of three submaximal and two maximal trials at each test velocity.[55]

Concentric extension/flexion was tested three times: three repetitions at 60°/s, five repetitions at 180°/s and 20 repetitions at 180°/s (endurance test). Five repetitions of eccentric extension and flexion were performed at 60°/s. Except for the endurance test, for which total work was extracted, peak torque was recorded as the main value for data analysis. Peak torque values have a high test–retest reliability for both concentric (ICC 0.82–0.91) and eccentric (ICC 0.82–0.86) knee extensor and flexor measurements.[14] Strength values were not normalised to body weight. Also, three different ratios were calculated:

- the conventional ratio (CVR) (hamstrings concentric divided by quadriceps concentric = Hconc/Qconc or H/Q), ICC 0.65–0.79;[27]
- the intramuscular ratio of the quadriceps (IRQ) (quadriceps eccentric divided by quadriceps concentric = Qecc/Qconc);
- the dynamic control ratio (DCR) (hamstrings eccentric divided by quadriceps concentric = Hecc/Qconc), ICC 0.80–0.87.[27]

Between each test, subjects were given a 45-second rest period; between concentric and eccentric tests, the rest period was 5 minutes.

Assessment of quality of movement

Two-dimensional video footage of the single-leg vertical jump and single-leg hop for distance was analysed with Templo Motion Analysis software (Biometrics, the Netherlands). The 2D video footage was chosen instead of a 3D method, because a 2D method can be easily implemented in everyday practice.

In addition to the single-leg hop tests, a drop jump was performed. Previous studies show that 2D analysis has a high test–retest reliability (ICC 0.72–0.91) and that it is valid for measuring dynamic knee valgus and knee flexion angles.[18,34-37,40,41] Subjects were instructed to drop down onto the floor from a platform 31 cm high and immediately to perform a maximum vertical jump.[18] Subjects performed the jump with both legs, and arm swing was allowed. Two practice trials were allowed before the three test sessions were executed. The drop jump test was used to register dynamic knee valgus and knee flexion angle at the first landing. Subjects were not instructed about its purpose.

Frontal plane video analysis
Frontal plane video analysis was used to measure dynamic knee valgus. Dynamic knee valgus was defined as the midpoint of the patella moving inward and ending up medial to the hallux. There was no dynamic knee valgus when the patella remained in line with the first toe.[18] Dynamic knee valgus was measured during the following tests:

- all three vertical jump test sessions at take-off and landing (at peak knee flexion);
- all three hop for distance test sessions at take-off and landing (at peak knee flexion);
- all three drop jump test sessions when landing from the ‘drop’ before performing the maximal vertical jump (at peak knee flexion).

A subject was qualified as having dynamic knee valgus in a specific test when at least two out of three sessions were scored positive.

Sagittal plane video analysis
Sagittal plane video analysis was used to measure knee flexion angle during landing. The knee flexion angle was recorded as the angle between the dorsal femur (line from greater trochanter to lateral femoral condyle) and the dorsal tibia (line from lateral femoral condyle to lateral malleolus).

The peak knee flexion angle when landing was measured during the following tests:

- all three hop for distance test sessions. Both legs were measured separately;
- all three drop jump test sessions when landing from the 'drop' before performing the maximal vertical jump; only the operated leg was filmed and thus measured.

The mean flexion angle of three test sessions was recorded for data analysis.[24,42]

Statistical analysis

To detect a 10° between-group difference in knee flexion angle in landing from a jump (with a standard deviation of 10°), with 90% power at the 5% significance level, a sample size calculation estimated that at least 22 subjects per group would be needed (Power and Sample Size Calculation version 3.1.2). In this study, the observed within-group standard deviation varied from 7° to 16°.

Data analysis was performed with IBM SPSS Statistics 19.0. Because no significant differences were found between the left and right legs of healthy controls, the mean of the left and right leg was used for analysis. To account for differences in follow-up time between BPTB and STG, a linear regression analysis was used to determine whether there was an effect of follow-up time and whether this was different between groups. Then, for the variables where no effect of follow-up time was found, a one-way ANOVA was used and if it was statistically significant, Bonferroni's post hoc analysis was used: the mean score of the healthy controls was compared with that of both the operated leg and nonoperated leg of the male BPTB and STG groups. This sequence of analyses was performed for males and females separately. For dynamic knee valgus, the operated leg and non-operated leg within a group were compared with a Chi-square test. For comparison between operated and healthy subjects, descriptive statistics were used to outline differences.

Results

All 184 eligible subjects followed a strict rehabilitation protocol after ACLR at our clinic, but 16% (n=30) of them were excluded because of an injury at the time of testing, and therefore, they were unable to perform the measurements. In the male STG group, 16% were unable to perform the test, in the male BPTB group 14%, in the female STG group 24% and in the female BPTB group 9%. Another 30 men (STG 33%; BPTB 26%) and 18 women (STG 24%; BPTB 18%) were untraceable/ not willing to participate (Figs. 1, 2). Table 1 summarises the demographic variables of the six participating groups, including the IKDC questionnaire and TAS. All results for quantitative measurements are listed in Table 2 for men and Table 3 for women. All results for qualitative measurements are listed in Tables 2 (knee flexion angles) and 4 (dynamic knee valgus) for men and Tables 3 (knee flexion angles) and 5 (dynamic knee valgus) for women.

The most important differences are listed below.

1. Men BPTB versus men STG (Tables 1, 2)
    - Time to follow-up in months is significantly longer for men BPTB compared with men STG. Regression analysis showed that follow-up time had a significant effect on outcome for six variables: the conventional H/Q ratio at 60°/s for the non-operated leg (decreasing in time for STG, increasing for BPTB), quadriceps strength at 180°/s for the non-operated leg (decreasing for both STG and BPTB), the conventional H/Q ratio at 180°/s for the non-operated leg (decreasing in time for STG, increasing for BPTB), quadriceps strength at the 180°/s endurance test for both the operated leg and non-operated leg (both decreasing in time for STG and BPTB) and hamstring power at the 180°/s endurance test for the operated leg (decreasing in time for both STG and BPTB
2. Women BPTB versus women STG (Table 3)
    - Regression analysis showed that follow-up time had a significant effect on outcome for seven variables: hamstring strength at 180°/s for the operated leg (decreasing in time for STG, increasing for BPTB), quadriceps strength at the 180°/s endurance test for the operated leg (decreasing in time for STG, increasing for BPTB), hamstring strength at the 180°/s endurance test for both the operated leg and non-operated leg (both decreasing in time for STG, but increasing for BPTB), eccentric hamstring strength for the non-operated leg (increasing in time for both STG and BPTB), non-operated knee flexion angle at the hop for distance (decreasing in time for STG, increasing for BPTB) and drop jump knee flexion angle 9 decreasing in time for STG, increasing for BPTB).

- Women STG have dynamic knee valgus significantly more often than women BPTB on the vertical jump, both at take-off and during landing.

3. Operated men versus healthy men (Tables 2, 4)
    - For strength measurements, all significant differences in peak torque and total work are in favour of the operated men.
    - Fifty percent of the operated men BPTB had dynamic knee valgus in the operated leg, compared with 41% of the operated men STG and 27% of the healthy men. The non-operated legs showed 38% and 30% dynamic knee valgus, respectively, for the BPTB and STG male groups.
4. Operated women versus healthy women (Tables 3, 5)
    - For strength measurements, all significant differences in peak torque and total work are in favour of the operated women.
    - Of the women BPTB and STG, 74% and 78%, respectively, had dynamic knee valgus in their operated legs, compared with 66% of the healthy women. Their non-operated legs showed 70% (BPTB) and 57% (STG) dynamic knee valgus.

Discussion

This study shows that 2–9 years after ACLR, 16% of the athletes could not be measured, because of lower extremity injuries. A higher number of the female STG group (24%) was injured at the time of testing than in the other three ACLR groups (9–16%).

In all subjects whose quantity and quality of performance was measured, the most important finding was that they had more dynamic knee valgus when landing from a jump than did healthy subjects. Almost no differences were found for isokinetic strength measurements and single-leg hop tests. Although this study is of a lower level of evidence (III), it is the first study to measure the four operated groups separately in comparison with healthy controls more than 2 years after ACLR.

The use of healthy subjects as controls, instead of the non-operated leg, meant a potential cross-over effect could be eliminated. However, the literature comparing ACLR patients with healthy controls at a follow-up of more than 2 years is scarce, and generally the main outcome parameter is based on quantitative assessments comparing the operated leg with the nonoperated leg.

Table 2: *Comparison of healthy men with men BPTB and STG for quantitative parameters and knee flexion angle.*

		♂ BPTB		♂ Healthy	♂ STG	
		OP	**NOP**		**OP**	**NOP**
60 °/sec Conc PT (3 reps) (Nm)	**Q**	198 ± 34	198 ± 32	183 ± 31	213 ± 46*	204 ± 34
	H	147 ± 21	145 ± 23	134 ± 23	147 ± 32	148 ± 30
	H:Q	756 ± 10	75 ± 15	74 ± 10	70 ± 14	74 ± 13
180 °/sec Conc PT (5 reps) (Nm)	**Q**	142 ± 26*	142 ± 25*	127 ± 23	149 ± 29*	149 ± 23*
	H	114 ± 17*	112 ± 21	107 ± 23	115 ± 21	117 ± 26
	H:Q	82 ± 9	79 ± 11	84 ± 12	77 ± 8	78 ± 11
180 °/sec Conc TW (20 reps) (Nm)	**Q**	2506 ± 542	2569 ± 539	2008 ± 387	2637 ± 523*	2686 ± 428*
	H	2198 ± 543	2112 ± 501	1769 ± 410	2051 ± 382	2259 ± 485*
	H:Q	88 ± 13	83 ± 11	89 ± 17	79 ± 12*	84 ± 13
60 °/sec Ecc PT (5 reps) (Nm)	**Q**	236 ± 50	228 ± 51	206 ± 58	246 ± 59	244 ± 61
	H	175 ± 35	174 ± 29	161 ± 36	182 ± 42	172 ± 40
IRQ (Qexc:Qconc)		119 ± 17	117 ± 28	113 ± 23	118 ± 24	120 ± 24
DCR (Hexc:Qconc)		90 ± 21	90 ± 25	89 ± 19	88 ± 25	85 ± 17
Vertical jump (m)		0.14 ± 0.04	0.15 ± 0.05	0.16 ± 0.04	0.14 ± 0.04	0.15 ± 0.04
Hop for distance (m)		1.20 ± 0.21	1.22 ± 0.20	1.24 ± 0.35	1.13 ± 0.28	1.20 ± 0.24
Side hop (N)		30 ± 13*	33 ± 10	41 ± 16	32 ± 13	32 ± 14
Knee flexion angle hop for distance		56 ± 147	58 ± 16	62 ± 16	56 ± 12	56 ± 10
Knee flexion angle drop jump		85 ± 17		84 ± 16	91 ± 19	

BPTB=bone-patellar tendon-bone graft, STG=semitendinosus/gracilis graft, OP=operated leg, NOP=non-operated leg, PT=peak torque, TW=total work, Conc=concentric, Ecc=eccentric, Q=m. quadriceps femoris, H=hamstrings, H:Q=conventional ratio, IRQ=intramuscular ratio quadriceps, DCR=dynamic control ratio, reps=repetitions

** differs significantly from healthy controls*

Table 3: *Comparison of healthy women with women BPTB and STG for quantitative parameters and knee flexion angle.*

		♀ BPTB		♀ Healthy	♀ STG	
		OP	NOP		OP	NOP
60 °/sec Conc PT (3 reps) (Nm)	**Q**	132 ± 28	147 ± 29*	123 ± 30	139 ± 24	141 ± 27
	H	93 ± 17	94 ± 20	87 ± 15	93 ± 15	99 ± 15*
	H:Q	71 ± 13	64 ± 11	72 ± 14	68 ± 8	72 ± 9
180 °/sec Conc PT (5 reps) (Nm)	**Q**	83 ± 17	93 ± 22	80 ± 21	93 ± 15*	92 ± 15*
	H	70 ± 15	71 ± 14	66 ± 12	70 ± 12	76 ± 11*
	H:Q	86 ± 14	78 ± 16	87 ± 20	76 ± 8	84 ± 10
180 °/sec Conc TW (20 reps) (Nm)	**Q**	1332 ± 282	1425 ± 365	1237 ± 383	1577 ± 351*	1561 ± 356*
	H	1292 ± 301	1265 ± 250	1102 ± 263	1302 ± 275*	1429 ± 257*
	H:Q	99 ± 24	93 ± 22	97 ± 32	83 ± 10	94 ± 14
60 °/sec Ecc PT (5 reps) (Nm)	**Q**	152 ± 32	167 ± 40	148 ± 40	155 ± 31	164 ± 35
	H	123 ± 31*	125 ± 31*	103 ± 21	114 ± 25	123 ± 28*
IRQ (Qexc:Qconc)		117 ± 23	114 ± 21	123 ± 36	113 ± 19	118 ± 218
DCR (Hexc:Qconc)		95 ± 28	86 ± 18	88 ± 26	83 ± 16	88 ± 17
Vertical jump (m)		0.12 ± 0.04	0.13 ± 0.04	0.11 ± 0.03	0.11 ± 0.04	0.12 ± 0.04
Hop for distance (m)		0.93 ± 0.26	1.02 ± 0.21	0.92 ± 0.26	0.90 ± 0.23	0.94 ± 0.24
Side hop (N)		18 ± 8	23 ± 9	23 ± 125	22 ± 13	25 ± 12
Knee flexion angle hop for distance		51 ± 12	53 ± 12	58 ± 9	56 ± 11	54 ± 7
Knee flexion angle drop jump		80 ± 14		76 ± 15	79 ± 20	

BPTB=bone-patellar tendon-bone graft, STG=semitendinosus/gracilis graft, OP=operated leg, NOP=non-operated leg, PT=peak torque, TW=total work, Conc=concentric; Ecc=eccentric, Q=m. quadriceps femoris, H=hamstrings, H:Q=conventional ratio, IRQ=intramuscular ratio quadriceps, DCR=dynamic control ratio, reps=repetitions

** differs significantly from healthy controls*

Table 4: *Comparison of healthy men with men with men BPTB and STG for dynamic knee valgus.*

		♂ BPTB		p-value‡	♂ Healthy		♂ STG		p-value‡
		OP	NOP		L	R	OP	NOP	
Vertical jump	T	8.3	4.2	ns	9.1	4.5	14.8	7.4	ns
% dynamic knee valgus	L	0.0	0.0	-	4.5	0.0	0.0	3.7	ns
Hop for distance	T	12.5	4.2	ns	4.5	18.2	14.8	11.1	ns
% dynamic knee valgus	L	0.0	0.0	-	4.5	0.0	0.0	3.7	ns
Drop jump % dynamic knee valgus		50.0	37.5	ns	31.8	22.7	40.7	29.6	ns

BPTB=bone-patellar tendon-bone graft, STG=semitendinosus/gracilis graft, OP=operated leg, NOP=non-operated leg, T=take-off, L=landing, % dynamic knee valgus=percentage of subjects with dynamic knee valgus
‡ p-value from comparison between operated and non-operated leg

Table 5: *Comparison of healthy women with women BPTB and STG for dynamic knee valgus.*

		♀ BPTB		p-value‡	♀ Healthy		♀ STG		p-value‡
		OP	NOP		L	R	OP	NOP	
Vertical jump	**T**	4.3	8.7	ns	4.5	13.6	21.7	4.3	ns
% dynamic knee valgus	**L**	0.0	0.0	-	4.5	0.0	17.4	4.3	ns
Hop for distance	**T**	21.7	4.3	ns	9.1	27.3	26.1	8.7	ns
% dynamic knee valgus	**L**	8.7	0.0	ns	0.0	4.5	13.0	0.0	ns
Drop jump % knee dynamic valgus		73.9	69.6	ns	54.5	77.3	78.3	56.5	ns

BPTB=bone-patellar tendon-bone graft, STG=semitendinosus/gracilis graft, OP=operated leg, NOP=non-operated leg, T=take-off, L=landing, % dynamic knee valgus=percentage of subjects with dynamic knee valgus
‡ p-value from comparison between operated and non-operated leg

Questionnaires

The IKDC questionnaire represents the individual's own perception of the operated knee. The operated male groups had a significantly lower IKDC score than the healthy males, suggesting a worse subjective knee function. On the other hand, TAS is similar for operated and healthy males, meaning they have a comparable level of activity. This could mean that the operated males still have some knee complaints (pain, stiffness, locking or giving way), but after all still participate in a recreative or competitive (pivoting) sport.

Quantity of movement

During rehabilitation, most physical therapists place the emphasis on quantity of movement. Since it is known that fatigue may reduce dynamic knee stability and therefore could be a causal factor in ACL (re)injuries, a concentric endurance test of 20 repetitions at 180°/s was also included in our strength-testing protocol.[13,21,25,33,52,54,58,61] We found no significant differences in the endurance strength between the BPTB and STG groups, but an influence of follow-up time on almost all parameters. However, the effect of time on endurance strength is clinically a small effect. Similarly, Taylor et al.[50] performed an endurance test of 20 repetitions at a test velocity of 300°/s comparing a BPTB group and an STG group at 2- to 5-year follow-up and found no differences between these two groups. Their results were combined for men and women and were not compared with healthy controls.

Whereas concentric muscle actions function primarily to move body parts, eccentric actions function to decelerate and control skeletal motion and joint stability. This holds especially for demanding motor tasks (i.e. sport activities) where high forces occur in different positions and where dynamic joint stability is required during the total range of motion.[39] During running, 80% of hamstring activity is eccentric, and landing after a jump requires eccentric contractions of the quadriceps femoris.[10,11,15,16,49] Moreover, pivoting sports like soccer, handball or basketball require frequent accelerating and decelerating movement patterns, putting high demands on eccentric activity of leg muscles.[22,29] In normal physiology, eccentric strength is expected to be higher than concentric strength within the same muscle.[29] The IRQs can be used to assess this relation (Q_{ecc}/Q_{con}). In our study, we found no significant differences between operated groups and between operated groups and healthy controls. Overall, the range of the IRQ was 113-120% for men and 113-123% for women. Hiemstra and colleagues also measured concentric and eccentric strength in 16 male and female ACLR subjects 40 months after STG reconstruction. At a test velocity of 50°/s, their IRQ was 117-125% compared with 122% for healthy male controls.[26]

Also, ratios between agonist and antagonist muscles could be used to assess components of dynamic joint stability. The most well known is the conventional

H/Q ratio (CVR; H_{conc}/Q_{conc}). Conversely, the DCR is a more functional approach to assessing muscle function (H_{ecc}/Q_{conc}). The DCR is particularly significant in situations where the agonist and antagonist are working simultaneously to avert potential jeopardy to the joint (e.g. pivoting sports).[17] With regard to the CVR at both 180°/s tests, we found a significant decrease for the operated leg of women STG compared with women BTPB (Table 3). This difference is mainly the result of higher quadriceps strength. For the DCR, we found no significant differences between STG and BPTB groups and between operated groups and healthy controls. Overall, the range of the DCR was 85-90% for men and 83-95% for women. CVRs and DCRs in this study were comparable with previous studies measuring male and female athletes of the same age.[1,44,45] Jenkins and colleagues described a healthy female soccer population and found DCRs of 84-89% at 60°/s.[28] The DCR is expected to be higher than the conventional H/Q ratios, because eccentric hamstring strength should be higher than concentric hamstring strength. In our study, CVRs for men and women at 60°/s were 64-76% and DCRs were 83-95%.

Besides muscle strength, single-leg hop tests are also a common way of measuring quantity of movement. Several studies showed that the sensitivity of single-leg hop tests increases when two or more different tests are performed.[6,7] The hop test battery of Gustavsson and colleagues consisting of three single-leg hop tests is known to have a high ability to discriminate between the injured and uninjured leg for patients who have undergone ACL reconstruction. The side hop test is a sideward endurance test which places a high demand on knee stability and has the highest ability to discriminate between the injured and uninjured leg.[19,23] In our study, only the side hop test for the operated leg of men BPTB showed a significant difference of ten hops from healthy controls. The non-operated leg of this group and both legs of the men STG also differed by eight to nine hops compared with the healthy controls. These differences were not significant, but could be of clinical importance.

Quality of movement

The quality of movement can be defined by the occurrence of dynamic knee valgus, the amount of knee flexion or (lateral)flexion of the trunk in landing from a jump.[18,19,57] In quality of movement, neuromuscular control plays an essential role and has no direct correlation with quantitative factors like muscle strength measured in an isokinetic condition and therefore should be tested separately.[19] This is confirmed in this study. Also, the quality of movement is often underexposed during rehabilitation and is known to be a risk factor for ACL (re)injuries.[20,24,42,46,60] To assess the quality of movement, we included video analysis of the vertical jump, hop for distance and drop jump. All three tests are used in previous research to provide a qualitative assessment of an athlete's ability to control the upper and lower extremity upon landing, but are often only used for quantity of performance when measuring patients rehabilitating after ACLR.[8,24,42] In our study, the knee flexion angle during landing did not differ between operated groups and between operated groups and healthy controls. The knee flexion angle range for men was 84°–91° for the drop jump and 56°–62° for the hop for distance. For women, these ranges were 76°–80° and 51°–58°, respectively. For dynamic joint stability after landing from a jump, Padua and colleagues showed that the quadriceps and hamstring muscles produce sufficient coactivation at flexion angles of 30° and more.[39,40] Nyland and colleagues measured 35 men and 35 women at a mean of 5.3 years after allograft ACLR. Subjects had to perform a single-leg vertical jump. Their knee flexion angles were similar to those we found for the hop for distance. For men, flexion angles were 57°, and for women, the flexion angles were 51°.[38] Their population was comparable to ours in terms of anthropometric characteristics and activity level.

Concerning dynamic knee valgus, our results show that operated subjects more often have dynamic knee valgus than healthy controls on the drop jump test, but because we have no preoperative data, it is unknown whether they already had a dynamic knee valgus before their ACL reconstruction. However, this study supports the importance of quality of movement measurements as part of rehabilitation after ACLR or the prevention of (re)injuries.

A limitation of this study is that we only measured ACLR subjects without complaints. Of all 184 eligible subjects, 16% could not participate because of a lower extremity injury. As a result, this study only represents the functional performance results of the ACLR subjects who are doing well at long-term follow-up. Besides, to account for the effect of follow-up time, linear regression analysis was used. For the male groups, there were six variables where follow-up time had a significant effect on outcome; for the females, seven variables were significantly influenced by follow-up time. Third, it should be noted that this study was not concerned with trunk (lateral)flexion, pelvic drop and gluteal strength, although these are important factors in lower extremity control during landing from a jump and injury prevention.[30,41,60]

Conclusion

Two–nine years after ACLR, 16% of the athletes could not be measured, because of lower extremity injuries. In the measured group, this study showed, in general, that quantity of movement is similar for males and females with BPTB and STG and is comparable to healthy controls. For quality of movement, only the occurrence of dynamic knee valgus in landing from a jump differs between operated and healthy subjects. This supports the relevance of a focus on quality of movement as part of ACLR rehabilitation programmes and return to sport criteria.

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Chapter 6

Less than half of ACL-reconstructed athletes are cleared for return to play based on practice guideline criteria: results from a prospective cohort study

Nicky van Melick
Thomas J. Hoogeboom
Yvette Pronk
Bas Rutten
Tony G. van Tienen
Maria W.G. Nijhuis-van der Sanden
Robert E.H. van Cingel

Submitted

Abstract

Objective: To analyse if physical therapists adhere to anterior cruciate ligament reconstruction (ACLR) practice guideline return to play (RTP) criteria, and to explore whether there is a difference in adherence between physical therapists specialised in sports or not.

Design: Prospective observational cohort study.

Setting: Secondary care.

Participants: Pivoting athletes (preinjury Tegner Activity Scale ≥6), scheduled for ACLR. Athletes were excluded if they underwent revision ACLR surgery, had a contralateral ACL injury or ACLR in the past.

Interventions: When the treating physical therapist cleared an athlete for RTP after ACLR, the primary researcher performed RTP measurements according to the ACLR practice guideline to investigate if RTP criteria were met. Main outcome measures: seven quantitative and two qualitative functional performance tests.

Results: Of the 158 athletes (54 females, mean age 24±6 years, 12±3 months after surgery), 69 (44%) were tested by their treating physical therapist. Of those, 23% met all RTP criteria compared to 10% of the athletes not tested (p=0.026). Of the athletes rehabilitated by a sports physical therapist, 52% was tested by their own physical therapist compared to 34% of the athletes who were rehabilitated by a non-sports physical therapist (p=0.024).

Conclusions: Although sports physical therapists more often adhered to the guideline compared to non-sports physical therapists, the adherence is still alarmingly low. More attention for the implementation of the ACLR guideline is needed. It might be useful to inform pivoting athletes about RTP criteria after ACLR by providing them insight and autonomy during rehabilitation and the RTP decision.

Introduction

For most pivoting athletes after anterior cruciate ligament reconstruction (ACLR), return to the preinjury sport level is the desired endpoint of rehabilitation.[1] A recently published Dutch practice guideline describes the rehabilitation process after ACLR and emphasizes that it should be criterion-based instead of time-based. As a consequence of this criterion-based rehabilitation, return to play should only be allowed when meeting the specific return to play (RTP) criteria as mentioned in the guideline.[16,17]

Even though it is advocated to use criterion based decisions on RTP,[16,17] the proportion of ACLR patients meeting RTP criteria when cleared to return to pivoting sports is extremely low. In Sweden, only 20% of adults and 28% of adolescents that already returned to play met quantitative RTP criteria 12 months after ACLR, while in the USA only 14% of adolescent athletes met quantitative RTP criteria when cleared for RTP.[2,32] Besides using RTP measurements for movement quantity (strength tests and single-leg hop tests), the Dutch ACLR practice guideline also highlights using movement quality measurements (single-leg hop-and-hold and double-leg countermovement jump) as RTP criteria to decrease second ACL injury risk.[5,10,18,25]

The ACLR practice guideline was developed commissioned by the Royal Dutch Society for Physical Therapy (KNGF) and should therefore be used by every Dutch physical therapist, regardless of their experience with pivoting athletes recovering from ACLR.[16,17] However, it remains to be seen whether the guideline has been properly implemented in clinical practice so that every physical therapist is able to work according to the guideline.

Therefore, the first aim of this study was to analyse if Dutch physical therapists follow the RTP criteria as defined in the ACLR practice guideline when clearing a pivoting athlete for RTP. This first aim is divided into two questions: 1) Do physical therapists use RTP measurements to guide RTP decision?, and 2) Do physical therapists correctly advise pivoting athletes to RTP based on the test results? The hypothesis is that most Dutch physical therapists are able to use the RTP measurements and know when to clear an athlete for RTP, since the practice guideline has been implemented by the KNGF in 2014 making it publicly available to all Dutch physical therapists. The second aim was to explore whether sports physical therapists perform better in practice guideline RTP measurement adherence than their colleagues without documented sports specialization. We hypothesize that sports physical therapists have a better adherence to the guideline, because they perform the RTP measurements more frequently and, in the Netherlands, have had additional education about pivoting athletes and RTP.

Methods

Design and participants

In this prospective observational cohort study, pivoting athletes with an ACL rupture (preinjury Tegner Activity Scale (TAS) ≥6)[6], aged 16-50 years, and scheduled for an ACLR between October 2014 and December 2016 were asked to participate. Athletes were excluded if they underwent revision ACLR surgery, had a contralateral ACL injury or ACLR in the past. ACLR surgery was performed by five experienced high-volume orthopaedic surgeons at Clinic ViaSana (Mill, the Netherlands) using an ipsilateral semitendinosus quadruple autograft and TLS® femoral and tibial fixation with all-inside technique (FH Orthopedics, Heimsbrunn, France).

Athletes were allowed to choose their own physical therapist albeit that the criterion-based rehabilitation occurred according to the Dutch practice guideline. They notified their choice of physical therapist to the primary researcher (NM), who consecutively contacted the physical therapist by phone or email to confirm that the rehabilitation was assumed to occur according to the guideline. The physical therapist was noted that in the Netherlands an online version of the guideline is freely accessible. Besides, the athlete handed a paper copy of the guideline to his own physical therapist.

Physical therapists were expected to perform the RTP measurements according to the guideline and only clear the athlete for return to play when all nine RTP criteria were met (see Table 1 and Appendix), but they were not additionally educated on how to perform the tests. Athletes that did not return to pivoting sports at the end of rehabilitation were also considered to meet all RTP criteria.

At the end of the rehabilitation period, as judged by the treating physical therapist, the primary researcher was notified that the athlete was ready for return to play, but actual results of RTP measurements were not corresponded to the primary researcher. Then, within one to four weeks, the primary researcher independently performed the RTP measurements as described in the ACLR practice guideline (Table 1) and thus re-evaluated the physical therapist's judgement on whether or not the athlete was able to return to play.[16,17] Besides, the athlete was asked if he/she was familiar with the RTP measurements, to check whether the physical therapist had performed RTP measurements at the end of the treatment when he decided that return to play was safe. When a patient was not familiar with RTP measurements, we considered this as the treating physical therapist not adhering to the guideline.

Table 1: *Return to play criteria according to the anterior cruciate ligament reconstruction practice guideline.*[16,17]

Tests on quantity of movement	**Return to play permitted when**
Isometric knee extensor strength	LSI > 90%
Isometric knee flexor strength	LSI > 90%
Eccentric knee flexor strength	LSI > 90%
Isometric hip abduction strength	LSI > 90%
Vertical jump	LSI > 90%
Hop for distance	LSI > 90%
Side hop	LSI > 90%
Tests on quality of movement	**Return to play permitted when**
Single-leg hop-and-hold	Score 'yes'
Counter Movement Jump (LESS score)	Score ≤ 5

LSI=Limb Symmetry Index, LESS=Landing Error Scoring System

Participating physical therapists

Physical therapists who participated in this study, were asked for their level of expertise. The specialisation level of expertise of the physical therapist as recorded in the Dutch national registry was noted. Distinction was made between registration as a sports physical therapist or not (in this study referred to as non-sports physical therapist). To become a registered sports physical therapist in the Netherlands one must follow additional three to four year education at Master level about sport specific training and return to play. Table 2 lists the similarities and differences between sports physical therapists and non-sports physical therapists.[27,34] In this study it was therefore expected that sports physical therapists performed RTP measurements more often than non-sports physical therapist .

It was allowed that one physical therapist treated more pivoting athletes participating in this study.

Measurement procedures

To address the first aim, which focussed on adherence to the guideline, an athlete was labelled as tested by his own physical therapist 'yes' or 'no' and meeting the RTP criteria 'yes' or 'no' (both dichotomous variables). For the second aim, exploring the difference in practice guideline adherence between sports physical therapists and non-sports physical therapists, the athlete was labelled as having had rehabilitation with a sports physical therapist 'yes' or 'no' (dichotomous variable).

Table 2: *Similarities and differences (in italics) between a physical therapist with and without specialisation in sports in the Netherlands.*[27,34]

	Physical therapist	**Sports physical therapist**
Degree	Bachelor's degree	*Master's degree*
Knowledge	Knowledge on movement problems in general	*Advanced* knowledge considering musculoskeletal problems and *sport specific demands*
Care	Regular and singular care	*Multiple and complex care* with specialised and advanced knowledge considering sport specific demands
Competencies		
Physical therapy activities	using methodical approach to provide effective and curative assistance to clients with movement problems, making decisions according to the evidence-based practice principles	using methodical approach to provide effective and curative assistance to clients with movement problems *with a specific question regarding sport*, making decisions according to the evidence-based practice principles
Communicating	both verbally and non-verbally in a clear, transparent, effective and efficient way to reach a high level of patient satisfaction	both verbally and non-verbally in a clear, transparent, effective and efficient way to reach a high level of patient satisfaction *within the sport specific context*
Collaborating	with relevant professionals and in collaborative networks	with relevant professionals, in collaborative *sports networks or as a member of a sport team*
Knowledge sharing and scientific research	working according to the principles of EBP and developing clinical expertise	working according to the principles of EBP and developing clinical expertise *in his own sport specific context, in close collaboration with scientists*
Acting in the interest of society	practicing his profession in a socially responsible way	practicing his profession in a socially responsible way, *promoting an active and healthy life style*
Organizing	acting as a manager for his own professional activities	acting as a manager for his own professional activities *and as a leader for his organisation*
Professional conduct	taking responsibility for his actions and carefully balancing his personal and professional roles	taking responsibility for his actions and carefully balancing his personal and professional roles

ACLR practice guideline criteria consisted of seven movement quantity tests and two movement quality tests (Table 1 and the Appendix).[5,10,16-18,25] Meeting the RTP criteria was recorded as 'yes' or 'no' (dichotomous variable). To score a 'yes' all nine quantitative and qualitative RTP criteria had to be met.

All RTP measurements were performed by the primary researcher (NM) at Clinic ViaSana. The primary researcher is a sports physical therapist with 11 years of experience, specialised in ACL rehabilitation, teaching how to perform RTP measurements to Dutch physical therapists and physical therapy students and the first author of the ACLR practice guideline.

Quantitative RTP criteria

Isokinetic dynamometry is the gold standard for strength measurements, but only accessible for a small group of Dutch physical therapists due to issues with portability and cost-effectiveness.[33] Therefore, to make sure all Dutch physical therapists were able to perform these tests in daily practice, strength tests for knee and hip muscles were executed with a MicroFET2® hand-held dynamometer (ProCare, the Netherlands). Hand-held dynamometry is a reliable method to measure strength of these muscles in healthy adults, with an intrarater ICC of 0.74-0.76 for side-lying hip abduction, 0.76-0.99 for seated (belt-resisted) knee extension and 0.99 for prone-lying knee flexion, and an interrater ICC of 0.88 for knee extension and flexion.[3,11-14,30,31,33,35] In this study, the primary researcher performed three make tests and one break test. During the make tests, the athlete applied a maximal force against the examiner and the position was maintained by the examiner. A make test was conducted for knee extensors, knee flexors and hip abductors. During the break test, the athlete held a position and the examiner pushed until the subject's maximal force was overcome and the joint gave way.[29] The break test was only conducted for the knee flexors and the primary researcher was possible to execute it with every athlete.

Besides the strength tests, three single-leg hop tests (vertical jump, hop for distance, and side hop) were performed according to Gustavsson et al.[10] This hop test battery is known to have a sensitivity (identifying an athlete as abnormal when at least one of the tests produced an abnormal value) of 91% and the intrarater reliability of the tests is 0.89, 0.94 and 0.87 respectively.[10]

For all these quantitative tests, the limb symmetry index (LSI) was calculated as the value of the operated leg divided by the value of the non-operated leg multiplied by 100. RTP was permitted when the LSI was >90% (Table 1).

Qualitative RTP criteria

The single-leg hop-and-hold test was the first qualitative test to be performed. Three test sessions were allowed, and at least one of these three sessions had to be performed correctly to score a 'yes' and to allow RTP. Reliability of this test is yet unknown.[20]

A double-leg countermovement jump (CMJ) with frontal and sagittal plane video analyses (iPad with Hudl technique video analyses application, Hudl, Lincoln, Nebraska) was the final return to play test.[19,21,22] The first landing of the CMJ was used to analyse with the Landing Error Scoring System (LESS).[23,25] The LESS is a reliable (intrarater ICC 0.97) count of 17 items of landing technique errors for a drop jump. However, a CMJ was chosen because pivoting athletes never perform a jump off an obstacle during sports but often jump from the surface, making a CMJ more sport specific. A higher LESS indicates poorer technique in landing from a jump (maximum score 19); a lower LESS indicates better jump-landing technique (minimum score 0).[25,28] A LESS score of ≤5 was defined as sufficient for RTP.[7,24]

Statistical analyses

Data analysis was performed with IBM SPSS Statistics 21.0 (IBM, Armonk, NY).

To address the first aim, which focussed on adherence to the practice guideline, athlete characteristics were analyzed using descriptive statistics and an independent samples T-test was performed to analyze differences between athletes tested by their own physical therapist and those not tested. For all RTP measurements means and standard deviations, as well as the number and percentages of athletes meeting the RTP criteria were calculated with descriptive statistics. There were no missing values. Crosstabs with a chi-square test were used for the percentage of athletes meeting the RTP criteria, comparing athletes that were already tested with those not yet tested by their own physical therapist.

To address the second aim, exploring the difference in practice guideline adherence between sports physical therapists and non-sports physical therapists, an independent samples T-test was performed to analyze differences in baseline characteristics between athletes treated by a sports physical therapist or a non-sports physical therapist. Besides, crosstabs with a chi-square test were used to compare the number of athletes already tested between sports physical therapists and non-sports physical therapists.

Ethical considerations

All subjects signed an informed consent for participation in this study, conducted according to the ethical guidelines and principles of the international Declaration of Helsinki. This study was part of a larger prospective study approved by the Medical Ethics Committee of the Radboudumc Nijmegen, the Netherlands (registration number 2013/368).

Results

One-hundred-and-fifty-eight pivoting athletes were included (54 females, mean age 24 (SD 6) years old) and all of them completed RTP testing at Clinic ViaSana, at a mean of 12 (SD 3) months after ACLR. Characteristics of the pivoting athletes are listed in Table 3. The TAS post-rehabilitation decreased compared to the pre-operative TAS (8.6±0.8 respectively 7.8±1.7; $p<0.001$). This is due to the fact that 24 of the athletes ceased performing pivoting sports after their rehabilitation.

The 158 athletes rehabilitated with 108 different physical therapists, of whom 49 were registered sports physical therapists. Of the 158 participating athletes, 25 (16%) met all nine RTP criteria when the primary researcher (NM) performed the tests.

Influence of guideline adherence

There were no differences in baseline characteristics between athletes tested by their own physical therapist and those not tested (Table 3). Of the 158 athletes, 69 (44%) already performed the RTP measurements with their treating physical therapist. Of these 69 athletes that were already tested, 16 (23%) met all RTP criteria when measured at Clinic ViaSana, compared to 9 (10%) of those not tested by their treating physical therapist ($p=0.026$) (Table 4).

Thirty athletes (19%) met the RTP criteria for all seven quantitative measurements and 81 athletes (51%) met the RTP criteria for both qualitative measurements (Table 5). Except for isometric knee flexor strength ($p=0.049$), there were no differences between athletes that were already tested by their own physical therapist and those that were not tested by their own physical therapist in terms of quantitative RTP measurements. However, athletes that were already tested by their own physical therapist more often met both qualitative RTP criteria (67% versus 39%; $p=0.001$) (Table 4).

The most common LESS errors were a small knee flexion angle (<30°) at initial contact, the presence of lateral trunk flexion at initial contact, a non-symmetrical initial foot contact and the presence of knee valgus during landing (Table 5).

Influence of physical therapist

There were no differences in baseline characteristics between athletes that rehabilitated with a sports physical therapist or non-sports physical therapist (Table 6). Eighty-seven athletes rehabilitated with a sports physical therapist and 45 of them (52%) had performed the RTP measurements with their own sports physical therapist. Seventy-one athletes rehabilitated with a non-sports physical therapist

Table 3: *Characteristics of the participating pivoting athletes and comparison between athletes already tested or not tested by their own physical therapist.*

	All athletes	**Athletes tested by their own physical therapist**	**Athletes not tested by their own physical therapist**	**p-value****
N	158	69	89	
Sex, *N (%)*				
Male	104 (66)	45 (65)	59 (66)	n.s.
Female	54 (34)	24 (35)	30 (34)	
Age in years, *mean* ± SD*	24 ± 6	24 ± 6	24 ± 7	n.s.
Weight in kg, *mean* ± SD*	73 ± 11	73 ± 11	74 ± 10	n.s.
Height in cm, *mean* ± SD*	177 ± 13	178 ± 9	176 ± 15	n.s.
Rehabilitation duration in months, *mean* ± SD	12 ± 3	12 ± 4	12 ± 3	n.s.
Tegner Activity Scale (TAS), *mean* ± SD				n.s.
Preoperative	8.6 ± 0.8	8.6 ± 0.8	8.5 ± 0.8	
Post-rehabiliation	7.8 ± 1.7	7.8 ± 1.7	7.8 ± 1.6	

** Age, weight and height were measured preoperatively*

*** p-value for comparison between athletes tested by their own physical therapist and those not tested by their own physical therapist*

Table 4: *Results on the return to play (RTP) measurements for all athletes (N=158) and comparison of results between athletes tested by their own physical therapist (N=69) and those not tested by their own physical therapist (N=89).*

Test movement quantity	**LSI, *mean (± SD)***	**Athletes passing the RTP criterion (all athletes), *N (%)***	**Athletes passing the RTP criterion (athletes tested by their own physical therapist), *N (%)***	**Athletes passing the RTP criterion (athletes not tested by their own physical therapist), *N (%)***	**p-value***
Isometric knee extensor strength	100 (± 11)	133 (84)	61 (81)	72 (88)	n.s.
Isometric knee flexor strength	94 (± 12)	101 (64)	50 (73)	51 (57)	0.049
Eccentric knee flexor strength	95 (± 14)	98 (62)	46 (67)	52 (58)	n.s.
Isometric hip abduction strength	102 (± 11)	136 (86)	60 (87)	76 (85)	n.s.
Vertical jump	93 (± 12)	101 (64)	48 (70)	53 (60)	n.s.
Hop for distance	98 (± 7)	139 (88)	61 (88)	78 (88)	n.s.
Side hop	94 (± 16)	107 (68)	47 (68)	60 (67)	n.s.
All quantitative tests	**-**	**30 (19)**	**17 (25)**	**13 (15)**	**n.s.**
Test movement quality					
Single-leg hop-and-hold					
Operated leg	-	136 (86)	61 (88)	75 (84)	n.s.
Non-operated leg	-	138 (87)	61 (88)	77 (87)	n.s.

Test movement quantity	LSI, *mean* (± *SD*)	Athletes passing the RTP criterion (all athletes), *N* (%)	Athletes passing the RTP criterion (athletes tested by their own physical therapist), *N (%)*	Athletes passing the RTP criterion (athletes not tested by their own physical therapist), *N (%)*	p-value*
CMJ	LESS, *mean* (± *SD*)				
Operated leg	4.8 (± 2.6)	101 (64)	52 (75)	49 (55)	0.024
Non-operated leg	4.8 (± 2.6)	103 (65)	55 (80)	48 (54)	0.003
Both qualitative tests					
Only the operated leg	-	**89 (56)**	47 (68)	42 (47)	0.009
Only the non-operated leg	-	**91 (58)**	50 (73)	41 (46)	0.001
	-				
Both legs together		**81 (51)**	46 (67)	35 (39)	0.001
All 9 tests together	**-**	**25 (16)**	**16 (23)**	**9 (10)**	**0.026**

RTP=return to play, LSI=Limb Symmetry Index, CMJ=counter movement jump, LESS=Landing Error Scoring System
**p-value for comparison between athletes tested by their own physical therapist and those not tested by their own physical therapist*

Table 5: *Countermovement Jump with Landing Error Scoring System (LESS) analysis and number of athletes having the error condition per LESS item.*[25]

<table>
<tr><th>LESS item (filmed in sagittal/frontal plane)</th><th>Error condition</th><th>Error condition with operated leg, N (%)</th><th>Error condition with non-operated leg, N (%)</th></tr>
<tr><td>Knee flexion angle at initial contact (sagittal)</td><td>Knee flexion <30°</td><td colspan="2">80 (51)</td></tr>
<tr><td>Hip flexion angle at initial contact (sagittal)</td><td>Thigh is in line with the trunk</td><td colspan="2">10 (6)</td></tr>
<tr><td>Trunk flexion angle at initial contact (sagittal)</td><td>Trunk is vertical on the hip</td><td colspan="2">47 (30)</td></tr>
<tr><td>Ankle plantarflexion angle at initial contact (sagittal)</td><td>Foot lands heel to toe or flat</td><td colspan="2">6 (4)</td></tr>
<tr><td>Knee valgus angle at initial contact (frontal)</td><td>Line straight down from centre of the patella is medial to the midfoot</td><td>53 (34)</td><td>58 (37)</td></tr>
<tr><td>Lateral trunk flexion angle at initial contact (frontal)</td><td>Midline of the trunk is to the left or right side of the body</td><td colspan="2">82 (52)</td></tr>
<tr><td>Stance width – wide (frontal)</td><td>Line straight down from the tip of the shoulder is inside the foot</td><td>19 (12)</td><td>16 (10)</td></tr>
<tr><td>Stance width – narrow (frontal)</td><td>Line straight down from the tip of the shoulder is outside the foot</td><td>36 (23)</td><td>36 (23)</td></tr>
<tr><td>Foot position – toe in (frontal)</td><td>Internal rotation of foot >30°</td><td>0 (0)</td><td>0 (0)</td></tr>
<tr><td>Foot position – toe out (frontal)</td><td>External rotation of foot >30°</td><td>0 (0)</td><td>1 (1)</td></tr>
<tr><td>Symmetric initial foot contact (frontal)</td><td>One foot lands before the other</td><td colspan="2">69 (44)</td></tr>
<tr><td>Knee flexion displacement (sagittal)</td><td>Knee flexion displacement <45°</td><td colspan="2">32 (20)</td></tr>
<tr><td>Hip flexion at max knee flexion (sagittal)</td><td>Thigh does not flex more on the trunk during landing</td><td colspan="2">12 (8)</td></tr>
<tr><td>Trunk flexion at max knee flexion (sagittal)</td><td>The trunk does not flex more during landing</td><td colspan="2">23 (15)</td></tr>
<tr><td>Knee valgus displacement (frontal)</td><td>Line straight down from centre of the patella is medial to the great toe during max knee valgus</td><td>88 (56)</td><td>81 (51)</td></tr>
</table>

6

and 24 of them (34%) had performed the RTP measurements with their own non-sports physical therapist ($p=0.024$) (Table 7).

Discussion

The first aim of this study was to analyse if Dutch physical therapists adhere to the RTP criteria as defined in the ACLR practice guideline when clearing a pivoting athlete for RTP. The answer to the first question of this aim “Do physical therapists use RTP measurements to guide RTP decision?” is disappointing: only 44% of the pivoting athletes is tested by their own physical therapist. The answer to the second question “Do physical therapists correctly advise pivoting athletes to RTP based on the test results?” is even more alarming: 77% of the athletes may have received an incorrect advice, based on the RTP measurements by the primary researcher.

Concerning the second aim, the most obvious finding was that athletes who rehabilitated with a sports physical therapist more often were tested according to the practice guideline RTP criteria than athletes who rehabilitated with a non-sports physical therapist; 52% versus 34%. This shows that sports physical therapists have a better adherence to the ACLR practice guideline than non-sports physical therapists. However, the percentage of sports physical therapists adhering to the guideline is still too low.

Only 16% of the pivoting athletes in this study actually met all nine RTP criteria. Two recently published studies found similar low numbers of athletes meeting the quantitative RTP criteria when the athletes are cleared for return to play. Toole et al[32] tested 115 pivoting athletes (mean age 17.1±2.5 years old) at the moment they were cleared to full unrestricted sports. They found that only 14% of all athletes met the RTP criteria (quadriceps and hamstring strength, four single-leg hop tests and the IKDC Subjective Knee form).[32] Also Beischer et al[2] found that only 20% of 102 adolescent athletes (mean age 17.4±1.3 years old) and 28% of 168 adult athletes (mean age 24.9±2.6 years old), that already returned to play, met the RTP criteria (isokinetic quadriceps and hamstring strength, three single-leg hop tests) 12 months after ACLR.[2]

The results of this study results are also similar to those of Grindem et al[9] who found that 18 of the 74 pivoting athletes (24%) passed the RTP criteria (isokinetic quadriceps strength and four single-leg hop tests) 12 months after ACLR. Kyritsis et al[15] tested 158 male professional pivoting athletes for isokinetic quadriceps and hamstring strength, three single-leg hop tests and an agility T-test. Within eight months, 116 (73%) of the athletes passed the RTP criteria.[15] The fact that these are all professional athletes could explain the high number of athletes passing the RTP criteria. Both the study of Grindem et al[9] and the study of Kyritsis et al[15] found

Table 6: *Comparison of athlete characteristics between athletes rehabilitating with a sports physical therapist or non-sports physical therapist.*

	Athletes rehabilitating with a sports physical therapist	**Athletes rehabilitating with a non-sports physical therapist**	**p-value****
N	87	71	6
Sex, *N (%)*			
Male	57 (67)	47 (66)	n.s.
Female	30 (33)	24 (34)	
Age in years, *mean* ± SD*	24 ± 6	24 ± 7	n.s.
Weight in kg, *mean* ± SD*	72 ± 10	75 ± 12	n.s.
Height in cm, *mean* ± SD*	177 ±15	177 ± 9	n.s.
Rehabilitation duration in months, *mean* ± SD	12 ± 3	12 ± 4	n.s.
Tegner Activity Scale (TAS), *mean* ± SD			
Preoperative	8.6 ± 0.8	8.6 ± 0.8	n.s.
Post-rehabiliation	7.8 ± 1.7	7.9 ± 1.6	n.s.

** Age, weight and height were measured preoperatively*

*** p-value for comparison between athletes rehabilitating with a sports physical therapist and those rehabilitating with a non-sports physical therapist*

6

Table 7: *Crosstabs of number of athletes who had return to play (RTP) measurements with their own physical therapist, compared between sports physical therapists and non-sports physical therapists.*

	Athletes rehabilitating with a sports physical therapist (N=87)	**Athletes rehabilitating with a non-sports physical therapist (N=71)**	**p-value**
RTP measurements by their treating physical therapist?, *N (%)*			
Yes	45 (52)	24 (34)	0.024
No	42 (48)	47 (66)	

that pivoting athletes that passed all the quantitative RTP criteria had a strongly reduced risk of sustaining a second ACL injury in the first two years after ACLR.

Concerning movement quality previous studies already found that altered hip and knee biomechanics when landing from a jump are predictors of a second ACL injury after ACLR rehabilitation and RTP.[26,28] The use of qualitative RTP criteria might be not as common as the use of quantitative criteria, but they are as important in the RTP decision.

All the above highlights the importance of measuring both the quantitative and qualitative components of functional performance and indicates that the athletes that do not pass the RTP criteria (84% in this study), but still returned to their pre-injury sport, might have a higher chance of a second ACL injury in the near future. Unless the publication and implementation of the Dutch ACLR practice guideline by the KNGF, Dutch physical therapists still struggle with using RTP measurements and deciding when to clear their pivoting athletes for RTP, since only 44% of the athletes had performed RTP measurements with their own physical therapist. Even more concerning is that 77% of the athletes that already performed RTP measurements may have received an incorrect RTP advice. This could indicate that RTP measurements are not the main factor in the RTP decision or it could be caused by an error in interrater reliability with testing. However, the athletes that were already tested, often told that their physical therapist did not test eccentric hamstrings strength or the side hop test; two criteria that are often not met. This could stress the importance of measuring eccentric hamstring strength and the side hop test, both known as important tests for determining a safe return to play after ACLR.[8-10,15]

Overall, the results of this study argue that the ACLR practice guideline was not implemented properly. We suggest incorporating ACLR rehabilitation and RTP measurements into general physical therapy education and thereby changing the underutilisation of rehabilitation.[8]

Limitations of the study

According to the practice guideline, movement quantity and quality measurements should already be performed during the rehabilitation process to guide progress of the athlete.[4,16] So it can be reasoned that pivoting athletes that recently had RTP tests with their treating physical therapist were probably better prepared for the RTP testing at Clinic ViaSana, introducing bias on how they performed on those tests. However, many athletes that were tested by the primary researcher did not meet the RTP criteria.

Because 24 (15%) athletes decided to cease pivoting sports after their ACLR rehabilitation, this could have created bias. However, their treating physical therapists was told that these athletes should also meet the RTP criteria as stated in the practice guideline. Three of the athletes that ceased performing pivoting sports (13%) met all the RTP criteria when tested at Clinic ViaSana, indicating they scored at a similar level compared to the all other athletes in this study.

Conclusion

Fifty-six percent of pivoting athletes were cleared for RTP by their physical therapist not using criterion-based decisions as advised in the ACLR practice guideline. Sports physical therapists more often adhered to the practice guideline than non-sports physical therapists (52% versus 34%), but with only half of them adhering, this percentage is still too low.

Only 16% of pivoting athletes actually met all RTP criteria, but athletes that were already tested by their own physical therapist more often met all RTP criteria (23% versus 10%), indicating those not tested might have a higher chance for a second ACL injury. Interestingly, 77% of the athletes tested by their own physical therapist were given an incorrect RTP advice, which obviously is concerning.

Based on these results, we argue for more attention in implementing the ACLR practice guideline and suggest incorporating ACLR rehabilitation and RTP measurements into general physical therapy education. Besides, we think it might be useful to inform pivoting athletes about RTP criteria after ACLR, empowering them to make the right choices for a physical therapist and providing them insight and autonomy during rehabilitation and the RTP decision.

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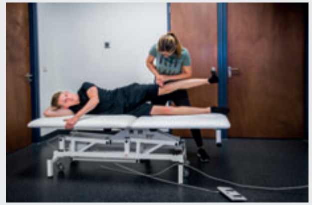
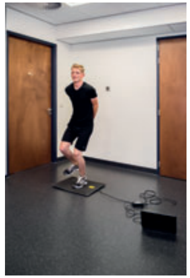
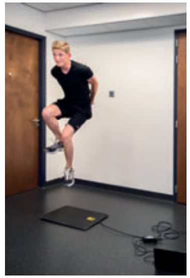
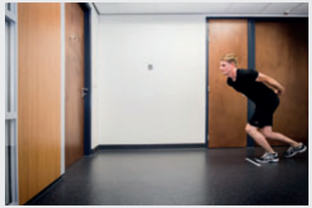
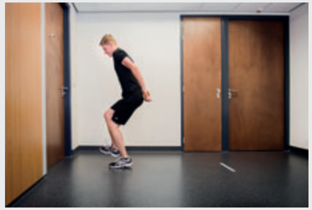
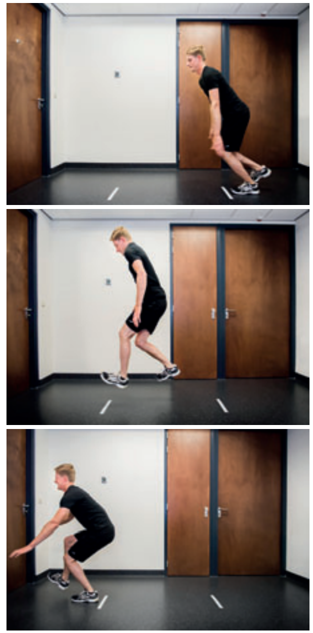
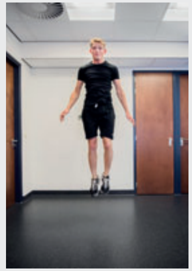
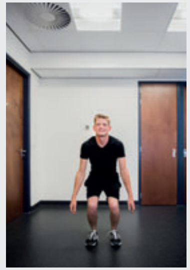
Appendix: Return to play (RTP) measurements

Test	Subject's start position	Procedure	Sessions	Recorded variable	Picture
Quantitative tests					
Isometric knee extensor strength (make test)	Seated at the end of an examination table and had to hold the side-edges with his hands.[18] The hips were placed at 90° of flexion and the tested knee at 60° of flexion. A belt was placed around the examination table perpendicular to the distal tibia of the test leg.[12]	The hand-held dynamometer was placed just above the talotibial joint line.[18] The subject had to build up his strength in two seconds and then hold a maximum voluntary contraction for three seconds.	Two practice sessions, before three test sessions for each leg. Between practice and test sessions, a one minute rest period. Between each test session, a 30 second rest period. The non-operated leg was tested before the operated leg.	The highest value (in kg) of the three test sessions for both legs. The Limb Symmetry Index was calculated as the strength of the operated leg divided by the strength of the non-operated leg multiplied by 100.	
Isometric knee flexor strength (make test)	Prone on an examination table with the tested knee at 30° of flexion and holding the side-edges of the table with his hands.[30]	The hand-held dynamometer was placed at the posterior part of the leg, two cm above the lateral malleolus.[18] The subject had to build up his strength in two seconds and then hold a maximum voluntary contraction for three seconds.	Two practice sessions, before three test sessions for each leg. Between practice and test sessions, a one minute rest period. Between each test session, a 30 second rest period. The non-operated leg was tested before the operated leg.	The highest value (in kg) of the three test sessions for both legs. The Limb Symmetry Index was calculated as the strength of the operated leg divided by the strength of the non-operated leg multiplied by 100.	
Eccentric knee flexor strength (break test)	Prone on an examination table with the tested knee at 60° of flexion and holding the side-edges of the table with his hands.[30]	The hand-held dynamometer was placed at the posterior part of the leg, one to two cm above the lateral malleolus.[18] The subject had to build up his strength in two seconds and then the examiner pushed the leg towards full extension in five seconds.	Two practice sessions, before three test sessions for each leg. Between practice and test sessions, a one minute rest period. Between each test session, a 30 second rest period. The non-operated leg was tested before the operated leg.	The highest value (in kg) of the three test sessions for both legs. The Limb Symmetry Index was calculated as the strength of the operated leg divided by the strength of the non-operated leg multiplied by 100.	 

Test	Subject's start position	Procedure	Sessions	Recorded variable	Picture
Isometric hip abduction strength (make test)	In sidelying on an examination table with the test leg facing upward. The examiner placed the test leg in slight hip abduction (approximate 10° as measured with respect to a line connecting the anterior superior iliac spines). The arms were placed in front of the subject with one hand holding the side-edge of the table.	The hand-held dynamometer was placed five cm above the lateral knee joint line.[12,18] The subject had to build up his strength in two seconds and then hold a maximum voluntary contraction for three seconds.	Two practice sessions, before three test sessions for each leg. Between practice and test sessions, a one minute rest period. Between each test session, a 30 second rest period. The non-operated leg was tested before the operated leg.	The highest value (in kg) of the three test sessions for both legs. The Limb Symmetry Index was calculated as the strength of the operated leg divided by the strength of the non-operated leg multiplied by 100.	
Vertical jump	Upright position, standing on one leg with the hands placed behind the back.[10]	The subject quickly bents his knee as much as desired and then immediately jumped upwards, attempting to maximise the height jumped. The subject had to perform a controlled, balanced landing and had to keep the landing foot in place (2–3 s).[10] A Pro-Jump contact mat (ProCare, the Netherlands) was used to measure jump height in centimeters.	Two practice sessions, before three test sessions for each leg. Between practice and test sessions, a one minute rest period. Between each test session, a 30 second rest period. The non-operated leg was tested before the operated leg.	The highest jump of the three test sessions for both legs. The Limb Symmetry Index was calculated as the value of the operated leg divided by the strength of the non-operated leg multiplied by 100.	 

Test	Subject's start position	Procedure	Sessions	Recorded variable	Picture
Hop for distance	Upright position, standing on one leg with the hands placed behind the back.[10]	The subject hopped as far as possible and landed on the same leg. Free leg swing was allowed. The subject had to perform a controlled, balanced landing and had to keep the landing foot in place until (2–3 s) the test leader had registered the landing position. Failure to do so resulted in a disqualified hop. The distance was measured in centimetres from the toe at the push-off to the heel where the subject landed.[10]	Two practice sessions, before three test sessions for each leg. Between practice and test sessions, a one minute rest period. Between each test session, a 30 second rest period. The non-operated leg was tested before the operated leg.	The furthest jump of the three test sessions for both legs. The Limb Symmetry Index was calculated as the value of the operated leg divided by the strength of the non-operated leg multiplied by 100.	 
Side hop	Upright position, standing on one leg with the hands placed behind the back.[10]	The subject jumped from side to side between two parallel strips of tape, placed 40 cm apart on the floor. The subjects were instructed to jump as many times as possible during a period of 30 s. The number of successful jumps performed, without touching the tape, was recorded. Touching the tape was recorded as an error.[10]	A few practice jumps were allowed to familiarise themselves with the jumping distance, before they performed one test session of 30 seconds. The non-operated leg was tested before the operated leg.	The amount of correct jumps for both legs. The Limb Symmetry Index was calculated as the value of the operated leg divided by the strength of the non-operated leg multiplied by 100.	 

Test	Subject's start position	Procedure	Sessions	Recorded variable	Picture
Qualitative tests					
Single-leg hop-and-hold	Upright position, standing on one leg.	A marker was placed at 90% of the distance jumped at the single-leg hop for distance. Arm swing was allowed during the jump. A minimum of the marked distance had to be jumped and the landing had to be with the knee in 90° of flexion. The subject had to hold this landing position for three seconds.[2]1	There were no practice sessions and three test sessions. The non-operated leg was tested before the operated leg.	At least one of the three test sessions had to be performed correctly to score a 'yes'. Otherwise, the subject scored a 'no'.	

Test	Subject's start position	Procedure	Sessions	Recorded variable	Picture
Double-leg coun-termovement jump	The subject started at two legs with the feet hip width apart.	Subjects had to jump as high as possible, perform a landing on two feet and immediately jump as high as possible again. Arm swing was allowed during the jumps.[22-24]	One practice session was allowed before two test sessions. One session was frontally filmed, one session was sagittally filmed.	The first landing of the countermovement jump was used to analyse with the Landing Error Scoring System (LESS).	 

6

Chapter 7

How to determine leg dominance: the agreement between self-reported and observed performance in healthy adults

Nicky van Melick
Bart M. Meddeler
Thomas J. Hoogeboom
Maria W.G. Nijhuis-van der Sanden
Robert E.H. van Cingel

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Abstract

Context: Since decades leg dominance is suggested to be important in rehabilitation and return to play in athletes with anterior cruciate ligament injuries. However, an ideal method to determine leg dominance in relation to task performance is still lacking.

Objective: To test the agreement between self-reported and observed leg dominance in bilateral mobilizing and unilateral stabilizing tasks, and to assess whether the dominant leg switches between bilateral mobilizing tasks and unilateral stabilizing tasks.

Design: Cross-sectional study.

Participants: Forty-one healthy adults: 21 men aged 36±17 years old and 20 women aged 36±15 years old.

Measurement and analysis: Participants self-reported leg dominance in the Waterloo Footedness Questionnaire-Revised (WFQ-R), and leg dominance was observed during performance of four bilateral mobilizing tasks and two unilateral stabilizing tasks. Descriptive statistics and crosstabs were used to report the percentages of agreement.

Results: The leg used to kick a ball had 100% agreement between the self-reported and observed dominant leg for both men and women. The dominant leg in kicking a ball and standing on one leg was the same in 66.7% of the men and 85.0% of the women. The agreement with jumping with one leg was lower: 47.6% for men and 70.0% for women.

Conclusions: It is appropriate to ask healthy adults: “If you would shoot a ball on a target, which leg would you use to shoot the ball?” to determine leg dominance in bilateral mobilizing tasks. However, a considerable number of the participants switched the dominant leg in a unilateral stabilizing task.

Introduction

Leg dominance is an often discussed factor amongst both healthy and injured athletes. In healthy adults, leg dominance seems to have no influence on knee open kinetic chain proprioception and single-leg postural control.[1,7] However, a systematic review on isokinetic quadriceps and hamstring strength and single-leg hop performance found non-significant but clinical important differences in the performance of the dominant leg compared to the non-dominant leg, with the dominant leg scoring higher values for all these tasks.[20] Furthermore, leg dominance appears to play a role in the etiology of anterior cruciate ligament injuries, because female recreational soccer players and skiers are more likely to injure their non-dominant leg, whereas males tend to injure their dominant leg.[5,22,25]

In the above studies, different methods to determine leg dominance are used, thus an ideal method to determine leg dominance is still lacking.[8,23] In 1998, Peters[24] defined the dominant leg as 'the leg used in order to manipulate an object or to lead out in movement'. This automatically leads to the definition of the non-dominant leg: 'the leg which performs the stabilizing or supporting role'.[24] Several footedness questionnaires have been developed over time in order to determine leg dominance.[6,10] These questionnaires have frequently been used by other authors, however hardly any statements on the correlation between the self-reported leg dominance in a questionnaire and the actual observed performance of those tasks have been made. To our knowledge, only Hart and Gabbard (1998)[16] investigated this relationship and stated that there is a strong agreement (98%) for right-footers between leg dominance indicated by responses in a questionnaire and leg dominance demonstrated on two tasks. For left-footers this agreement was 84%. These tasks were rolling a golf ball around a circle as quickly and accurate as possible with one foot while seated, and drawing initials in a sandbox using one foot while seated.[16] It should be noted that the tasks used in this study are not very common in daily life. Besides, there is no supporting leg in these seated tasks, which makes it unclear whether the definition of Peters can be used in determining the dominant leg in sport activities.

One of the uncertainties in determining leg dominance is the fact that literature reports variation in leg dominance between different types of tasks.[20] In bilateral mobilizing tasks, such as kicking a ball while standing, both legs are involved. In unilateral stabilizing tasks, however, such as standing on one leg, merely only one leg is active. In this case the standing leg is the dominant leg, according to Peters.[24] Hart and Gabbard (1997)[17] claimed that the dominant leg in bilateral mobilizing tasks, in general, is also the dominant leg in unilateral stabilizing tasks, thus the standing leg will switch. However, in their own study, only 62% of the right-handed and 44% of the left-handed participants switched the standing leg in the bilateral task compared to the unilateral task, so apparently there is not one dominant leg for all tasks.[17]

The first aim of this study is to determine the most accurate question to ask for leg dominance based on the agreement between the self-reported leg dominance using the Waterloo Footedness Questionnaire-Revised (WFQ-R) questionnaire and the observed leg dominance in four bilateral mobilizing tasks and two unilateral stabilizing tasks.[10] The second aim of this study is to retest the phenomenon described by Hart and Gabbard, that the standing leg is switched between a bilateral mobilizing task and a unilateral stabilizing task to remain the same dominant leg.

Materials and methods

Participants

All participants in this study were healthy volunteers (students or teachers at the Radboud university medical center), recruited by personal contacts of the authors. They were unaware of the actual purpose of this study and were told that this study investigated their lower extremity coordination. The inclusion criteria were: age between 18 and 65 years old, practice of symmetrical sports (e.g. running, cycling, swimming, rowing) or sports which involve the lower extremities only (e.g. soccer) or people who do not practice any type of sport. Participants that practiced sports in which the upper extremity is predominantly used (e.g. handball, tennis, volleyball) were excluded, because of the introduction of a possible bias as stated by Peters, who mentioned that in athletics, the choice of arm usually influences the choice of the leg.[24] Other exclusion criteria were surgery to one or both legs in the past three years, a back or lower extremity injury at the moment of testing, the use of medication which influences balance, and the presence of any disease which affects balance or coordination.

Forty-one healthy adults were eligible for inclusion: 21 men aged 35.8±16.5 years old and 20 women aged 36.1±15.2 years old. 90% of them were right-handed, which is comparable to the world population.[15] All participants agreed to take part in this study and gave their written informed consent to their inclusion in this study. This study was approved by the Medical Ethics Committee Arnhem/Nijmegen (registration number 2017-3373).

Test procedures

Self-reported leg dominance

The WFQ-R was used in order to identify the participant's own experienced leg dominance.[10] To this 12-item questionnaire, eight questions were added based on other tasks previously described for determining leg dominance (Fig 1).[26] The participants were asked to complete the questionnaire first, before the tasks were performed, and they were unaware of the fact that some tasks, which were part of the questionnaire, had to be performed later on. To avoid recollection of questionnaire items when performing the tasks as much as possible, a higher number of tasks was used in the questionnaire than those that actually had to be performed.

Observed leg dominance
Only six of the tasks were executed by the participants: kicking a ball at a target placed four meters away, picking up five marbles which are arranged in a vertical line and putting them in a box by using one foot while standing, stomping out an imaginary fire displayed on a sheet of paper using one foot while standing, tracing the shape of a house using one foot while standing, standing on one leg on an unstable foam surface with eyes closed, and jumping as far as possible with one leg. The first four tasks were labeled as reliable bilateral mobilizing tasks by Schneiders et al. (kappa's between 0.61 and 0.88) and were recommended to be used in a test battery to determine leg dominance.[26] Standing on one leg and jumping with one leg were added as unilateral stabilizing tasks in order to assess the dominant leg in these types of tasks for the second aim.

All tasks were performed three times in a randomly assigned order, without any footwear. For each task, the dominant leg was recorded as the dominant leg used in at least two out of three repetitions. Besides, the stability within a tasks was registered. A task was named stable when all three repetitions were performed with the same leg as the dominant leg.

For each task, the starting position for the participant was marked with a piece of tape on the floor. Feet were placed at hip width apart and parallel to each other. In order to prevent any external influence on the selected leg to perform the task, the objects used for the tasks (such as a ball or marbles) were placed on marked positions midway between the feet. The researcher made no mention regarding limb choice.[16,26] Additionally, during each task, a supplementary cognitive calculating task was given, which started prior to the execution of the task and lasted until task execution was completed. This cognitive distraction was implemented to draw away the focus on the selected leg used to perform the task.[9]

Statistical analysis

All data were analyzed using SPSS 19.0.0. Descriptive statistics was used to describe the percentage of participants choosing the right leg in the self-reported and observed leg dominance tasks. In addition, the percentage of agreement in leg choice between the self-reported and observed choice during task execution was reported with Crosstabs. Subsequently, the bilateral mobilizing task with the highest agreement was used to determine the most accurate question to ask for leg dominance.

The bilateral mobilizing task with the highest percentage of agreement was compared to the unilateral stabilizing tasks to investigate our second study aim.

Questions for determining leg dominance	Left	Right
If you were asked to shoot a ball on a target, which leg would you use to shoot the ball?*		
If you had to pick up marbles while standing and put the marbles in a box, which foot would you use to pick them up?*		
When you had to trace a figure drawn on the floor, which foot would you use?		
Which foot would you use if you had to stomp out a small fire while standing?		
If you were asked to stand on one leg, on which leg would you stand?*		
Which foot would you use to smooth sand while standing?*		
If you had to step up onto a chair, which foot would you place on the chair first?*		
Which foot would you use to stomp an insect while you were standing?*		
If you were to balance on one foot on a railway track, which foot would you use?*		
If you had to hop on one foot, which foot would you use?*		
Which foot would you use to help push a shovel into the ground while digging?*		
During relaxed standing, people initially put most of their weight on one foot, leaving the other leg slightly bent. Which foot do you put most of your weight on first?*		
Are you right or left handed?		
Questions for inclusion/exclusion	**Yes**	**No**
Have you ever had an anterior cruciate ligament rupture and/or reconstruction?		
Have you underwent any surgery to legs and/or lower back in the past 3 years? If yes, what kind of surgery and when?		
In this moment, do you suffer from an injury to your lower back, hip, leg, ankle or foot?		
Do you use medication which may influence your balance?		
Do you suffer from a disease which may affect you balance and/or coordination?		
In the past, have you had any special training which stimulates the use of a certain leg in a certain situation or activity? (Sports and/or work related?)*		
Is there a reason why your leg preference has changed, such as an injury?*		

Figure 1: *Leg dominance questionnaire used in this study. The original questions of the WFQ-R are marked with a *.*

Results

The results of the analysis of the first aim are displayed in Table 1 for both bilateral mobilizing tasks and unilateral stabilizing tasks. Only for kicking the ball, the observed leg dominance 100% matches the self-reported leg dominance and is a stable task for both men and women. Therefore, this bilateral mobilizing task was used to compare the dominant leg with the unilateral stabilizing tasks for the second study aim. The results of this analysis are shown in Table 2. The agreement with standing on one leg is the highest, with 66.7% for men and 85.0% for women. The agreement with jumping with one leg is lower: 47.6% for men and 70.0% for women.

Discussion

This study on leg dominance examined two research questions in healthy adults. The first aim was to determine the most accurate question to ask for leg dominance based on the agreement between the self-reported and observed leg dominance in four bilateral mobilizing tasks and two unilateral stabilizing tasks. Our results show that the question "If you would shoot a ball on a target, which leg would you use to shoot the ball?" showed the highest agreement (100% for both men and women) and was the most stable task (95.2% for men and 100.0% for women) of the bilateral mobilizing tasks. Of the unilateral stabilizing tasks standing on one leg showed the highest agreement (85.7% for men and 95.0% for women) and also was the most stable task (85.7% for men and 90.0% for women). Only one study previously made a statement about the correlation between self-reported and observed leg dominance. According to Hart and Gabbard, 98% of right-footers and 84% of left-footers showed an agreement between the preferred leg in unilateral mobilizing (seated) tasks.[16] Right-handed people performed activities more consistently with one lower extremity when compared with left-handed adults.[4] The results in our study for kicking a ball are more conclusive, as this is 100% for both right- and left-handed participants. A remark in the study by Hart and Gabbard is that unilateral mobilizing tasks have been used in order to determine the dominant leg, whereas in our study bilateral mobilizing tasks have been used. The tasks used in our study presumably require more dexterity and accuracy compared to the unilateral mobilizing tasks and may be executed using different spinal pathways, possibly impeding a direct comparison.[18] Moreover, it should be noted that unilateral mobilizing tasks are hardly present during daily life or in sports and therefore show a more unstable pattern in leg preference than tasks that are more common.[2] This makes the tasks used by Hart and Gabbard less applicable in a general athletic population. We postulate that a more automatically performed task, with no or a minor motor learning effect, could provide a better agreement between the question asked which leg will be used and the actual task performance.

Table 1: *Percentages of agreement between self-reported and observed leg dominance and task stability for the four bilateral mobilizing tasks and two unilateral stabilizing tasks.*

Task		**Men**	**Women**
Kicking ball	Self-reported (% using right leg)	95.2	100.0
	Observed (% using right leg)	95.2	100.0
	Agreement (%)	100.0	100.0
	Task stability (% of participants with stable task)	95.2	100.0
Picking marbles	Self-reported (% using right leg)	85.7	95.0
	Observed (% using right leg)	90.5	100.0
	Agreement (%)	95.2	95.0
	Task stability (% of participants with stable task)	90.5	100.0
Tracing shape	Self-reported (% using right leg)	81.0	100.0
	Observed (% using right leg)	81.0	100.0
	Agreement (%)	90.5	100.0
	Task stability (% of participants with stable task)	90.5	100.0
Stomping out fire	Self-reported (% using right leg)	81.0	100.0
	Observed (% using right leg)	95.2	100.0
	Agreement (%)	90.5	100.0
	Task stability (% of participants with stable task)	95.2	100.0
Standing one leg	Self-reported (% using right leg)	71.4	85.0
	Observed (% using right leg)	76.2	80.0
	Agreement (%)	85.7	95.0
	Task stability (% of participants with stable task)	85.7	90.0
Jumping one leg	Self-reported (% using right leg)	61.9	65.0
	Observed (% using right leg)	52.4	70.0
	Agreement (%)	71.4	85.0
	Task stability (% of participants with stable task)	81.0	85.0

Table 2: *Percentage of agreement between the dominant leg of the best bilateral mobilizing task (kicking a ball) with the unilateral stabilizing tasks.*

	Men	**Women**
Standing one leg	66.7	85.0
Jumping one leg	47.6	70.0

The second aim of this study was to retest the phenomenon described by Hart and Gabbard, that the standing leg is switched between a bilateral mobilizing task and a unilateral stabilizing task to remain the same dominant leg.[17] The agreement in Hart and Gabbard's study was 62% in a right-handed population and 44% in a left-handed population. In our opinion, this percentage is low. The results from our study show a higher percentage of participants (66.7% for men and 85.0% for women) who have the same dominant leg when comparing kicking a ball and standing on one leg. However, jumping on one leg more resembles the need of athletes compared to standing on one leg. When comparing kicking a ball and jumping on one leg, more than 50% of the men and 30% of the women had a different dominant leg for both tasks. These numbers are similar to the percentage of Hart and Gabbard. With respect to these findings, there still is an amount of variability between the dominant leg in the bilateral mobilizing and unilateral stabilizing context. This task dependency is previously mentioned by other authors. A strong preference for one foot in mobilization tasks is contrasted to large interindividual variability and weak foot preference in stabilization tasks, as can be seen when task stability is compared between bilateral mobilizing tasks and unilateral stabilizing tasks (Table 1).[2,12,26]

Our study results may have implications for lower limb injury rehabilitation and return to play. For example, the Limb Symmetry Index (LSI) is a popular tool for monitoring progression trough rehabilitation and determining the moment athletes can return to play after lower limb injuries.[11,14,19] The LSI is used to compare the operated to the non-operated leg when measuring quantitative components of movement like strength tests or hop tests.[14,21] If the operated leg is compared to the non-operated leg, the LSI does not take leg dominance into account.[3] Nowadays there is still a debate whether it is relevant to discriminate between the dominant and non-dominant leg in lower limb rehabilitation.[3,14,,28,29] However, literature suggests the LSI should be above 100% when calculated as the value of the dominant leg divided by the value of the non-dominant leg to determine safe return to play.[13,20,27,30] Future research should indicate whether the dominant leg has a superior performance compared to the non-dominant leg and what the LSI values for safe return to play should be.

Strengths and limitations

A strength of this study is that we also chose bilateral mobilizing tasks to answer the first aim. Tasks, like kicking a ball, are related to daily life of many athletes and therefore are more stable in foot preference than unilateral mobilizing tasks as used by Hart and Gabbard.[16] However, in this study we only examined healthy adults.

A limitation of this study is that only 10% of the study population was left-handed. Therefore, the results for the left-handed participants should be interpreted with caution. The proportion right- and left handed adults in this study, however, is comparable to the world population.[15]

Conclusions

To determine leg dominance in healthy adults, the question "If you would shoot a ball on a target, which leg would you use to shoot the ball?" is accurate for bilateral mobilizing tasks. The dominant leg in this bilateral mobilizing task is also the dominant leg in a unilateral stabilizing task (e.g. jumping on one leg) in about 50% of men and 70% of women.

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7

Chapter 8

Fatigue affects quality of movement more in ACL-reconstructed soccer players than in healthy soccer players

Nicky van Melick
Lisa van Rijn
Maria W.G. Nijhuis-van der Sanden
Thomas J. Hoogeboom
Robert E.H. van Cingel

Knee Surgery, Sports Traumatology, Arthroscopy
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Abstract

Purpose: Athletes who meet return to play (RTP) criteria after anterior cruciate ligament reconstruction (ACLR) rehabilitation still have a substantially increased risk of second ACL injury. One of the contributing factors to this increased risk could be that the RTP criteria are often not tested in an ecologically valid environment and in a fatigued state. The purpose of this cross-sectional case-control study was to investigate the influence of neuromuscular fatigue on both movement quantity and quality in fully-rehabilitated soccer players after ACLR and to compare them with healthy soccer players.

Methods: ACL-reconstructed soccer players (n=14) and healthy soccer players (n=19) participated in the study and were matched by playing level and training hours. RTP measurements were performed on the soccer field, in both a non-fatigued and fatigued state. The RTP measurements focussed on both movement quantity (hop tests) and quality [countermovement jump with a Landing Error Scoring System (LESS) score].

Results: Movement quantity did not differ between ACL-reconstructed and healthy soccer players, both expressed in absolute values and the LSI-D/ND (calculated as dominant/non-dominant*100%). However, movement quality decreased more in the ACL-reconstructed soccer players in the fatigued state compared to the non-fatigued state.

Conclusions: Ideally, RTP measurements should focus on movement quality and should be conducted on the soccer field in a fatigued state, creating an ecologically valid environment. The LSI-D/ND can be used as an outcome parameter for RTP measurements of movement quantity and should be at least 95%.

Introduction

Athletes recovering from anterior cruciate ligament reconstruction (ACLR) need to be adequately evaluated during and after their rehabilitation process to ensure a safe return to play (RTP). To aid health professionals in this process, a specific set of evidence-based RTP criteria have been reported.[8,14,21] These criteria consist of functional performance tests based on movement quantity and quality.[10,21] However, athletes who meet these RTP criteria still have a substantially increased risk of sustaining a second ACL injury compared with previously uninjured athletes: 10% versus 3%, respectively.[17,23,31]

One of the contributing factors to this increased risk could be that the RTP criteria are often not tested in ecologically valid environments nor in a fatigued state, despite evidence indicating that neuromuscular fatigue is a risk factor for lower extremity injuries in healthy individuals.[7,9,20] There is also evidence demonstrating that neuromuscular fatigue decreases functional performance, decreases knee stability and increases tibial translation in healthy athletes and athletes after ACLR, resulting in both reduced movement quantity and quality and a probable increased risk of ACL injury.[1,2,4,7,12,18,33,37]

For RTP tests of movement quantity, the Limb Symmetry Index (LSI) is used as the primary outcome parameter. The LSI quantifies strength and hop performance of the operated leg as a percentage of the non-operated leg. At the end of the rehabilitation process, the LSI should be at least 90% to minimise the risk of re-injury; for pivoting athletes, strength measures should be at least 100%.[34] However, the LSI might overestimate the function of the operated knee as deficits in strength and hop performance have also been demonstrated in the non-operated leg following ACL injury.[13,36] Consequently, although the LSI is higher than 90%, the absolute values of strength or hop tests can still be insufficient compared with preinjury values or healthy peers.[13,36] Therefore, a new way to calculate the LSI is proposed, namely by dividing the value of the dominant leg (D) by the value of the non-dominant (ND) leg; this is called the LSI-D/ND.[3,22] This method allows comparison between injured and healthy athletes.

Athletes who do meet the current quantitative criteria for RTP after ACLR may not do so in an ecologically valid environment and a fatigued state or might be underperforming compared to their healthy peers. Furthermore, neuromuscular fatigue might cause a deterioration of movement quality that is different in athletes after ACLR compared to healthy peers. Therefore, the aim of this study was to investigate the influence of neuromuscular fatigue on both movement quantity (absolute values and the LSI-D/ND) and quality in ACL-reconstructed soccer players and to compare them with healthy soccer players in an ecologically valid environment: the local soccer field.

The first hypothesis is that both outcome measures for movement quantity (absolute values and the LSI-D/ND) will not differ between ACL-reconstructed and healthy soccer players in a non-fatigued state. In a fatigued state, we hypothesize that the LSI-D/ND will not differ between ACL-reconstructed and healthy soccer players, while the absolute values are expected to be different. The second hypothesis is that neuromuscular fatigue will decrease movement quality more in ACL-reconstructed than in healthy soccer players. To our knowledge, this is the first study to determine the relevance of ecologically valid RTP testing (i.e. in a fatigued state at the local playing field). Testing in this way could avoid false positive RTP testing scores in ACL-reconstructed soccer players.

Materials and methods

Recreational ACL-reconstructed soccer players and healthy recreational soccer players participated in this cross-sectional study. Two groups of healthy soccer players were chosen based on the playing level and training hours of ACL-reconstructed soccer players. ACL-reconstructed soccer players were included if their own physical therapist considered them to be fully rehabilitated based on the hop test battery of Gustavsson (LSI >90%).[16,21]

Participants

Male recreational ACL-reconstructed soccer players aged between 18 and 30 years old who had ACLR in the VieCuri hospital (Venlo/Venray, the Netherlands), Bernhoven hospital (Oss/Veghel/Uden, the Netherlands) or Clinic ViaSana (Mill, the Netherlands) were invited to participate in this study at the end of their rehabilitation. Up until that point, they attended two to three physiotherapy sessions a week with an experienced sports physical therapist that worked according to ACLR practice guidelines.[21] Exclusion criteria for the ACL-reconstructed soccer players were: other injuries of the lower back, hip, knee or ankle at the moment of testing, knee effusion at the moment of testing, a contralateral ACL injury or previous ipsilateral ACLR.

The control group consisted of healthy male recreational soccer players that played soccer less than, or equal to, three times per week but did not follow a professionally designed training program.[8] Exclusion criteria for the healthy soccer players were: ACL injury or ACLR in the past, other injuries in the lower back, hip, knee, or ankle in the past 4 weeks.

All subjects provided signed, informed consent for participation in this study.

Study procedure

Soccer players were not allowed to participate in strenuous physical activities on the day before testing and wore their own soccer footwear during the measurements, except for the vertical jump (to avoid possible damage to the contact mat). All activities were performed on the soccer field.

Before the RTP measurements in the non-fatigued state, all soccer players completed a warmup session consisting of 5 minutes running at an average speed of 9 km/h and 10 jumping squat repetitions with a knee angle of 90°. The Borg Rating of Perceived Exertion (RPE) scale was used to measure fatigue on a 6 to 20 scale before measurements were taken in the non-fatigued state.[6] After the initial RTP measurements, the soccer players participated in a 1-hour, soccer-specific field training session. In addition to soccer specific drills, exercises focussing on speed, stability, and coordination were included in this session. After the field training, fatigue was measured again using the Borg RPE scale and RTP measurements were performed in the fatigued state.

RTP measurements

The RTP measurements focussed on both quantitative and qualitative aspects of functional performance. All ACL-reconstructed soccer players were familiar with the RTP measurements as these were implemented during their rehabilitation. The healthy soccer players had never performed these RTP measurements previously.

All measurements were performed by the same independent examiner and physical therapist (LvR) who was not involved in the rehabilitation of the included ACL-reconstructed soccer players. The examiner was not blinded for operated/healthy status or operated leg.

Measurements of movement quantity

The hop test battery according to Gustavsson et al.[16] was used for movement quantity measurement: a single-leg vertical jump, a single-leg hop for distance, and a single-leg side hop. This test battery has a sensitivity of 91% and the test–retest reliability of the tests is 0.89, 0.94 and 0.87 respectively.[16] For the absolute values of the hop tests (in meters or number of hops), the results of the operated leg of the soccer players after ACLR and the results of the non-dominant leg of the healthy soccer players were used for data analysis.[26] In addition to the absolute values, the LSI-D/ND was calculated and used for data-analysis.[3,22] To determine the dominant leg for calculation of the LSI-D/ND, the question "if you were to shoot a ball at a target, which leg would you shoot with?" was used.[22] The number of athletes not meeting the RTP criterion of LSI >90% was also calculated.

Measurement of movement quality

A double-leg countermovement jump (CMJ) (test–retest reliability: 0.98) with frontal and sagittal plane video analyses (iPad with Hudl technique application) was used for movement quality measurement, with the first landing analysed using the Landing Error Scoring System (LESS).[11,19,24,25,27,28,30] The LESS is a reliable (intra-rater ICC 0.97) measure, consisting of 17 items of landing technique errors on a range of readily observable items. A LESS score ≥6 indicates poor technique when landing from a jump (maximum score 19) and might increase the risk for an ACL injury.[28,30,32] For the LESS score, the results of the operated leg of the soccer players after ACLR and the results of the non-dominant leg of the healthy soccer players were used for data analysis. The number of athletes not meeting the RTP criterion of LESS <6 was also calculated.

All measurements of movement quantity and quality are described in detail in the Appendix.

This study was conducted according to the ethical guidelines and principles of the international Declaration of Helsinki and was approved by the medical ethics committee of the Radboudumc Nijmegen (2017-3361).

Statistical analyses

Sample size was calculated with G*Power, using fatigue-induced decline in functional performance in soccer players after ACLR compared with healthy controls as a primary outcome measure. Augustsson et al.[1] compared the single-leg hop performance under non-fatigued and fatigued conditions in patients after ACLR. Based on this research, the following values were used for sample size calculation: (1) mean result non-fatigued hop condition involved side 141 cm, (2) mean result fatigued hop condition involved side 109 cm, (3) standard deviation (SD) group 1: 21, (4) SD group 2: 21.[1] An alpha of 0.05 and a power of 0.80 was used for power calculation. A sample size of 14 subjects was required.

For statistical analyses, first, to describe our study population, means and dispersion values were calculated for all soccer players' characteristics. To compare the baseline characteristics between the ACL-reconstructed soccer players and their healthy peers, Chi-square tests and independent samples t-tests were used, where appropriate. Second, to test our hypotheses, means and dispersion values were calculated for the movement quantity and quality measurements. Repeated measures ANOVA was used to determine whether there was an effect of fatigue (i.e. non-fatigued versus fatigued) and/or group (i.e. ACLR versus healthy) on movement quantity and quality measurement results. Levene's test was used to test equality of variances. A Chi-square test was used to calculate if there was a difference between groups in the number of athletes not meeting the RTP criterion in both the non-fatigued and fatigued state.

Data analysis was performed with IBM SPSS Statistics 22.0 (SPSS Inc., Chicago, Illinois).

Results

Between December 2016 and July 2017, 14 soccer players at a mean time of 12.4 months after ACLR and 19 healthy soccer players were included. Characteristics of all soccer players are listed in Table 1. There were no significant differences between groups at baseline. For both groups, there was a significant difference ($p<0.001$) between the Borg RPE scale in the non-fatigued and fatigued state.

Table 1: *Characteristics of the soccer players.*

	ACLR	Healthy	p-value
Number of soccer players	14	19	-
Age, *years* (mean ± sd)	23.2 ± 3.6	21.3 ± 3.0	n.s.
Body Mass Index, *kg/m²* (mean ± sd)	23.4 ± 1.8	21.5 ± 4.8	n.s.
Time post-surgery, *months* (mean ± sd)	12.4 ± 3.5	-	-
Operated leg, *right* (N [%])	7 [50]	-	-
Dominant leg, *right* (N [%])	10 [71]	15 [79]	n.s.
Training hours (mean ± sd)	3.7 ± 2.1	4.3 ± 1.5	n.s.
Borg RPE scale non-fatigued (mean ± sd)	7.3 ± 1.1	8.2 ± 2.3	n.s.
Borg RPE scale fatigued (mean ± sd)	14.9 ± 1.1	14.1 ± 2.7	n.s.

RPE=rate of perceived exertion

Measurement of movement quantity

Mean absolute values of the hop tests (Table 2) showed no significant before-after effect, no group effect and no time*group interaction for the vertical jump. For the hop for distance, no significant before-after effect or group effect was found but a significant time*group interaction was found ($p=0.042$) indicating that the ACL-reconstructed soccer players jumped a shorter distance in the fatigued state (1.70 versus 1.66 m), while their healthy peers did not. For the side hop, no significant before-after effect or group effect was found but a significant time*group interaction ($p=0.022$) was reported, indicating that the number of hops for the ACL-reconstructed soccer players decreased in the fatigued state (59 versus 56 hops) while the number of hops for their healthy peers did not.

For the LSI-D/ND (Table 2), no significant effects were found for the vertical jump, hop for distance or side hop.

In the non-fatigued state, there were two (vertical jump and hop for distance) to four (side hop) ACL-reconstructed soccer players that did not meet the RTP criterion for LSI >90%, despite their own physical therapist reporting that they had met this criterion. However, there were no significant differences between the number of athletes not meeting the RTP criterion when comparing ACL-reconstructed with healthy soccer players, neither in the non-fatigued state nor in the fatigued state (Table 2).

Measurement of movement quality

LESS scores increased significantly in the fatigued state ($p<0.001$), were significantly higher in the ACL-reconstructed soccer players ($p=0.026$), and increased significantly more in the ACL-reconstructed soccer players compared to their healthy peers ($p<0.001$) (Table 3; Figure 1).

In the non-fatigued state two athletes in both groups were not able to meet the RTP criterion of LESS <6. However, in the fatigued state there was a significant difference between groups ($p=0.002$), with 12 (86%) of the ACL-reconstructed soccer players not meeting the criterion compared to six (32%) of the healthy soccer players (Table 3).

Discussion

The most important finding of the present study was that, in a fatigued state, the LESS score increased more in the ACL-reconstructed soccer players compared to healthy soccer players, when tested on the soccer field (ecologically valid environment). Moreover, the number of athletes not meeting the LESS RTP criterion increased drastically in the fatigued state. Movement quantity (both absolute values and LSI-D/ND) did not differ between ACL-reconstructed and healthy soccer players. These findings suggest that movement quality measurement in a fatigued state should be used in RTP testing of ACL-reconstructed soccer players.

For movement quantity measurements, the first hypothesis that both outcome measures (absolute values and the LSI-D/ND) would not be different between ACL-reconstructed soccer players and their healthy peers in a non-fatigued state was confirmed. However, in the fatigued state there was also no difference in both absolute values and the LSI-D/ND between ACL-reconstructed and healthy soccer players, while it was expected that absolute values would be different. Nevertheless, the ACL-reconstructed soccer players had a significantly decreased performance when comparing the non-fatigued with the fatigued state. The first

Table 2: *Mean absolute values, limb symmetry indices (LSI) and number of athletes not meeting the RTP criterion of LSI >90% of the hop test battery of Gustavsson (movement quantity) in the non-fatigued and fatigued state.*

	ACLR N-F	ACLR F	Healthy N-F	Healthy F
Vertical jump, *absolute value in m* (mean ± sd)	0.24 ± 0.05	0.23 ± 0.05	0.23 ± 0.06	0.24 ± 0.06
Vertical jump, *LSI-D/ND in %* (mean ± sd)	100.1 ± 15.4	99.1 ± 19.7	97.7 ± 12.5	97.6 ± 11.4
Athletes not meeting the LSI >90% criterion, *N (%)*	2 (14)	3 (21)	8 (42)	6 (32)
Hop for distance, *absolute value in m* (mean ± sd)	1.70 ± 0.18*	1.66 ± 0.18	1.61 ± 0.28	1.66 ± 0.28
Hop for distance, *LSI-D/ND in %* (mean ± sd)	97.2 ± 5.5	95.6 ± 8.0	96.8 ± 8.4	96.3 ± 8.0
Athletes not meeting the LSI >90% criterion, *N (%)*	2 (14)	4 (29)	6 (32)	4 (21)
Side hop, *absolute value in N* (mean ± sd)	59 ± 11*	56 ± 12	55 ± 12	57 ± 10
Side hop, *LSI-D/ND in %* (mean ± sd)	95.8 ± 10.6	95.1 ± 14.3	100.0 ± 17.9	99.7 ± 9.6
Athletes not meeting the LSI >90% criterion, *N (%)*	4 (29)	3 (21)	4 (21)	4 (21)

N-F=non-fatigued, F=fatigued

** Significant difference between non-fatigued and fatigued state*

Table 3: *Landing Error Scoring System (LESS) score at the double-leg countermovement jump (movement quality) in the non-fatigued and fatigued state.*

	ACLR N-F	ACLR F	Healthy N-F	Healthy F
LESS, *score (mean ± sd)*	4 ± 2*	7 ± 1**	4 ± 2	4 ± 2
Athletes not meeting the LESS <6 criterion, *N (%)*	2 (14)	12 (86)**	2 (11)	6 (32)

N-F=non-fatigued, F=fatigued

** Significant difference between non-fatigued and fatigued state*

*** Significant difference with healthy soccer players*

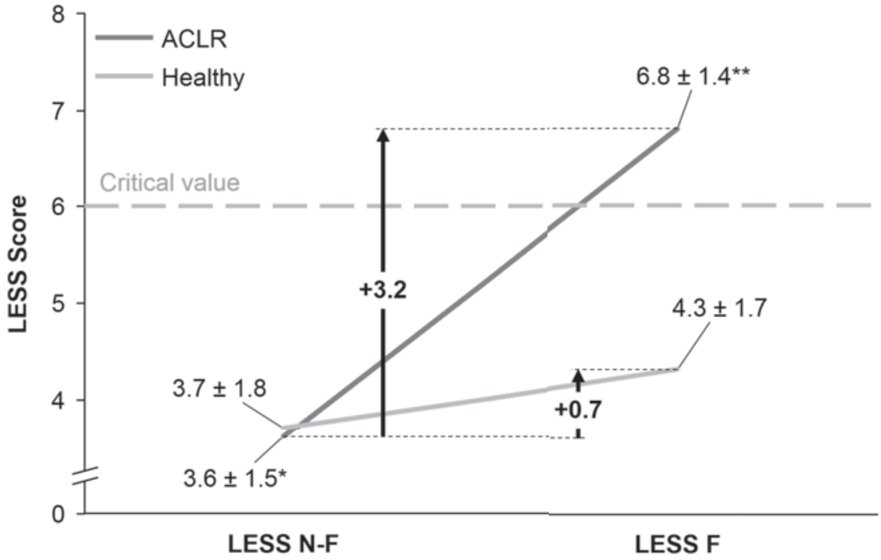

Figure 1. *Landing Error Scoring System (LESS) score for ACL-reconstructed and healthy soccer players in the non-fatigued and fatigued state.*

hypothesis was based on the findings of Wellsandt et al.[36] and Gokeler et al.[13] who found that ACLR patients were able to reach the LSI cut-off of 90% at 6 and 7 months, respectively, without reaching their estimated preinjury capacity or the normative values of healthy controls. It is unclear whether the ACLR patients in the study of Wellsandt et al.[36] and Gokeler et al.[13] had completed their rehabilitation. The aforementioned results imply that they had not, which is also supported by the findings that ACLR rehabilitation should last at least 9 months to minimise the risk for a second ACL injury.[15] An alarmingly high number of pivoting athletes (72–86%) are released to full, unrestricted sports activities without meeting the RTP criteria, despite a plethora of evidence showing that not meeting the quantitative RTP criteria increases the risk for a second ACL injury.[5,15,17,35]

The LSI-D/ND, which compares the values of the dominant and non-dominant leg, showed no differences between ACL-reconstructed and healthy soccer players, both in a non-fatigued and fatigued state. Therefore, using the LSI-D/ND could be useful in RTP measurements of pivoting athletes after ACLR. Normally, a cut-off value of 90% is sought[15,17,34] but the results in this study (see Table 2) suggest that the LSI-D/ND should be at least 95% for hop tests at the end of ACLR rehabilitation.

For movement quality measurement, the LESS was significantly higher in the ACL-reconstructed soccer players than in their healthy peers (6.8 and 4.3, respectively) in a fatigued state, but not in the non-fatigued state (3.6 and 3.7, respectively). Gokeler et al.[12] found different results in their study when comparing the LESS between patients 10 months after ACLR and healthy controls in a non-fatigued and fatigued state. They used a fatigue protocol of 10 double-legged squats to 90 degrees of knee flexion and 2 double-legged CMJ's, which were repeated until it was no longer possible to reach 70% of the maximum CMJ height for 2 trials.[12] They also used an RPE score to rate fatigue, however, their fatigued state RPE of 18.7 was higher than the 14.1 (healthy soccer players) and 14.9 (soccer players after ACLR) in this study. Gokeler et al.[12] found that ACLR patients already had a higher LESS in the non-fatigued state (6.5 versus 2.5). In a fatigued state, the difference was smaller: 7.0 for ACLR patients and 6.0 for healthy controls. It is unclear if these patients had finished their rehabilitation but considering two patients did not feel confident enough to perform the LESS protocol in the fatigued state, it would suggest that they were not fully rehabilitated.[12] The ACLR patients in this study were 12.4 months postoperative and had completed their rehabilitation, which might explain the difference in the non-fatigued LESS with the ACLR patients of Gokeler et al.[12]

The majority of ACL-reconstructed soccer players in this study might still be at risk for a second ACL injury, because it was found that, on the soccer field, four soccer players did not meet at least one RTP criterion in the non-fatigued state. Interestingly, all soccer players met the hop test RTP criterion of LSI >90% in the physical therapy practice before partaking in the study. Apparently, the different conditions (e.g. surface and wind) of this ecologically more valid environment appear to make it more difficult to meet the hop test RTP criterion. Moreover, considering that soccer players with a LESS ≥6 are suspected to be more prone to a first-time ACL injury (which also might hold true for the risk for a second ACL injury), 86% of the ACL-reconstructed soccer players and 32% of their healthy peers in our study, had an increased risk.[29]

This study has some limitations. First, the use of a soccer-specific training in this study, with a Borg scale as the measurement of fatigue, could cause a different form of fatigue than fatigue protocols used in other studies. However, the training produced soccer-specific fatigue, implying an ecologically valid fatigue protocol used in this study. Second, all ACL-reconstructed soccer players were familiar with the RTP measurements as these were implemented during their rehabilitation, but the healthy soccer players had never performed these RTP measurements before. Healthy soccer players could have had a learning effect in movement quantity, visible in the absolute values of all hop tests increasing in the fatigued state compared to the non-fatigued state. However, this still implies that the ACL-reconstructed soccer players have an acceptable performance compared to their healthy peers.

The results of the present study can be used in day-to-day clinical practice when rehabilitating ACL-reconstructed soccer players. Determining the moment for RTP based on hop tests and movement quality measurement performed in the physical therapy practice could cause false positive RTP scores, allowing soccer players to return to play too early, with a possible increased risk for a second ACL injury. According to the results of the present study, when testing on the soccer field and in a fatigued state (ecologically valid environment), prolonged rehabilitation seems necessary to meet the RTP criteria for movement quality and have comparable results to healthy peers.

Conclusions

For ACL-reconstructed soccer players, the LSI-D/ND should ideally be at least 95% for hop tests at the end of rehabilitation. Moreover, hop tests and movement quality measurement are suggested to be performed in an ecologically valid environment (i.e. in a fatigued state at the local playing field) to avoid false positive RTP testing scores in ACL-reconstructed soccer players.

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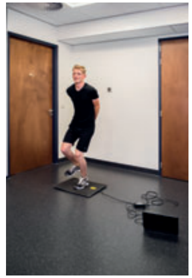
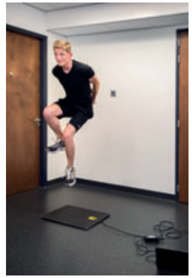
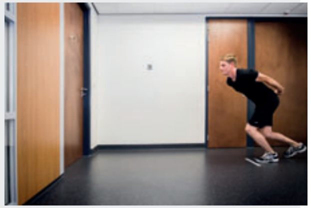
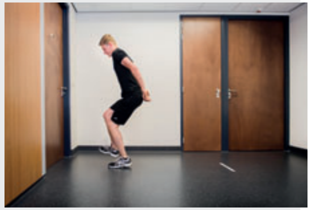
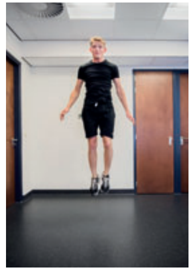
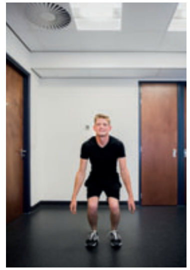
Appendix: Measurements of functional performance

Test	Subject's start position	Procedure	Sessions	Recorded variable	Picture*
Quantity of movement					
Vertical jump	Upright position, standing on one leg with the hands placed behind the back.[16]	The subject quickly bents his knee as much as desired and then immediately jumped upwards, attempting to maximise the height jumped. The subject had to perform a controlled, balanced landing and had to keep the landing foot in place (2–3 s).[16] A Pro-Jump contact mat (ProCare, the Netherlands) was used to measure jump height in centimeters. This test was performed on football socks, because of the chance of damage to the contact mat when wearing soccer foot-wear.	Two practice sessions, before three test sessions for each leg. Between practice and test sessions, a one minute rest period. Between each test session, a 30 second rest period. The non-operated leg was tested before the operated leg.	The highest jump of the three test sessions in meter. The LSI-D/ND was calculated as the value of the dominant leg divided by the value of the non-dominant leg multiplied by 100.	 

Test	Subject's start position	Procedure	Sessions	Recorded variable	Picture*
Hop for distance	Upright position, standing on one leg with the hands placed behind the back.[16]	The subject hopped as far as possible and landed on the same leg. Free leg swing was allowed. The subject had to perform a controlled, balanced landing and had to keep the landing foot in place until (2–3 s) the test leader had registered the landing position. Failure to do so resulted in a disqualified hop. The distance was measured in centimetres from the toe at the push-off to the heel where the subject landed.[16]	Two practice sessions, before three test sessions for each leg. Between practice and test sessions, a one minute rest period. Between each test session, a 30 second rest period. The non-operated leg was tested before the operated leg.	The furthest jump of the three test sessions in meter. The LSI-D/ND was calculated as the value of the dominant leg divided by the value of the non-dominant leg multiplied by 100.	 
Side hop	Upright position, standing on one leg with the hands placed behind the back.[16]	The subject jumped from side to side between two parallel lines. The lines were created by foam (Kadeem marker spray) placed 40 cm apart on the soccer field. The subjects were instructed to jump as many times as possible during a period of 30 s. The number of successful jumps performed, without touching the tape, was recorded. Touching the tape was recorded as an error.[16]	A few practice jumps were allowed to familiarise themselves with the jumping distance, before they performed one test session of 30 seconds. The non-operated leg was tested before the operated leg.	The amount (N) of correct jumps. The LSI-D/ND was calculated as the value of the dominant leg divided by the value of the non-dominant leg multiplied by 100.	 

Test	Subject's start position	Procedure	Sessions	Recorded variable	Picture*
Quality of movement					
Double-leg countermovement jump	The subject started at two legs with the feet hip width apart.	Subjects had to jump as high as possible, perform a landing on two feet and immediately jump as high as possible again. Arm swing was allowed during the jumps.[27,28,30]	One practice session was allowed before two test sessions. One session was frontally filmed, one session was sagittally filmed at the side of the operated leg (soccer players after ACLR) and non-dominant leg (healthy soccer players).[24]	The first landing of the countermovement jump was used to analyse with the Landing Error Scoring System (LESS).	 

The pictures are examples of the tests in a clinical setting. All tests in this study were performed on the soccer field.

Chapter 9

General discussion

This thesis provides new insights into the rehabilitation of pivoting athletes following anterior cruciate ligament reconstruction (ACLR) and the functional performance measurements required to determine the appropriate moment for return to play (RTP).

In Part I of this thesis "Reconstructing the rehabilitation program" we described the development of a postoperative rehabilitation protocol for athletes after ACLR. In **Chapter 2** we presented a state-of-the-art, evidence-based ACLR rehabilitation practice guideline, which fills gaps in the available scientific literature regarding the optimal treatment protocol with expert-opinion.[49] In **Chapter 3** we questioned the use of an accelerated rehabilitation for athletes after ACLR using hamstrings (HS) grafts, due to probable tunnel widening and incomplete restoration of strength and neuromuscular control within a 6 to 8 month period.[35,72] From Chapter 2 and 3 we concluded that the incorporation of functional goal-based criteria into the rehabilitation protocol is necessary: the so-called traffic-light method. This is a relatively new concept in rehabilitation, but assures a more patient-tailored rehabilitation process.[35,49,60] The practice guideline in Chapter 2 uses the International Classification of Functioning, Disability and Health (ICF)[73] to identify rehabilitation interventions and goals for progression to the next rehabilitation phase. Using this method, rehabilitation following ACLR consists of three phases, with a total duration of 9 to 12 months.[49]

In Part II of this thesis "Playing with return to play criteria" we reviewed the best-evidence for an RTP test battery. Firstly, we clarified that most previous research is lacking clear test recommendations, since only strength tests or hop tests were employed. Therefore, an extensive test battery is proposed, which includes strength tests, hop tests (all assessing movement quantity) and measurement of movement quality, as described in **Chapter 4**. Thereafter, we used this test battery to compare healthy and ACLR athletes 2 to 9 years after ACLR. No differences exist in movement quantity, but movement quality is worse in athletes after ACLR, especially regarding dynamic knee valgus (**Chapter 5**). In **Chapter 6** we showed the results for implementation of the practice guideline from Chapter 2. Only 44% of all pivoting athletes are tested by their own physical therapist before RTP and 77% were given incorrect RTP advice. Although sports physical therapists more often adhere to the practice guideline criteria compared to physical therapists without a specialisation in sports, the adherence is still too low.

Regarding criteria probably influencing RTP, we found that "if you were to shoot a ball at a target, which leg would you shoot with?" is the most appropriate question to determine leg dominance in healthy adults (**Chapter 7**). This question is needed when comparing healthy athletes with athletes after ACLR. We discovered that movement quality again is an issue when comparing ACL-reconstructed soccer players with healthy soccer players, tested in an ecologically valid environment. We clearly demonstrated that movement quality is worse under fatigue when comparing ACL-reconstructed soccer players with healthy soccer players, implying that rehabilitation might need to be extended to improve performance under fatiguing conditions (**Chapter 8**).

The first part of this discussion compares the practice guideline, as presented in Chapter 2, with previous ACLR rehabilitation programs and discusses the differences in light of graft remodelling and motor learning.

In the second part of this general discussion, the current recommendations regarding RTP measurements are discussed and compared with the proposed extensive test battery from Chapter 2 and 4.

Reconstructing the rehabilitation program

Chapter 2 and 3 comment on the accelerated rehabilitation protocol as first described by Shelbourne[66] in the 90's and still used by many orthopaedic surgeons world-wide, regardless of graft choice.[28,61] To understand the criticism of the accelerated rehabilitation, the term "accelerated" needs to be clarified. In our opinion, a distinction needs to be made between an accelerated, brace-free start to rehabilitation allowing immediate full extension and full weight-bearing, with accelerated return to play within 6 months of surgery. Nowadays, early progression to full range of motion and immediate weight-bearing as tolerated without a brace is widely accepted and proven non-harmful, in terms of graft laxity.[10,11,30,45,54,62,65,66,70] As stated in the practice guideline of **Chapter 2**, this thesis fully supports the use of an accelerated brace-free start to rehabilitation after ACLR as a brace might not protect graft stability, but can alter neuromuscular control.[43,68] An accelerated RTP, however, is not encouraged due to two factors a physical therapist must take into account during rehabilitation: biological aspects of graft healing (e.g. graft remodelling) and aspects of functional performance (e.g. motor learning strategies).

Recently, ACL experts suggested that RTP probably should be delayed until two years after ACLR, because of both biological healing and time needed to optimise functional performance, thereby drastically reducing the chance for second ACL injuries.[55]

Graft remodelling and consequences for strength training during rehabilitation

Chapter 3 of this thesis clearly states that an optimal balance between training and graft loading is necessary to prevent ACL graft elongation and optimise graft healing during rehabilitation.[35] The practice guideline in **Chapter 2** pays attention to graft remodelling with the selected strength exercises in phase 1 and 2 of the rehabilitation program (ICF domain of body functions and structures). Quadriceps strength exercises that limit the load on the ACL graft are needed in the first two phases of rehabilitation.

Graft remodelling process

Graft healing after ACLR occurs at two sites: intra-tunnel graft incorporation and intra-articular graft remodelling, often referred to as ligamentization.[36,37] Immediately after ACLR, the weak link is the fixation of the graft into the femoral and tibial tunnels. The incorporation of a HS graft into the tunnels takes approximately 6 to 12 weeks.[21,37] During this 12-week period, the ACL graft undergoes two intra-articular remodelling phases: the early graft healing phase, marked by necrosis in the centre of the graft and hypocellularity in the first four weeks, and the proliferation phase, characterised by increased numbers of myofibroblasts, production of type III collagen, increase of cellularity and revascularization until week 12. This latest phase corresponds with the lowest mechanical properties of the intraarticular part of the ACL graft between 6 and 8 weeks after ACLR.[36,37] This underlines the need to select proper strength exercises during phase 2 of the rehabilitation after ACLR. The final phase of intra-articular graft remodelling, starting from week 12 and called the ligamentization or maturation phase, is defined by decreased vascularity and organization of collagen fibers. In this phase, the ACL graft restructures toward the properties of the intact ACL. In animals, the biological properties of the intact ACL will be restored between 6 and 12 months.[36] However, in humans, full restoration of the mechanical strength of the intact ACL will probably never be reached due to increased collagen type III synthesis, which has lower mechanical strength than the original type I collagen. The complete remodelling process in humans may take up to two years.[14,37]

Quadriceps strength exercise selection during rehabilitation

ACL injury is known to reduce upper leg strength and functional performance. A preoperative quadriceps strength deficit of more than 20% has a negative consequence on outcomes up to two years after ACLR.[18] Therefore, quadriceps strengthening is an important part of both preoperative and postoperative rehabilitation. Table 1 depicts the progression of strength exercises in the history of postoperative rehabilitation protocols. According to the practice guideline of **Chapter 2**, closed kinetic chain (CKC) exercises at low knee flexion angles (0 to 50 degrees), like mini squats and lunges, are the most appropriate choice.[21,49] Within this range, graft loading is sufficient enough to stimulate graft cell production of cellular and extracellular components for preservation of graft stability, without compromising graft integrity.[36] In contrast to open kinetic chain (OKC) exercises, adding external resistance during CKC exercises does not increase load on the ACL graft, making CKC exercises particularly suitable for strength training in the first three months after ACLR (phase 2 and the start of phase 3 in rehabilitation).[21,44] Shelbourne already incorporated these CKC exercises into the accelerated rehabilitation protocol and in recent decades, Risberg et al. adopted this method of quadriceps strength training.[62,66] However, the most prominent disadvantage of these protocols is that they are merely time-based and there is little to no possibility of accounting for inter-individual variation in recovery and baseline level.

The practice guideline in **Chapter 2** states that OKC exercises are also useful to regain quadriceps strength, however they can only be used from the fourth postoperative week, in a restricted range of motion (90-45 degrees of flexion) and without additional weight for HS grafts. It is not until the third postoperative month that a full range of motion and additional weight is allowed for OKC quadriceps exercises with a HS graft, typically also comprising the first two phases of remodelling.[31,49] This differs from the evidence-based protocol of Van Grinsven et al. who state that both OKC and CKC quadriceps exercises can be performed from week two, in a limited range of motion from 90-40° and 0-60° respectively.[30] However, several studies have demonstrated that it is better to postpone these restricted OKC exercises until week four, to prevent graft elongation.[23,31,74]

Table 1: *Time-based quadriceps strength exercise prescription during the history of ACLR rehabilitation protocols.*

Week	Traditional rehabilitation, Shelbourne[66]	Accelerated rehabilitation, Shelbourne[66]	Neuromuscular & strength rehabilitation, Risberg[62]	Evidence-based rehabilitation, van Grinsven[30]
1	Active straight leg raises	Active straight leg raises	Active straight leg raises; 4x 20-30 repetitions	Active straight leg raises; OKC exercises ROM 90-40°; CKC exercises ROM 0-60°(squats)
2-4	Leg extension 90-60° without resistance	Add step up, leg press and squat		OKC exercises from week 5 an extra 10° toward extension every week; CKC exercises ROM 0-60°
5-8	Active straight leg raises with increased weight; Leg extension 90-45° without resistance	Gradually increase intensity and weights	Add squat, step up; 3x 15-20 repetitions	
9-19	Add step up and step down; Gradually increase intensity and weights of all exercises		Add step down, leg press and squat lunge; 3x 12-15 repetitions	CKC exercises ROM 0-90°; Gradually increase intensity and weights of all exercises
20-25			Change to 3x 6-8 repetitions with increased load	
26-52	Add squats			

Motor control and learning during rehabilitation

As already described in **Chapter 2**, the native ACL contains mechanoreceptors and thereby influences the neuromuscular control of the knee. ACL deficiency causes partial de-afferentation, and thereby diminished activation of sensorimotor cortical areas and altered spinal and supraspinal motor control.[15,38,77] Since motor control is an interface between function, activities and participation, the changes in motor control need to be addressed during the rehabilitation after ACLR. Considering the ACL graft does not completely replace the neuromuscular function of the native ACL, due to a lack of ingrowth of new mechanoreceptors and the changes in sensorimotor cortical activation, motor learning should be emphasised during rehabilitation. Besides this, rehabilitation after ACLR will be different for every individual, partially based on individual differences in neuromotor learning capacity and flexibility after ACLR. That is why the ACLR rehabilitation practice guideline in **Chapter 2** underlines an individual approach and stresses the importance of a shift from time-based rehabilitation to goal-based rehabilitation with neuromuscular goals and criteria to manage the rehabilitation process at the ICF domains of activity and participation.[49]

Motor learning principles

Motor learning is a set of processes associated with practice or experience leading to relatively permanent changes in the capability for skilled movement.[64] According to the motor learning model of Fitts and Posner there are three different phases when learning a new skill.[22] The first phase, or cognitive phase, is characterized by a step-by-step execution of the skill, which requires considerable attentional capacity. As a consequence, movements are controlled in a conscious manner, making them relatively slow, abrupt, and inefficient. This results in a rather inconsistent performance.[2,22] When learning an active dynamic gait pattern in the first weeks after ACLR, for example, the physical therapist often needs to give a verbal instruction to extend the knee more during the stance phase (i.e. explicit instruction). In this way the athlete typically uses an explicit motor learning technique with an internal focus of attention (e.g. focus on the knee itself).[2,22,75] This appeals more to cortical control, while spinal control is important to automatically perform movement patterns. Once the athlete has acquired the basic movement pattern, the second, or associative, phase of learning begins. This phase is characterized by more subtle movement adjustments. The movement outcome is more reliable, inefficient co-contractions are gradually reduced, and the movement becomes more economical. In addition, at least parts of the movement are controlled more automatically and more attention can be directed to other aspects of performance.[2,22] When taking the gait pattern as an example, the athlete now is able to talk during walking while maintaining an active dynamic gait pattern. After extensive practice, the athlete reaches the third, or autonomous, phase, which is characterized by fluent and seemingly effortless motions. Movements are not only accurate, with few or no errors, but also very consistent. In addition, movement production is very efficient and requires relatively little muscular energy. The skill is performed largely automatically at this stage, and movement execution requires little or no attention. Most of the time, the physical therapist does not need to give any verbal feedback and the athlete is able to use an implicit motor learning technique (i.e. focus on the outcome of the movement).[2,22] Implicit learning makes movements more efficient and more effective and reduces the chance of choking under pressure, compared to explicit learning.[3,4,25] Therefore, implicit learning has gained popularity in rehabilitation after ACLR and also in the prevention of (second) ACL injuries.[24,47] The physical therapist has several options to stimulate implicit motor learning: learning with an external focus of control, including learning by observation and differential learning.[5,6] Learning with an external focus of control is induced when a patient's attention is directed towards the outcome or effect of a movement.[24] For example instruct the athlete to push to the ground with his foot to facilitate knee extension during the stance phase. With differential learning, variability during the motor learning process is a fundamental basis for motor learning. Variability can be administered by changing the athlete (for example raising the arms when kicking a ball), the task (kicking the ball from the right or the left to a goal), or the environment (kicking the ball on grass or on the street). During this process, the athlete will create his own optimal movement pattern.[5,32]

Neuromuscular and sport specific exercise selection during rehabilitation

Due to the changes in the sensorimotor system, training of neuromuscular control has to be part of rehabilitation after ACL injury or ACLR. Table 2 displays the progression in neuromuscular and sport specific exercises in the different rehabilitation protocols. According to the practice guideline in **Chapter 2**, enhancing functional performance (e.g. neuromuscular and sport specific training) should be highlighted during rehabilitation after ACLR, especially in phase 2 and 3 of the practice guideline.[49]

Both the traditional and accelerated rehabilitation protocol of Shelbourne do not highlight the importance of neuromuscular training.[16,66] Risberg et al. are the first to incorporate neuromuscular training into the ACLR rehabilitation protocol. They describe that a patient must be able to maintain static balance before dynamic joint stability exercises are performed and that sensory feedback is challenged by changing the base of support (from an even surface to a wobble board) or using distractions (a ball or perturbation). Thereafter, jumping, running and agility drills are allowed.[62] Van Grinsven et al. include neuromuscular training as soon as walking without crutches is possible. They use the same progression through static balance exercises, dynamic balance exercises, running, jumping and agility drills as per Risberg's rehabilitation protocol.[30]

Table 2: *Time-based neuromuscular and sport specific exercise prescription during the history of ACLR rehabilitation protocols.*

Week	Traditional rehabilitation, Shelbourne[66]	Accelerated rehabilitation, Shelbourne[66]	Neuromuscular & strength rehabilitation, Risberg[62]	Evidence-based rehabilitation, van Grinsven[30]
1	None	None	None	None
2-4	None	Stationary bicycling	Stationary bicycling; Single-leg balance exercises stable surface	Stationary bicycling; Single leg balance exercises stable to unstable surface; Dynamic joint stability exercises
5-8	None	Lateral shuffles and cariocas; Running; Agility drills	Single-leg balance exercises unstable surface and/or an added motoric or cognitive task; Dynamic joint stability exercises (i.e. lunges, step up/down)	
9-19	Stationary bicycling	Increased agility drills	Dynamic joint stability exercises unstable surface or with extra weight; Two-legged jumps; Running	Dynamic joint stability exercises; Two-legged jumps to single-leg jumps; Bicycling outside; Running
20-25			Single-leg jumps; Agility drills	Agility drills
26-52	Lateral shuffles; Running; Agility drills			

The challenge with motor learning strategies is to incorporate implicit learning strategies to enhance functional performance. Our recommendation is to use these strategies as soon as possible during the rehabilitation after ACLR, or at least when a patient reaches the associative phase of learning a new skill, which should be during phase 2 of the rehabilitation process according to the practice guideline in **Chapter 2**. There also needs to be a transition from a predictable context (e.g. physical therapy practice, gym) to a context with unpredictable changes (e.g, soccer field). With this in mind, physical therapists nowadays need to make the transfer to the daily sporting environment of the specific athlete. This on-field rehabilitation is necessary for the motor learning process and is already extensively used in professional athletes.[34,76] Therefore, our recommendation would be to train in an ecologically valid environment (e.g. on the soccer field for a soccer player) to stimulate an athlete's capability and performance, at least during phase 3 of the rehabilitation process according to the practice guideline in **Chapter 2**.

Playing with return to play criteria

RTP criteria are an important part of the rehabilitation program after ACLR. Several RTP tests already exist and can be used to monitor an athlete's progression during rehabilitation, as stated in **Chapter 2**.[17,39,49,60] In the discussion below, we distinguish between movement quantity and movement quality measurements.

Movement quantity measurements

In **Chapter 1** of this thesis we showed that previous ACLR rehabilitation protocols already describe the use of movement quantity measurements. Strength and hop tests are the most commonly used movement quantity measurements. In both the traditional and accelerated rehabilitation protocol of Shelbourne, only strength measurements were included,[66] but Risberg et al. introduced the use of hop tests in their protocol.[62] Since then, hop tests are commonly used in general practice as these tests are relatively cheap and easily accessible for every physical therapist.

Recently, two research groups showed that movement quantity measurements are associated with second ACL injuries. By using isokinetic strength tests and a hop test battery as RTP criteria, athletes meeting the discharge criteria of an LSI above 90% on all tests have a decreased risk for new acute knee injuries and second ACL injuries.[29,40] In **Chapter 6** we showed that only 19% of all pivoting athletes meet the quantitative RTP criteria of an LSI above 90% on 4 strength tests and 3 hop tests,[50] implying that the remaining 81% in this group might have an increased risk for a second ACL injury when returning to play without meeting the RTP criteria

Use of the limb symmetry index when measuring movement quantity
Measurements of movement quantity are often expressed in the LSI, which is calculated by dividing the value of the injured leg by that of the non-injured leg multiplied by 100%. In the early 90's, Barber et al. described that an LSI of 85% or more would allow an athlete to return to his preinjury level. They based this on the finding that 93% of a group of healthy pivoting athletes scored an LSI of 85% or more on a single-leg vertical jump, a single-leg hop for distance, and a single-leg timed hop.[1] Most experts have adopted this LSI of 85% over the years, but others only allow return to play when the LSI is above 90%.[29,40]

Recently, Thomeé et al. suggested that an LSI of more than 100% is required for knee extensor and flexor strength when returning to pivoting and contact sports, compared to 90% for non-pivoting or non-contact sports. For hop test performance, an LSI of 90% or more would be reasonable for both categories of sports.[69]

Recently, the use of the LSI is criticised by several ACL experts. An ACL rupture might seem a single-leg injury, but in practice seems to be a double-leg problem.[7] Since movement quantity of the non-injured leg also deteriorates during the period of ACL rupture, reconstruction and rehabilitation, the LSI overestimates the function of the operated leg.[26,71] In this way, comparison with healthy athletes or preoperative movement quantity measurements seems to be a better option. However, preoperative measurements are lacking for almost all amateur athletes and comparison with healthy athletes is difficult, because reference values are scarce. In **Chapter 5** we showed that athletes more than two years after ACLR have comparable absolute values with healthy athletes for both strength and hop tests. Furthermore, in **Chapter 8** we described that soccer players, who are adequately rehabilitated according to the practice guideline of Chapter 2, have comparable absolute hop test values and LSI's compared with healthy soccer players at the end of their rehabilitation period.[52]

In **Chapter 7** we investigated how to determine leg dominance in healthy adults. This could have implications for movement quantity measurement, since this allows comparison between healthy athletes and ACLR athletes, calculating the LSI as the value of the dominant leg divided by the value of the non-dominant leg, multiplied by 100.[51] In **Chapter 8** we used this LSI-D/ND and suggest that it should be above 95% for hop tests at the moment of RTP.[52] The LSI-D/ND and absolute values for strength and hop test from **Chapter 5 and 8** might be used as reference values for the specific subgroup of ACLR patients they describe.

Movement quality measurements

In **Chapter 5 and 8** we described a difference in movement quality between ACLR athletes and healthy athletes.[19,52] Apparently, even with rehabilitation according to the practice guideline from Chapter 2, neuromuscular control is difficult to target and focus on motor learning strategies need to be implemented more.

Movement quality is often referred to as a risk factor for primary and secondary ACL injuries,[33,57,59] but it is still not a standard component of return to play test batteries. Therefore, we proposed a test battery in **Chapter 2 and 4** including movement quality measurements. Movement quality measurement should include more than just dynamic knee valgus, as hip and knee flexion angles and lateral flexion of the trunk also contribute to correct quality.[20,33,49,57,59] The Landing Error Scoring System (LESS) is a valid and reliable way to measure movement quality and takes into account 15 different items of neuromuscular control during a drop jump.[56,58] A LESS below 6 is required to minimize the risk of a second ACL injury.[57] In **Chapter 6** we showed that 64% of pivoting athletes are able to meet the LESS return to play criterion, indicating a possible higher risk for a second ACL injury in those not meeting the criterion but still returning to play.

Neuromuscular fatigue and movement quality

Neuromuscular fatigue is one of the main risk factors for lower extremity injuries in general and probably also contributes to the occurrence of ACL injuries. The reasons for this include an increased strain on the ACL, decreased energy absorption capacity of muscles and tendons, decreased coordination and therefore reduced functional performance under fatigue.[13,48,53] In **Chapter 8** we showed that soccer players after ACLR, that completed rehabilitation according to the practice guideline in Chapter 2, have insufficient movement quality after a one-hour soccer training, as expressed by the LESS. 86% do not meet the LESS return to play criterion when fatigued, compared to 32% of healthy soccer players.[52] This highlights the need to measure movement quality in neuromuscular fatigued conditions.

ACLR rehabilitation practice guideline adherence

In **Chapter 6** we showed that only 16% of all pivoting athletes meet all nine quantitative and qualitative RTP criteria as proposed in the practice guideline in **Chapter 2**,[50] implying that the other 84% of this group might have an increased risk for a second ACL injury by returning to play despite not meeting the RTP criteria. The most prominent challenge with this is that physical therapists do not adhere to the ACLR practice guideline concerning the use of RTP criteria in daily practice. Only 44% of all athletes were tested according to practice guideline criteria before the RTP decision. There is a difference between physical therapists with different clinical specialisation; 52% of the athletes rehabilitated by a sports physical therapist were tested according to the guideline versus 34% of the athletes rehabilitated by a physical therapist without a specialisation in sports.[50] This is in line with previous studies on guideline adherence in physical therapy in Belgium and the United States. These studies also found a moderate adherence level to knee osteoarthritis and low back pain guidelines and a better adherence for physical therapists with a specialisation compared to those without.[41,67] Apparently, the implementation of practice guidelines into clinical practice remains difficult and deserves more attention from the Royal Dutch Society for Physical Therapy (KNGF).

Conclusion

To enhance functional performance following ACLR, physical therapists are advised to follow the practice guideline from **Chapter 2** and ACL rehabilitation infographic (see Addendum) when rehabilitating pivoting athletes, taking into account graft remodelling and motor learning principles when selecting strength and neuromuscular exercises. In addition, movement quality needs to be a subject of attention during the rehabilitation process, both in non-fatigued and fatigued conditions. At the end of the rehabilitation process there needs to be a transfer from the physical therapy practice to the sport specific environments.

Based on this thesis, we postulate that pivoting athletes after ACLR are allowed to return to play when:

- rehabilitation lasted for at least 9 months. Two years might be ideal to minimise the risk for second ACL injury, especially in terms of movement quality, but it is extremely difficult to explain this to our athletes;
- there is no pain, no effusion, no functional instability and a full range of motion;
- strength tests for quadriceps and hamstrings, including an endurance test, score an LSI above 90% and are similar to preoperative or reference values;
- a hop test battery, including an endurance test, and performed in an ecologically valid environment scores an LSI-D/ND above 95% and is similar to preoperative or reference values;
- the LESS score for movement quality is lower than 6, preferable tested in a neuromuscular fatigued condition, for example after a training with the athletes' own team;
- on-field rehabilitation is completed and neuromotor control is considered optimal for the specific sport;
- the athlete is mentally ready to return to play.

Figure 1 integrates all RTP criteria into the ICF and biopsychosocial model.

Challenges for future research

Considering the results of this thesis, there are four main challenges for future research.

Firstly, because of the lack of high-level evidence, the practice guideline for rehabilitation after ACLR is based on a large amount of low-level evidence and expert opinion. Specifically, it is not clear which exercises should be performed at what time during the rehabilitation process. Technical model-based research, exploring the effects of specific exercises on graft elongation during the different phases of the ligamentization process could be important to guide exercise selection and personalise rehabilitation after ACLR.

Secondly, the use of the LSI during ACLR rehabilitation should be investigated further. The use of the LSI has become a subject of discussion, since the uninvolved leg also has a reduced functional performance after ACLR, because of the long period of inactivity and rehabilitation.[71] Therefore, this thesis proposes the utilisation of the LSI-D/ND, taking into account leg dominance, and minimising the effect of the operated leg. However, up until now the LSI-D/ND has only been used with hop tests in a small group of healthy athletes, so it remains unclear what the cut-off value should be for determining RTP after ACLR. Besides, most studies describing reference values investigate an elite athlete population, making comparison with recreational athletes in daily practice nearly impossible.[12,27,63,78] Therefore, more research for reference values in healthy recreational athletes

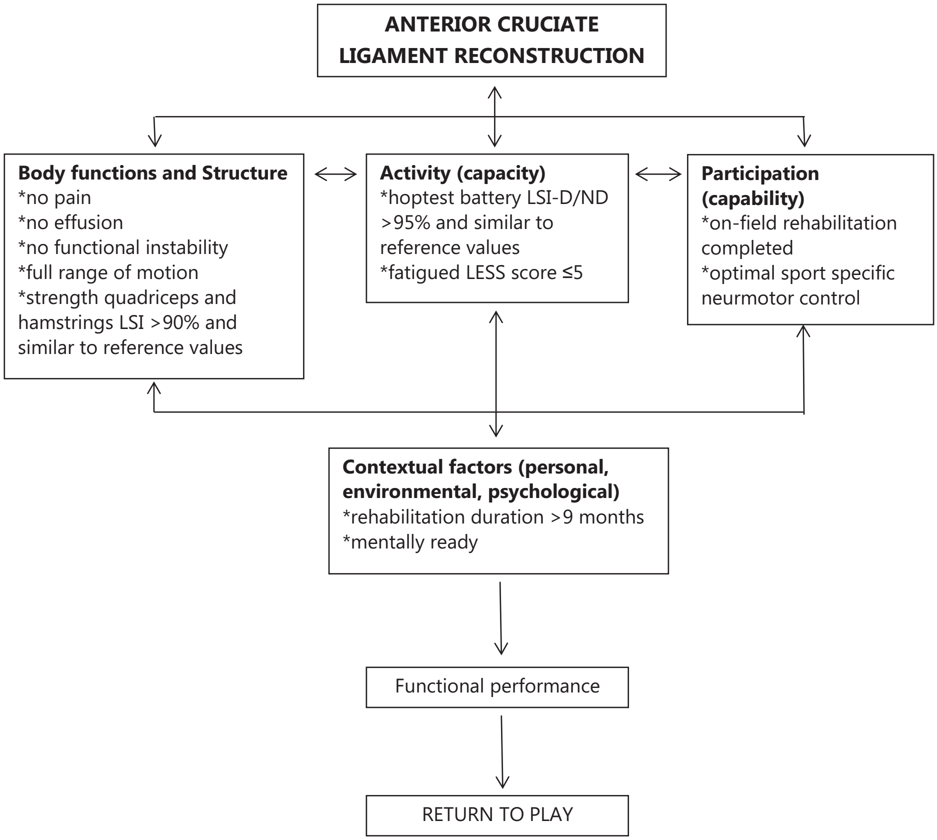


Figure 1: *ACLR RTP criteria integrated into the ICF and biopsychosocial model.*

(both absolute values and LSI-D/ND) is needed for comparison with athletes after ACLR. This could be done in cross-sectional studies in large groups of recreational healthy athletes, but it would also be interesting to perform multiple measurements during a season, since previous studies showed that strength values of healthy elite athletes can vary during a season.[42,46]

Thirdly, ACL rupture and ACLR are a single-leg injury, but a double-leg problem, so more emphasis should be placed on motor learning strategies for secondary prevention.[7] An issue with the current RTP measurements is that both movement quantity and quality are measured in a non-functional context with tests that do not involve sport specific movements. When considering motor learning, it is necessary to develop a test (or test battery) that is able to measure improvement in neuromotor control in a sport specific context, for example by defining which motor learning strategies are required during accelerating, decelerating or side-step cutting.[8,9] In this way, the athlete's performance is measured, considering both the physical and social environment.[34] For this purpose, translational studies investigating the relation between specific tasks and spinal and supraspinal motor control in ACL injured or reconstructed athletes is necessary.

Finally, a longitudinal prospective study needs to evaluate whether athletes after ACLR who are rehabilitated according to the practice guideline differ in second ACL injury rates from athletes who are not rehabilitated according to the guideline. Based on this thesis, we postulate that those athletes rehabilitated according to the guideline, and above all return to their preinjury sport level when meeting all quantitative and qualitative RTP criteria, have a lower chance for second ACL injury. The challenge would be to identify factors that contribute to a higher risk for second ACL injury and create a personal risk profile for each individual athlete.

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Summary

Pivoting athletes (e.g. soccer, basketball or handball players) that sustain an anterior cruciate ligament (ACL) injury often opt for ACL reconstruction (ACLR). They desire to return to the previous (level of) sport, ignoring the possibility that a second ACL injury might occur. However, high-level evidence paints a less optimistic picture: only 65% of athletes reach their preinjury level after ACLR and re-injury rates are as high as 24%.

After ACLR, function, activity and participation levels decrease and pain, effusion, limited range of motion, gait problems, decreased upper leg strength and neuromuscular impairments should be addressed with rehabilitation. However, since the introduction of arthroscopic ACLR in the 90's, rehabilitation programs have changed dramatically. Rehabilitation has shifted from a 12-month period, focussing on strength training with two months of immobilization, towards a six-month accelerated programme focussing on strength and neuromuscular training without immobilisation.

Ideally, the decision regarding return to play (RTP) after ACLR rehabilitation is based on an objective evaluation of function, activity and participation levels. As rehabilitation has changed in the past decade, this is also true for RTP criteria. While no pain or effusion, full range of motion (ROM) and adequate quadriceps strength (defined as Limb Symmetry Index (LSI) above 80%) were used in the 90's, hamstring strength and hop tests have been added in the last decade, with LSI values increasing to 85%.

Reflecting on the changes in the past decades, I wanted to increase the evidence for general practice and started this thesis. The objectives of this thesis were to create an evidence-based rehabilitation program for pivoting athletes after ACLR (Part I) and to contribute to the development of functional performance measurements that need to be used for determining the moment for return to play (Part II).

In **Part I** of this thesis, the central theme was "*Reconstructing the rehabilitation program*". In **Chapter 2** we described the development of an evidence-based practice guideline for rehabilitation after ACLR, based on a systematic review and multidisciplinary consensus. A total of 90 studies, covering nine clinical topics, were used as the scientific basis for this guideline. For each topic, conclusions were drawn with the corresponding level of evidence according to the Dutch Evidence Based guideline development (EBRO) criteria. For both the prehabilitation and postoperative rehabilitation, gaps in the practice guideline are filled with lower level evidence and expert opinion.

Rehabilitation after ACL injury should include a prehabilitation phase to reduce impairments such as limited extension range of motion or a quadriceps strength deficit. Important level 1 recommendations that affect long-term results are: to use cryotherapy for decreasing pain only in the first postoperative week, to include both closed kinetic chain (CKC) and open kinetic chain (OKC) quadriceps exercises for regaining strength (dependent on the phase of the graft remodelling process), to include eccentric quadriceps strength training, and to add neuromuscular training. In addition, the criteria to progress through rehabilitation are based on expert opinion. In this way, the practice guideline has changed ACLR rehabilitation from time-based to criterion-based and can be used by all physical therapists in day-to-day clinical practice.

In the systematic review of **Chapter 3**, we studied whether the clinical outcomes after ACLR are explained by differences in rehabilitation protocols or patient characteristics. Moreover, we discuss the use of an accelerated rehabilitation protocol (i.e. return to play in 4-6 months) in terms of biological healing and tunnel widening. A total of 29 articles were included and their methodological quality was assessed with the Cochrane Risk of Bias tool. Two important conclusions of this systematic review were, despite being supported by a limited level of evidence, that accelerated rehabilitation might cause tunnel widening and return to play after 4-6 months is questionable when considering biological graft healing.

The objective of Part I was to create an evidence-based rehabilitation program for pivoting athletes after ACLR. Based on the results of Chapter 2 and 3, we concluded that the postoperative rehabilitation should continue for 9-12 months and consist of three criterion-based phases: (1) impairment-based, (2) sport-specific training and (3) return to play.

In the general discussion section of this thesis (**Chapter 9),** we discussed this criterion-based rehabilitation program regarding graft remodelling and motor learning strategies. The three phases of intra-articular graft remodelling require an optimal balance between quadriceps strength training and graft loading to optimise healing without elongating the ACL graft. Therefore, CKC exercises are highly suitable for quadriceps strength training in the first two phases (until about three months postoperative); OKC exercises can only be performed through a full range of motion from three months onwards. Motor learning is an important concept in ACLR rehabilitation because a loss of native mechanoreceptors secondary to ACL injury causes partial de-afferentation, diminished activation of sensorimotor cortical areas, altered spinal and supraspinal motor control. Implicit motor learning strategies should be incorporated into the rehabilitation exercises to improve functional performance.

The main purpose of **Part II** of this thesis "*Playing with return to play criteria*" was to develop a test battery that can be used to determine the moment for return to play. This part started with a systematic review of measurement procedures to assess functional performance after ACLR in **Chapter 4**. This study included 27 studies, but only six of them had a good methodological quality and were described further. Five studies used strength measurements, three used a single-leg hop for distance and two combined strength and hop measurements with an LSI as the main outcome parameter. Several measurements are missing in the reported studies and therefore the RTP test advice from Chapter 4 is also based on expert opinion. The suggested RTP test battery advises to: (1) use strength tests for both quadriceps and hamstrings, including an endurance test; (2) use a battery of hop tests; (3) assess movement quality; and (4) use the LSI with caution and preferably compare test results with healthy controls of the same sex.

In **Chapter 5** we used the proposed test battery from Chapter 4 to measure functional performance in athletes 2-9 years after ACLR. We compared the results between athletes with hamstring (HS) and bone-patellar tendon-bone (BPTB) grafts and also compared them with healthy controls. We included 97 athletes in this cross-sectional study: 24 men BPTB, 27 men HS, 23 women PBTB and 23 women HS. In addition, 22 healthy men and 22 healthy women were matched and included. All subjects performed isokinetic strength tests, a hop test battery and a drop jump with video analysis for assessment of dynamic knee valgus and knee flexion angles (movement quality). There were no differences in strength and hop tests or knee flexion angles between the BPTB, HS and healthy groups. However, operated men and women more often had a dynamic knee valgus (both on the operated and non-operated leg) compared to healthy men and women. These results support the relevance of assessing movement quality as part of ACLR rehabilitation programmes and RTP criteria.

In **Chapter 6,** we evaluated the implementation of the practice guideline from Chapter 2 amongst Dutch physical therapists. 158 pivoting athletes were included in this prospective cohort study. They completed their rehabilitation with 108 different, self-selected physical therapists, of which 49 were sports physical therapists. The physical therapists were informed that they were expected to follow the practice guideline and determine the moment for RTP using the criteria listed in this guideline (and Chapter 4). When the physical therapist decided the athlete was able to return to play, RTP measurements were also performed by the primary researcher, at a mean of 12 months following ACLR. Although all 158 athletes were cleared to return to play by their treating physical therapist, only 69 (44%) had performed the RTP measurements. Of these 69, 16 (23%) met all RTP criteria when measured by the primary researcher. We concluded that 77% of the athletes tested by their own physical therapist had been given incorrect RTP advice. Of the 78 athletes that were rehabilitated by a sports physical therapist, 52% had performed the RTP measurements; a significantly higher percentage than the 34% who rehabilitated with a non-sports physical therapist. Apparently, sports physical therapists more often adhere to the practice guideline. These results are concerning and suggest that more emphasis should be placed on implementing the ACLR practice guideline into general physical therapy education. Likewise, it might be beneficial to inform ACLR athletes of the rehabilitation guidelines, empowering them to select a physical therapist that works in accordance with the guideline and providing them insight and autonomy during rehabilitation and the RTP decision.

In **Chapter 7** and **8** we introduced two criteria that might be important to implement in RTP test batteries: leg dominance and neuromuscular fatigue in an ecologically valid environment. In the cross-sectional study in **Chapter 7** we assessed the agreement between the self-reported and observed dominant leg, to decide which question can be used to determine leg dominance. In bilateral mobilizing tasks, which are often used by pivoting athletes, the dominant leg is the leg used to manipulate an object or to lead the movement. 21 healthy men and 20 healthy women practicing symmetrical sports, sports involving the lower extremity only or no sport at all, performed six tasks, of which four were bilateral mobilizing tasks and two were unilateral stabilizing tasks. For both men and women, kicking a ball had 100% agreement between self-reported and observed performance; therefore the question "*if you were to shoot a ball at a target, which leg would you shoot with*?" is an accurate means of determining the dominant leg in bilateral mobilizing tasks. When taking into account leg dominance, we suggest calculating the LSI for strength and hop tests as "the value of the dominant leg divided by the value of the non-dominant leg, multiplied by 100%" instead of "the value of the operated leg divided by the value of the non-operated leg, multiplied by 100%". This new method is called the LSI-D/ND but cut-off values for the LSI-D/ND are not yet known.

Therefore, in the cross-sectional study of **Chapter 8**, we used this LSI-D/ND to evaluate hop test performance in 14 fully rehabilitated, ACL-reconstructed and 19 healthy soccer players. Both groups scored similar LSI-D/ND's on a vertical jump, hop for distance and side hop test, with values between 95 and 100%. Additionally, we evaluated the influence of neuromuscular fatigue in an ecologically valid environment (the soccer field) on hop test performance and movement quality during a countermovement jump using the LESS score. Neuromuscular fatigue was achieved by a one-hour soccer specific training. There were no differences between ACL-reconstructed and healthy soccer players in hop test absolute score or number of players not meeting an LSI >90% RTP criterion, neither in the non-fatigued state nor in the fatigued state. When considering movement quality, the LESS score in the non-fatigued state was similar for the ACL-reconstructed and healthy soccer players. However, in the fatigued state the LESS score of the ACL-reconstructed soccer players increased significantly (from 4 to 7) and also significantly differed from the LESS score of the healthy soccer players, which remained 4. As a consequence, 86% of the ACL-reconstructed players did not meet the LESS <6 RTP criterion in the fatigued state, compared to a significantly lower percentage of 32% in the healthy soccer players. From this study, we conclude that the LSI-D/ND should be above 95% for ACL-reconstructed soccer players when performing hop tests at the end of rehabilitation. Moreover, we suggest performing hop tests and movement quality measurement in an ecologically valid environment (i.e. in a fatigued state on the soccer field).

The objective of Part II was to contribute to the development of functional performance measurements that need to be used for determining the moment for return to play.

Based on the results of Chapter 4, 5, 6, 7 and 8 we concluded in **Chapter 9** that an RTP test battery for pivoting athletes should consist of the following:

- absence of pain, effusion and functional instability, with full range of knee motion;
- strength tests for quadriceps and hamstrings, including an endurance test, score above 90% on the LSI and are similar to preoperative or reference values;
- a hop test battery, including an endurance test, and performed in an ecologically valid environment score above 95% on the LSI-D/ND and are similar to preoperative or reference values;
- the LESS score for movement quality lower than 6, preferably tested in a neuromuscular fatigued condition, for example after a training with the athletes' own team.

In **Chapter 9**, we further discuss the challenges for future research in the field of ACLR rehabilitation and RTP. These four challenges are: (1) exploring the effects of different exercises on graft elongation during the different phases of ligamentization, (2) further investigating the influence of leg dominance and exploring LSI-D/ND and absolute reference values in different populations of pivoting athletes, (3) developing a test (battery) measuring neuromotor control in a sport specific context, and (4) evaluating whether athletes after ACLR who are rehabilitated according to the practice guideline differ in second ACL injury rates from athletes who are not rehabilitated according to the guideline. Until these challenging questions are answered, the rehabilitation program and RTP decision of every pivoting athlete after ACLR remain the challenge of the treating physical therapist.

Samenvatting

Sporters die veel draaibewegingen maken tijdens hun sport (zoals voetballers, basketballers of handballers) lopen risico op een blessure van de voorste kruisband van de knie (VKB). Als de VKB afscheurt, kiezen zij meestal voor een VKB-reconstructie met de verwachting weer op hun oude sportniveau terug te keren zonder dat ze risico lopen op een nieuwe VKB-blessure. Echter, wetenschappelijk bewijs van hoog niveau laat een minder rooskleuring beeld zien: slechts 65% van de sporters komt weer terug op het oude niveau en het aantal sporters met een nieuwe VKB-blessure kan oplopen tot 25%.

Na een VKB-reconstructie zijn zowel het functie-, activiteiten- als participatieniveau van de sporter verminderd. Een fysiotherapeutisch revalidatietraject is nodig om symptomen als pijn, zwelling of een beperking in de beweeglijkheid te verminderen, het veranderd looppatroon te verbeteren, en de verminderde kracht en neuromusculaire controle weer op het oude peil te brengen.

De revalidatie na VKB-reconstructie heeft sinds de invoering van de artroscopische VKB-reconstructie in de jaren '90 drastische veranderingen ondergaan. Zo lag de focus in eerste instantie vooral op krachttraining en duurde het traject 12 maanden startend met twee maanden immobilisatie. Dit veranderde naar een "versneld" traject van zes maanden zonder immobilisatie met naast aandacht voor krachttraining ook een focus op neuromusculaire training.

Idealiter wordt de beslissing om weer terug te keren naar sport (in het Engels *return to play*; RTP) na VKB-reconstructie gemaakt op basis van een objectieve evaluatie van het functie-, activiteiten- en participatieniveau. Net zoals het revalidatietraject zelf, zijn ook de RTP criteria in het afgelopen decennium aan verandering onderhevig geweest. Waar in de jaren '90 geen pijn of zwelling, een volledige beweeglijkheid en een goede quadricepskracht (gedefinieerd als een *Limb Symmetry Index* (LSI) van minimaal 80%) de criteria voor RTP waren, zijn daar circa tien jaar geleden hamstringkracht en sprongtesten aan toegevoegd. Daarnaast werd de afkapwaarde voor de LSI verhoogd naar minimaal 85%.

Mede op basis van deze veranderingen in het afgelopen decennium, wilde ik een bijdrage leveren aan het verbeteren van de bewijslast voor de onderbouwing van de dagelijkse praktijk en dat heeft geleid tot het schrijven van dit proefschrift. Met dit proefschrift wilde ik een revalidatieprogramma ontwerpen en onderbouwen met wetenschappelijk bewijs (deel I) en bijdragen aan de ontwikkeling van de criteria die nodig zijn om terug te mogen keren naar sport (deel II).

In **deel I** van dit proefschrift was "*Reconstructing the rehabilitation program*" het centrale thema. Deel I bestaat uit hoofdstuk 2 en 3. In **hoofdstuk 2** beschreven we de ontwikkeling van een praktijkrichtlijn voor revalidatie na VKB-reconstructie, gebaseerd op een systematische review en multidisciplinaire consensus. In totaal werden 90 studies, verdeeld over 9 onderwerpen, gebruikt als wetenschappelijke basis voor deze richtlijn. Per onderwerp werd een conclusie getrokken met daarbij het niveau van het wetenschappelijk bewijs volgens de Evidence-Based Richtlijn

Ontwikkeling (EBRO) criteria. Voor zowel het preoperatieve als het postoperatieve revalidatietraject werden hiaten in de richtlijn ingevuld met wetenschappelijk bewijs van lagere kwaliteit of de mening van deskundigen.

De revalidatie na een VKB-blessure zou een preoperatieve fase moeten bevatten om zo beperkingen als een verminderde beweeglijkheid naar strekking of een tekort aan kracht van de quadriceps al aan te pakken voorafgaand aan de operatie. Belangrijke aanbevelingen met een hoge bewijslast die invloed hebben op het lange termijn resultaat na de operatie zijn: het gebruik van cryotherapie om pijn te verminderen in de eerste postoperatieve week, het inzetten van zowel gesloten keten als open keten quadricepsoefeningen (afhankelijk van de fase van het remodelleringsproces van de graft) om kracht op te bouwen, het gebruik van excentrische quadricepstraining, en het toevoegen van neuromusculaire training aan de krachttraining. De criteria die tijdens de revalidatie bepalen wanneer een sporter naar de volgende fase over mag, zijn echter gebaseerd op de mening van deskundigen. Door op deze manier de revalidatie na VKB-reconstructie in te delen, heeft de richtlijn in **hoofdstuk 2** het revalidatieproces dat op tijd was gebaseerd veranderd in revalidatietraject dat op het behalen van criteria is gebaseerd. Dit stappenplan kan door alle fysiotherapeuten in de dagelijkse praktijk gebruikt worden.

In de systematische review beschreven in **hoofdstuk 3** onderzochten we of de resultaten na VKB-reconstructie verklaard kunnen worden door verschillen in het revalidatieprotocol of in de patiëntkarakteristieken. Daarnaast bediscussieerden we het gebruik van een versnelde revalidatie (terugkeer naar sport in vier tot zes maanden) in het kader van de biologie van de nieuwe kruisband en het mogelijk wijder worden van de bottunnels. In totaal werden 29 artikelen geïncludeerd en beoordeeld met de Cochrane Risk of Bias tool. Ondanks dat er maar een beperkt niveau van wetenschappelijk was, waren er twee belangrijke conclusies uit deze systematische review: een versnelde revalidatie kan ervoor zorgen dat de bottunnels verwijden en daarnaast is terugkeer naar sport binnen vier tot zes maanden onverstandig in het kader van het biologisch herstel van de nieuwe kruisband.

Het doel van deel I was om op basis van wetenschappelijk bewijs een revalidatieprogramma na VKB-reconstructie te ontwikkelen dat geschikt is voor sporters die veel draaibewegingen maken tijdens hun sport. Gebaseerd op de resultaten van hoofdstuk 2 en 3 kunnen we concluderen dat de postoperatieve revalidatie 9-12 maanden zou moeten duren, opgedeeld in drie fases: (1) gericht op de beperkingen in functieniveau, (2) sportspecifieke training en (3) terugkeer naar sport.

In de discussie van dit proefschrift (**hoofdstuk 9**) bespraken we dit revalidatietraject in het kader van het remodelleringsproces van de nieuwe kruisband en motorisch leren. De drie fases van intra-articulaire remodellering van de nieuwe kruisband vragen om een optimale balans tussen training van de quadricepskracht en het belasten van de nieuwe kruisband, om zo het herstel van de nieuwe kruisband te optimaliseren zonder deze met teveel trekkracht te belasten, waardoor

elongatie kan optreden. Daarom zijn gesloten keten quadriceps oefeningen uiterst geschikt voor de eerste twee fases (tot circa drie maanden postoperatief); open keten oefeningen mogen pas vanaf drie maanden in een volledige range van bewegen uitgevoerd worden.
Motorisch leren is een belangrijk concept tijdens de revalidatie na VKB-reconstructie omdat het verlies van mechanoreceptoren als gevolg van de VKB-blessure gedeeltelijk de-afferentiatie veroorzaakt, waardoor er een lagere activatie is van sensorimotorische hersenschorsgebieden en een veranderde spinale en supraspinale motorische controle. Impliciet leren zou daarom toegepast moeten worden bij het uitvoeren van oefeningen tijdens de revalidatie om zo de functionele prestatie te verbeteren.

Het doel van **deel II** van dit proefschrift, getiteld "*Playing with return to play criteria*", was om een testbatterij te ontwikkelen die gebruikt kan worden om het moment van terugkeer naar sport te bepalen. Deel II bestaat uit hoofdstuk 4, 5, 6, 7 en 8. Dit deel startte in **hoofdstuk 4** met een systematische review naar het gebruik van meetinstrumenten om de functionele prestatie na VKB-reconstructie vast te leggen. Er werden 27 studies geïncludeerd, waarvan slechts zes met een goede methodologische kwaliteit. Alleen deze laatste zes werden verder beschreven. Vijf studies gebruikten krachtmetingen, drie gebruikten een *single-leg hop for distance* (vertesprong op één been) en twee combineerden kracht- en sprongmetingen met de LSI als hoofduitkomstmaat. Verschillende metingen ontbraken in de geïncludeerde studies en daarom is het advies van hoofdstuk 4 deels ook gebaseerd op de mening van deskundigen. De testbatterij die wordt aangeraden om het moment van terugkeer naar sport te bepalen, bevat het volgende: (1) krachttesten voor zowel quadriceps als hamstrings, inclusief een duurtest; (2) minimaal drie verschillende sprongtesten; (3) metingen voor de kwaliteit van bewegen; (4) voorzichtigheid met de interpretatie van de LSI, omdat de testresultaten beter vergeleken kunnen worden met gezonde sporters van hetzelfde geslacht.

In **hoofdstuk 5** gebruikten we de testbatterij uit hoofdstuk 4 om de functionele prestatie te meten bij sporters twee tot negen jaar na VKB-reconstructie. We vergeleken de resultaten van sporters met een nieuwe kruisband gemaakt met een hamstringpees (HS) en een nieuwe kruisband gemaakt met de kniepees (BPTB) met gezonde controles. Er werden 97 sporters na VKB-reconstructie geïncludeerd in deze studie: 24 mannen met BPTB, 27 mannen met HS, 23 vrouwen met BPTB en 23 vrouwen met HS. Daarnaast werden 22 gezonde mannen en 22 gezonde vrouwen gematcht en geïncludeerd. Alle proefpersonen voerden isokinetische krachttesten uit, drie sprongtesten en een drop jump met videoanalyse voor het bepalen van de dynamische knievalgus en knieflexiehoeken (kwaliteit van bewegen). Er waren geen verschillen in kracht- of hoptesten en knieflexiehoeken tussen BPTB, HS en gezonde controles. Geopereerde mannen en vrouwen hadden echter vaker een dynamische knievalgus (zowel in het geopereerde als niet-geopereerde been) dan gezonde mannen en vrouwen. Deze resultaten ondersteunen het belang van het testen van de kwaliteit van bewegen tijdens de revalidatie na VKB-reconstructie en als onderdeel van RTP criteria.

In **hoofdstuk 6** evalueerden we de implementatie van de praktijkrichtlijn uit hoofdstuk 2 onder Nederlandse fysiotherapeuten. In deze prospectieve cohortstudie werden 158 sporters geïncludeerd die veel draaibewegingen maken tijdens hun sport. Ze rondden hun revalidatie af bij 108 verschillende, zelf gekozen, fysiotherapeuten, waarvan er 49 sportfysiotherapeut waren. De fysiotherapeuten werden geïnformeerd dat er van ze verwacht werd dat ze de revalidatie volgens de richtlijn uitvoerden en het moment voor terugkeer naar sport bepaalden aan de hand van de RTP criteria in de richtlijn (en hoofdstuk 4). Als de fysiotherapeut besloot dat de sporter klaar was om terug te keren naar sport, werden de RTP metingen ook uitgevoerd door de hoofdonderzoeker, op gemiddeld 12 maanden na VKB-reconstructie.
Alhoewel alle 158 sporters van hun fysiotherapeut weer mochten terugkeren naar sport, waren er slechts 69 (44%) die vertelden dat ze daadwerkelijk alle RTP testen hadden uitgevoerd bij hun eigen fysiotherapeut. Van deze 69 sporters waren er 16 (23%) die alle RTP criteria haalden wanneer ze getest werden door de hoofdonderzoeker. Daarom concludeerden we dat 77% van de sporters die al getest waren door hun eigen fysiotherapeut een incorrect advies hadden gekregen ten aanzien van de terugkeer naar sport.
Van de 78 sporters die bij een sportfysiotherapeut hadden gerevalideerd, had 52% al een keer de RTP testen uitgevoerd; een significant hoger percentage dan de 34% die had gerevalideerd bij een niet-sportfysiotherapeut. Blijkbaar lukt het sportfysiotherapeuten vaker om zich te houden aan de richtlijn. De resultaten van deze studie zijn zorgwekkend en wijzen erop dat er meer gedaan moet worden aan implementatie van de VKB-reconstructie richtlijn in de dagelijkse praktijk en het onderwijs van fysiotherapeuten. Daarnaast zou het zinvol kunnen zijn om sporters na VKB-reconstructie op de hoogte te brengen van het bestaan van de richtlijn, zodat ze een weloverwogen keuze kunnen maken voor een fysiotherapeut die werkt volgens de richtlijn en ze zelf ook inzicht hebben in de revalidatie en RTP criteria.

In **hoofdstuk 7** en **8** introduceerden we twee criteria die mogelijk belangrijk zijn om mee te nemen bij de verdere ontwikkelingen van testbatterijen met RTP criteria: het dominante been en neuromusculaire vermoeidheid in een ecologisch valide omgeving. In de cross-sectionele studie van **hoofdstuk 7** onderzochten we de overeenstemming tussen het zelf gerapporteerde en geobserveerde dominante been, om zo te achterhalen welke vraag we moeten gebruiken om het dominante been te bepalen. Bij bilateraal mobiliserende taken, die veel gebruikt worden door sporters, is het dominante been het been dat wordt gebruikt om een object te verplaatsen of het been dat de beweging inzet.
21 Gezonde mannen en 20 gezonde vrouwen die ofwel een symmetrische sport, ofwel een sport waarbij alleen de onderste extremiteit wordt gebruikt, ofwel geen sport beoefenden, voerden zes taken uit, waarvan er vier bilateraal mobiliserende taken waren en twee unilateraal stabiliserende taken. Voor zowel mannen als

vrouwen had het schieten van een bal 100% overeenstemming tussen het zelf gerapporteerde en geobserveerde dominante been. Daarom is de vraag "*Als je een bal op doel wil schieten, welk been gebruik je dan om te schieten?*" de meest accurate vraag om het dominante been bij bilateraal mobiliserende taken te bepalen. Om rekening te houden met het dominante been, is onze suggestie om de LSI voor kracht- en hoptesten te berekenen als "de waarde van het dominante been gedeeld door de waarde van het niet-dominante been, vermenigvuldigd met 100%" in plaats van "de waarde van het geopereerde been gedeeld door de waarde van het niet-geopereerde been, vermenigvuldigd met 100%". Deze nieuwe methode wordt de LSI-D/ND genoemd, maar grenswaardes voor de LSI-D/ND zijn nog niet bekend.

Daarom gebruikten we deze LSI-D/ND in de cross-sectionele studie van **hoofdstuk 8** om de uitvoering op sprongtesten te evalueren bij 14 voetballers die klaar waren met hun revalidatie na VKB-reconstructie en 19 gezonde voetballers. Beide groepen scoorden vergelijkbare LSI-D/ND's op een éénbenige *vertical jump* (hoogtesprong), *hop for distance* (vertesprong) en *side hop* (zijwaartse duurtest) met waardes tussen de 95% en 100%.
Daarnaast evalueerden we de invloed van neuromusculaire vermoeidheid in een ecologisch valide omgeving (het voetbalveld) op de uitvoering van sprongtesten en de kwaliteit van bewegen tijdens een *countermovement jump* (tweebenige sprong waarbij je twee keer achter elkaar zo hoog mogelijk springt) met de LESS score als uitkomstmaat. Een voetbalspecifieke training van één uur werd gebruikt om neuromusculaire vermoeidheid te bereiken. Er waren zowel in de niet-vermoeide als vermoeide toestand geen verschillen tussen de voetballers na VKB-reconstructie en de gezonde voetballers in de absolute scores op de sprongtesten of in het aantal voetballers dat de grenswaarde van LSI >90% niet bereikte. Wat betreft de kwaliteit van bewegen was de LESS score in de niet-vermoeide toestand gelijk voor de voetballers na VKB-reconstructie en de gezonde voetballers. Echter, in de vermoeide toestand steeg de LESS score van de voetballers na VKB-reconstructie significant (van 4 naar 7) en deze verschilde ook significant van de LESS score van de gezonde voetballers, die 4 bleef. Het gevolg hiervan was dat 86% van de voetballers na VKB-reconstructie het criterium van LESS score <6 niet haalde, vergeleken met een significant lager percentage van 32% bij de gezonde voetballers. Uit de resultaten van deze studie concludeerden we dat de LSI-D/ND voor sprongtesten boven de 95% moet zijn voor voetballers die na VKB-reconstructie terug willen keren naar sport. Bovendien raadden we aan de sprongtesten en de metingen voor kwaliteit van bewegen in een ecologisch valide omgeving uit te voeren (dat wil zeggen op het voetbalveld in een vermoeide toestand).

Het doel van deel II was om bij te dragen aan de ontwikkeling van metingen voor de functionele prestatie die gebruikt kunnen worden om het moment van terugkeer naar sport te bepalen bij sporters na een VKB-reconstructie.

Gebaseerd op de resultaten van hoofdstuk 4, 5, 6, 7 en 8 concludeerden we in **hoofdstuk 9** dat een RTP testbatterij voor sporters die veel draaibewegingen uitvoeren tijdens hun sport moet bestaan uit:

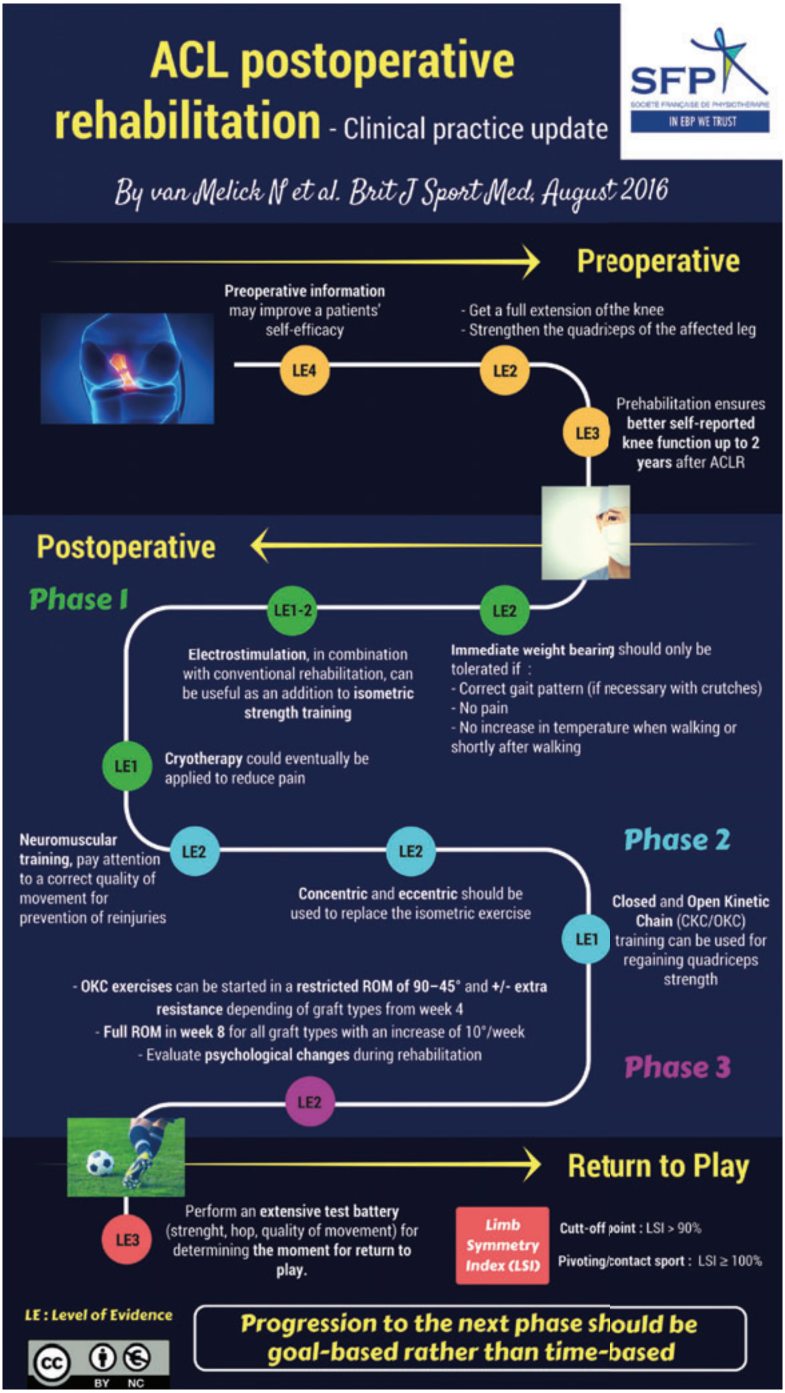
- afwezigheid van pijn, zwelling en functionele instabiliteit, met een volledige beweeglijkheid;
- krachttesten voor quadriceps en hamstrings, inclusief een duurtest, met een score op de LSI boven de 90% en waardes die gelijk zijn aan preoperatieve of referentiewaardes;
- drie verschillende sprongtesten, inclusief een duurtest, uitgevoerd in een ecologisch valide omgeving met een score op de LSI-D/ND boven de 95% en waardes die gelijk zijn aan preoperatieve of referentiewaardes;
- een LESS score voor de kwaliteit van bewegen lager dan 6, bij voorkeur uitgevoerd onder neuromusculaire vermoeidheid, bijvoorbeeld nadat de sporter heeft meegedaan aan een training met het eigen team.

In **hoofdstuk 9** bediscussieerden we daarnaast de uitdagingen voor toekomstig onderzoek op het gebied van VKB-reconstructie en RTP. De vier uitdagingen zijn: (1) uitzoeken wat het effect van verschillende oefeningen tijdens de verschillende fases van remodellering op elongatie van de nieuwe kruisband is, (2) verder onderzoeken wat de invloed is van het dominante been en in verschillende populaties sporters absolute referentiewaarden en LSI-D/ND waarden verzamelen, (3) ontwikkelen van een test(batterij) die neuromusculaire controle in een sportspecifieke context kan meten, en (4) evalueren of sporters die volgens de praktijkrichtlijn gerevalideerd zijn een lager risico hebben op een nieuwe VKB-blessure dan de sporters die niet volgens deze richtlijn gerevalideerd zijn.
Tot het moment dat deze uitdagingen opgelost worden, blijft het de uitdaging voor de behandelend fysiotherapeut om goed te monitoren tijdens de revalidatie en een onderbouwde RTP beslissing te nemen in overleg met de sporter.

Addendum

ACL rehabilitation infographic
Dankwoord
Curriculum Vitae
List of publications

ACL rehabilitation infographic



Dankwoord

Al zo lang als ik me kan herinneren, ben ik goed in het onthouden van speciale data. Zo weet ik bijvoorbeeld altijd verjaardagen uit mijn hoofd en weet ik van alle voorste-kruisbandpatiënten die ik behandel precies op welke datum ze geopereerd zijn. Maar als iemand me vraagt wanneer ik ben gestart met mijn promotie onderzoek, dan kan ik daar geen antwoord op geven. Het is meer een proces dat als vanzelf ontstaan is. Eén moment was er in elk geval de aanleiding voor: een gesprek met Robert van Cingel in de tijd dat ik bij Sport Medisch Centrum Papendal (SMCP) werkte. Ik was al enkele jaren aan het werk als algemeen fysiotherapeut, maar wilde meer. Er was twijfel: een master binnen de fysiotherapie volgen of meer met onderzoek gaan doen. Robert was degene die de voorzet gaf om te gaan promoveren. En zo geschiedde.

Een aantal belangrijke data in de afgelopen jaren, in chronologische volgorde, maar niet persé in volgorde van belangrijkheid.

17 September 2007: De start van mijn carrière als fysiotherapeut en bewegingswetenschapper bij SMCP. Robert, jij was destijds mijn werkgever en later ook mijn copromotor. Dat voorstel destijds was het beste voorstel dat je had kunnen doen. Bedankt daarvoor! Tijdens mijn werkjaren bij SMCP was er de mogelijkheid om enkele uren per week in werktijd mijn onderzoek uit te voeren. Het contact met collega en mede-promovendus Marsha Tijssen was erg waardevol. Marsha, bedankt voor het delen van ideeën, feedback en opbeurende woorden in die tijd! Pas later, toen ik alles in eigen tijd moest doen, realiseerde ik me hoe waardevol dat was. Toen ik in 2014 bij jullie weg ging, bleef je gelukkig mijn copromotor. Robert, je hebt met jouw uitgebreide netwerk en kennis vele deuren voor mij geopend en er mede voor gezorgd dat ik sta waar ik nu sta!

20 Oktober 2010: Mijn eerste kennismaking met mijn promotor Ria Nijhuis-van der Sanden. In dit gesprek werd mij verteld dat ik een 'buitenpromovendus' zou worden. Klinkt gezellig, maar pas later besefte ik dat dit betekend dat je bijna al het werk in je eigen tijd uitvoert. Je moet er dus een klein beetje een *nerd* voor zijn om dat voor elkaar te krijgen. Het plan was om mijn eerste systematische review te schrijven en me daarna officieel aan te melden als promovendus bij de Radboud Universiteit.

Ria, er volgden nog veel gesprekken in de 8 jaar daarna. Ik ben je erg dankbaar voor je kritische en constructieve feedback. Het was voor mij soms een worsteling, maar meer met mezelf in het omgaan met jouw feedback, dan met jou. Je was altijd in staat om van een afstand naar mijn onderzoek te kijken, waardoor het overzicht goed behouden bleef. Ik ben er trots op dat je mijn promotor bent geweest!

20 Maart 2013: Dr. R.P.A. Janssen, orthopedisch chirurg-traumatoloog, of gewoon Rob. Op deze datum deden we de eerste search voor jouw systematische review. Voor jou één van de laatste dingen die je nog moest doen om te kunnen promoveren; voor mij het begin van een mooie samenwerking. Je bent voor mij een voorbeeld en inspirator in hoe je het klinische werk combineert met onderzoek. Onze gezamenlijke lezingen in de afgelopen jaren waren een feestje. Er liggen alweer nieuwe gezamenlijke plannen klaar en ik kan niet wachten om eraan te beginnen!

1 Oktober 2014: De officiële start van het voorste-kruisbandonderzoek bij Kliniek ViaSana. Klaas en Tony, bedankt voor jullie enthousiasme en vertrouwen in mij. Zonder jullie had ik dit onderzoek nooit kunnen starten. Johan, Ronald, Bas, Martijn, Roland, Mike, Klaartje en alle poli-assistentes, jullie hebben op de achtergrond erg veel werk verricht, bedankt daarvoor! Yvette, jij verdient speciale aandacht. Je deed eerst je afstudeeronderzoek voor Bewegingswetenschappen bij mij en kon daarna meteen als onderzoeker aan de slag bij Kliniek ViaSana. Je bent mijn vaste aanspreekpunt en komt altijd met goede ideeën en adviezen. Je bent mede verantwoordelijk voor het slagen van ons onderzoek. Dat jij daarnaast ook mijn paranimf bent, is de kers op de taart. Heel erg bedankt!

11 December 2015: Lisa, we hadden ons eerste gesprek omdat jij je afstudeerstage voor Bewegingswetenschappen bij mij wilde doen. In de loop van de tijd heb ik ontdekt dat je net zo'n vakgek bent als ik. Jouw aanstekelijke enthousiasme en harde werk hebben ervoor gezorgd dat we een erg mooie studie hebben gepubliceerd. Natuurlijk ben je ook gewoon een lief en gezellig mens en hoop ik dat er nog verschillende etentjes en drankjes zullen volgen!

9 Februari 2016: Het eerste overleg met mijn nieuwe copromotor Thomas Hoogeboom. In de jaren ervoor worstelde ik met het schrijfwerk en de uitvoering van statistiek in mijn onderzoeken. Thomas, wat ben ik blij dat Ria jou voorstelde als toevoeging aan mijn promotieteam. Je bent die laatste paar jaar erg waardevol geweest. Niet alleen qua feedback op mijn schrijven en de hulp bij de statistiek, maar ook als bemiddelaar tijdens de scherpe discussies die plaatsvonden tijdens de overleggen. Je wist altijd ervoor te zorgen dat de neuzen dezelfde kant op stonden als het overleg was afgelopen. Ontzettend bedankt!

25 Maart 2017: Deze datum staat in mijn geheugen gegrift. Behalve expert, was ik ineens ook ervaringsdeskundige, toen ik tijdens een handbalwedstrijd mijn voorste kruisband (gedeeltelijk) scheurde. Een bizarre wending, maar wat ik heb er veel van geleerd! De struggles (vooral ook mentaal), de euforie als het beter ging en de frustratie als iets niet lukte. Ik ben hier zeker weten ook een betere fysiotherapeut door geworden!

Niels, bedankt dat je mijn fysiotherapeut wilde zijn! Jouw inzet, motivatie en passie voor het vak zijn inspirerend. Daarnaast was het gewoon erg leuk om te kunnen discussiëren over voorste-kruisbandrevalidatie en de onderzoeken waarin je hebt meegewerkt.

1 September 2017: Na een paar wisselingen van baan in de afgelopen jaren, heb ik nu echt mijn plek gevonden bij het Knie Expertise Centrum in Eindhoven. Ik kan hier precies doen wat ik graag wil: het klinische werk met kniepatiënten combineren met onderzoek en managementtaken. Dennis, bedankt voor het vertrouwen, ook al in eerdere jaren als docente bij Progress Educations. Het was erg prettig om de vreugde en sores rondom het promoveren met je te kunnen delen. Nog even volhouden jij! Paul, bedankt voor je nuchtere kijk op onderzoek. Dat werkt voor mij heel verhelderend en zet me weer met twee benen op de grond. Karin, Aukje, Sanne, Laura, Milou, Isabelle, Xandra, Elia, Caroline, Marloes, Evelien en natuurlijk ook al mijn andere collega's bij PECE Zorg: de gezelligheid onderling maakt deze werkplek en nog betere plek! Bedankt voor de steun!

Daarnaast zijn er nog een aantal mensen waar ik geen datum aan kan verbinden, simpelweg omdat er teveel data zijn die speciaal zijn geweest.

Alle patiënten na voorste-kruisbandreconstructie, fysiotherapeuten en stagiaires die hebben meegewerkt aan mijn onderzoek. Bedankt voor jullie belangeloze inzet!

To all my foreign fellow knee-geeks; thank you for your trust, the inspiring discussions, the help with my English grammar and the invitations to speak at lectures, congresses or courses! Rich, a special thank you to you for all time you spend on checking my English grammar!

Jeroen van de Camp (bij het grote publiek bekend als FC Kruisband), bedankt voor alle ideeën, overpeinzingen, gedachtewisselingen, gezellige momenten en het enige echte FC Kruisband revalidatieshirt. Vanuit een heel andere invalshoek hebben we hetzelfde ideaal: de beste zorg voor elke voorste-kruisbandpatiënt. We gaan de komende jaren nog een mooie samenwerking tegemoet!

Anke, Miranda, Kim, Dillys, Miriam en Chantal, vanaf de start van onze studie zijn jullie op elk gebied een grote steun en bende gezelligheid geweest. Thanks ladies!

Anouk, het begon op de Beukenhof en 30 jaar later is het nog steeds erg gezellig! Veel lief en leed en nog meer lief gedeeld. Extra speciaal dus dat jij mijn paranimf bent. Ik hoop dat we over 30 jaar nog steeds zo doorgaan!

Mijn lieve schoonfamilie Marjo, Wim, Barbara, Stefan Miranda, Mathijs en Daan. Jullie zijn een gezellige en warme familie waar ik me helemaal thuis voel. Het was soms lastig uit te leggen wat ik nou precies uitvoer op die dagen dat ik 'thuis werk'. Hier is het resultaat!

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Ja, lieve Gerrald, dan ben jij aan de beurt. Hoe jij in het leven staat, intrigeerde me vanaf dag één. Jij hebt me geleerd om niet altijd te luisteren naar mijn innerlijke criticus. Daarnaast heb je me de kunst van het tot rust komen door gewoon te relaxen en niks te doen bijgebracht. Je luisterende oor was erg prettig als ik weer eens gefrustreerd was door de zoveelste afwijzing van een artikel. Mede door jou zijn die laatste jaren van mijn promotie één groot feest geweest. Eigenlijk ben jij gewoon mijn voorste kruisband: je zorgt voor stabiliteit in mijn leven, maar zorgt wel dat ik de vrijheid heb om me te bewegen. Je bent een fantastisch mooi mens en ik hou superveel van jou! Oja, nadat je dit proefschrift hebt gelezen, hoop ik dat je weet dat het toch echt wel iets anders is dan een scriptie..

Dit was het dan. Het is tijd om te relaxen..

"To do nothing at all is the most difficult thing in the world"

(Oscar Wilde)

Curriculum Vitae

Nicky van Melick werd geboren op 5 april 1983 in Heythuysen. Ze rondde het Gymnasium af aan Sg. St. Ursula in Horn in 2001 en startte datzelfde jaar met de opleiding Gezondheidswetenschappen aan Maastricht University, waar ze in het tweede jaar koos voor de afstudeerrichting Bewegingswetenschappen. Nadat ze bij een keuzevak kennis had gemaakt met fysiotherapie, begon ze in 2004 aan de opleiding Fysiotherapie aan de Hogeschool Zuyd in Heerlen. In 2007 rondde ze beide opleidingen tegelijk af na haar eindstage bij het Sport Medisch Centrum KNVB.

In september 2007 ging ze aan de slag als fysiotherapeute en bewegingswetenschapper bij Sport Medisch Centrum Papendal, waar ze bijna zeven jaar lang met veel plezier heeft gewerkt. Hier specialiseerde Nicky zich in het behandelen van knieklachten en begeleidde ze verschillende groepen topsporters, waaronder de HandbalAcademie en de Kernploeg Aangepast Sporten van de Nederlandse Handboogbond.

Vanaf 2011 verbond Nicky zich als buitenpromovenda aan het Radboud Institute of Health Sciences afdeling Scientific Institute for Quality of Healthcare voor haar PhD onder leiding van prof. dr. M.W.G. Nijhuis-van der Sanden en copromotoren dr. T.J. Hoogeboom en dr. R.E.H. van Cingel (Sport Medisch Centrum Papendal).

Omdat ze zich toch ook verder wilde verdiepen in de fysiotherapie heeft Nicky van 2014 tot 2016 de opleiding Sportfysiotherapie gevolgd en afgerond aan de NEXUS in Gennep.

Ook richtte ze in 2014 haar eigen bedrijf KneeSearch op. Vanaf die tijd heeft ze lezingen en cursussen over knierevalidatie en voorste-kruisbandrevalidatie gegeven door heel het land en haar onderzoek gepresenteerd op verschillende internationale congressen. Daarnaast werkte ze mee aan de ontwikkeling en herziening van meerdere multidisciplinaire richtlijnen op het gebied van de knie voor o.a. het KNGF, de NOV en het NHG.

Vanaf september 2017 is Nicky manager en sportfysiotherapeute bij het Knie Expertise Centrum Eindhoven, waar ze haar passie voor de knie nog meer vorm kan geven. De combinatie van het klinische werk met uitsluitend mensen met knieklachten en de mogelijkheden om vanuit de managementkant en het onderzoek de zorg rondom knieklachten te verbeteren, maakt dat ze op deze plek nog lang niet is uitgekeken.

Meer over Nicky is te lezen op www.nickyvanmelick.nl.

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