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Rehabilitation after Anterior Cruciate Ligament Reconstruction using patellar tendon or hamstring grafts

open and closed kinetic chain exercises

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“When you are prepared to loose everything,
you are on your way to manage everything”

T.D Lakalama 1997

English Summary

Aim:

The overall aim of this thesis was to improve the knowledge of appropriate exercises, the influence of preoperative factors for good clinical outcome as well as the patient's experience of the rehabilitation after anterior cruciate ligament (ACL) reconstruction with patellar tendon or hamstring graft.

Methods:

The strain in the anteromedial bundle of the ACL was measured with the strain gauge technique in nine patients scheduled for meniscectomy. The measurement was performed during a step-up, a step-down, a lunge and a one-leg sit to stand exercise (Study I). Sixty-eight patients, 36 males and 32 females, with either patellar tendon graft (34 patients) or hamstring graft (34 patients) were randomly allocated to either early (4^{th} postoperative week) or late start (12^{th} postoperative week) of open kinetic chain (OKC) quadriceps exercises. The four groups consisted of patellar tendon reconstruction, early start (P4) or late start (P12), hamstring tendon reconstruction, early start (H4) or late start (H12). Range of motion, anterior knee laxity, pivot shift, postural sway, thigh muscle torques and anterior knee pain were evaluated prior to surgery and 3, 5 and 7 months after surgery (Study II). The variables investigated in Study II, and demographic data were calculated in a multiple regression model to find the strongest predictors of the 12 months outcome, measured with two subgroups of KOOS *(Function in sport and recreation; Quality of life)*, one-leg hop test, and Tegner Activity Scale (Study III). Ten patients were interviewed focusing on expectations and challenges from injury to one year after ACL reconstruction. The transcribed interviews were analyzed using a qualitative thematic content interpreted analysis (Study IV).

Results:

No significant differences in ACL strain were shown between exercises. There was a significant increase in ACL strain towards extension in all studied exercises (Study I).

No significant group differences were found in range of motion, postural sway and anterior knee pain 3, 5 and 7 months, postoperatively. The H4 group showed a higher mean difference of laxity over time of 1.0 mm than the P4 group (p=0.04) and 1.2 mm than the H12 group (p=0.01). All groups, except for the P4 group reached preoperative values of quadriceps torques, while the H4 and the H12 groups showed significantly lower hamstring torques at the 7 months follow-up compared with preoperatively (Study II). Step-wise regression showed that absence/less preoperative AKP and low knee influence on pre-operative activity level explained 31 % in Sport/Rec – KOOS outcome. Additionally, high scores on the AKP score predicted the outcome alone to 14 % in QOL – KOOS. Absence of or minor AKP was the strongest predictor for Sport/Rec – KOOS and QOL – KOOS. Patellar tendon graft in favor of hamstring tendon graft and a short time (< 6 months) between injury and ACL surgery partly explained a higher level of activity (TAS). Absence of cartilage damage explained 6 % of good outcome as measured with the one-leg hop test (Study III). The participants perceived no real choice between operative and non-operative treatment. Only surgery symbolized a full return to the pre-injury level of sport activity, and surgery was understood as the only way to become a completely restored “functional human being”. A major source of frustration was that the meaning of and progress during the rehabilitation did not match their expectations. Three different responses to the challenge of a prolonged rehabilitation were expressed: “*going for it”*, *“being ambivalent”*, and *“giving in*”. Fear of re-injury was common; however some participants decided not to return to their pre-injury level of sporting activity due to other reasons than physical limitations or fear of re-injury (Study IV).

Conclusion:

The studied exercises did not produce greater strain on the ACL than the traditional two-legged squat**.** Early start of OKC quadriceps exercises leads to greater anterior knee laxity than late start after hamstring ACL reconstruction as well as after patellar tendon ACL reconstruction. No group differences in postural sway and AKP were found. The evaluated preoperative variables could partly predict clinical outcomes. Absence of or minor AKP before surgery was the strongest predictor for the outcome 12 months after ACL reconstruction. Preoperative information in terms of the meaning and extent of rehabilitation would have been helpful as well as guidance in realistic goal-setting and coaching throughout the entire rehabilitation process.

Key words: ACL injury, activity level, anterior knee pain, clinical outcome, concomitant injuries, coping, fear of re-injury, goal-setting, interviews, in-vivo, knee laxity, KOOS, lunge, muscle strength, step, patient satisfaction, risk factors

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Contents

Svenska Sammanfattningar (Swedish summaries)

Studie I

Titel: The strain on the anterior cruciate ligament during closed kinetic chain exercises.

Annette Heijne, Braden C. Fleming, Per A. Renström, Glenn D. Peura, Bruce D. Beynnon, Suzanne Werner. *Med Sci Sports Exerc, 2004, 36 (6):935-941*

Syfte: Att studera uttöjningsgraden av det främre korsbandet under fyra vanligt förekommande ’closed kinetic chain’ (CKC) övningar i den tidiga fasen efter främre korsbandsrekonstruktion; trappsteg upp, trappsteg ner, utfallssteg och en-bens uppresning från sittande. Vår hypotes var att uttöjningen av det främre korsbandet under utfallssteg och en-bens uppresning från sittande (övningar som kräver mer muskelkraft i nedre extremiteten och som genererar en högre grad av höftflexion) blir mindre jämfört med den uttöjning som uppstår under trappsteg upp och trappsteg ner.

Metod: Nio patienter med normala främre korsband, planerade för artroskopisk meniskektomi under lokalbedövning, deltog i studien. En trådtöjningsgivare (DVRT) placerades på den främre mediala tredjedelen av det främre korsbandet. Därefter ombads försökspersonerna att utföra tre repetitioner av respektive övning i randomiserad ordning. Uttöjningsgraden av det främre korsbandet och aktuell knäledsvinkel registrerades och jämfördes.

Resultat: Ingen signifikant skillnad förelåg beträffande uttöjning av det främre korsbandet (M ± SEM) mellan de fyra övningarna (trappsteg upp: 2.5 ± 0.36; trappsteg ner: 2.6 ± 0.34; utfallssteg: 1.9 ± 0.50; en-bens uppresning från sittande: 2.8 ± 0.27). Skillnaden i medelvärde för uttöjningsgraden av det främre korsbandet som en funktion av knäledsflexion var inte signifikant. Uttöjningsgraden av det främre korsbandet under de fyra övningarna ökade med minskad knäledsflexion.

Sammanfattning: Denna studie visar att trappsteg upp, trappsteg ner, utfallssteg och en-bens uppresning från sittande inte skiljer sig åt vad gäller uttöjning av det främre korsbandet. De är dessutom jämförbara med andra, tidigare in-vivo testade, rehabiliteringsövningar som används i rehabiliteringen efter främre korsbandsrekonstruktion (två-bens knäböj, aktiv knäledsextension utan yttre belastning).

Studie II

Titel: Early versus late start of open kinetic chain quadriceps exercises after ACL reconstruction with patellar tendon or hamstring grafts. A prospective randomised outcome study. Annette Heijne, Suzanne Werner. *Knee Surg, Sports Traumatol, Arthrosc published on-line January, 2007*

Syfte: Att utvärdera hur tidigt respektive sent påbörjade 'open kinetic chain' övningar (OKC) för quadriceps påverkar olika mätvariabler efter främre korsbandsrekonstruktion med graft från patellarsenan eller hamstringsenan.

Metod: 68 patienter, 36 män och 32 kvinnor, som genomgått främre korsbandsrekonstruktion med antingen patellarsenegraft (n=34) eller hamstring graft (n=34) ingick i studien. Alla patienter randomiserades till tidig start (4:e postoperativa rehabiliteringsveckan) eller sen start (12:e postoperativa rehabiliteringsveckan) av OKC övningar för quadriceps, vilket resulterade i fyra undergrupper: patellarsenerekonstruktion, tidig start (P4) eller sen start (P12) av OKC övningar, hamstringsrekonstruktion, tidig start (H4) eller sen start (H12) av OKC övningar för quadriceps. Preoperativt, 3, 5 och 7 månader postoperativt, mättes rörelseomfång (goniometer), främre knäledslaxitet (KT-1000), posturalt svaj (KAT 2000), lårmuskelstyrka (Kin-Com dynamometer) och främre knäsmärta (anterior knee pain score).

Resultat: Inga signifikanta skillnader påvisades vad gäller knäledsrörlighet 3, 5 eller 7 månader postoperativt. I H4-gruppen förelåg en signifikant högre grad av främre knäledslaxitet över tid 1.0 mm (M ± CI:0.18-1.86) jämfört med P4-gruppen (P=0.04). Inom grupperna som genomgått samma typ av främre korsbandsrekonstruktion, hamstringsgraft, var skillnaden över tid 1.2 mm (M ± CI: 0.37-2.1) högre i H4-gruppen jämfört med H12-gruppen (P=0.01). Ingen signifikant skillnad i posturalt svaj eller främre knäsmärta förelåg mellan grupperna vid något av mättillfällena.

Signifikanta skillnader i förändring över tid noterades vid jämförelse av de fyra grupperna för både quadricepsstyrka (P<0.001) och hamstringstyrka (P<0.001). Alla grupperna, bortsett från P4-gruppen hade återfått preoperativa styrkevärden i quadriceps muskeln vid 7-månaders kontrollen. I H4 och H12 gruppen noterades signifikant lägre styrka i hamstrings vid 7-månaders kontrollen jämfört med preoperativa styrkevärden.

Konklusion: Tidig start av OKC övningar för quadriceps efter genomgången främre korsbandsrekonstruktion med hamstringgraft resulterade i signifikant högre grad av främre knäledslaxitet i jämförelse med sen start och i jämförelse med både tidig och sen start efter genomgången främre korsbandsrekonstruktion med patellarsenegraft. Dessutom påverkades inte utvecklingen av quadricepsstyrkan av tidig start jämfört med sen start av OKC övningar för quadriceps vare sig för patienter opererade med patellarsene- eller hamstringsgraft. Det verkar som om valet av graft påverkar förändring av styrka av en specifik muskel snarare än valet av övningar. Resultaten i föreliggande studie kan inte ligga till grund för att fastställa den exakta tidpunkten för start av OKC övningar för quadriceps hos patienter opererade med hamstrings graft. Ytterligare studier krävs för att utvärdera långtidseffekten på främre knäledslaxitet och funktionellt 'outcome' efter främre korsbandsrekonstruktion med hamstringgraft.

Studie III

Titel: Predictive factors for the 12 months outcome after anterior cruciate ligament reconstruction. Annette Heijne, Björn Äng, Suzanne Werner. *In manuscript*

Syfte: Syftet med föreliggande studie var att studera möjliga preoperativa subjektiva och objektiva faktorer som kan predicera ett lyckat kliniskt 'outcome' utvärderat med delskalorna *Funktion, fritid och idrott* och *Livskvalitet* från Knee injury Osteoarthritis Outcome Score (KOOS), en-bens längdhoppstest och Tegner's aktivitetsskala, 12 månader efter främre korsbandsrekonstruktion.

Material och Metod: Sextiofyra patienter som genomgått främre korsbandsrekonstruktion, 35 män och 29 kvinnor, med patellarsenegraft (n=32) eller hamstringgraft (n=32) deltog i studien. Bakgrundsdata, rörelseomfång i knäleden, främre knäledslaxitet, 'pivot shift test', lårmuskelstyrka, främre knäsmärta och upplevd knäfunktion, utvärderades inom fyra veckor före ACL rekonstruktion. Dessa variabler studerades därefter genom att genomföra en multipel regressionsanalys i syfte att finna de starkaste predicerande faktorerna som kan påverka klinisk 'outcome' 12 månader efter ACL rekonstruktion utvärderat med delskalorna *Funktion, fritid och idrott* och *Livskvalitet* från KOOS, en-bens längdhoppstest och Tegner's aktivitetsskala.

Resultat: Delskalorna *Funktion, fritid och idrott* – KOOS och *Livskvalitet* – KOOS var de beroende variabler som bäst kunde prediceras. Frånvaro av, eller liten grad av främre knäsmärta samt att patienterna uppgav att knäet endast i låg grad påverkade deras aktivitetsnivå innan operation, förklarade till 31 % höga poäng i delskalan *Funktion, fritid och idrott* – KOOS. Frånvaro av eller liten grad av främre knäsmärta förklarade till 14 % höga poäng i delskalan *Livskvalitet* – KOOS. Att genomgå rekonstruktion med patellarsenegraft istället för hamstringgraft samt en kortare tid mellan skada och ACL operation (< 6 månader) förklarade delvis en högre grad av aktivitetsnivå (Tegners aktivitetsskala) 12 månader efter främre korsbandsrekonstruktion. Frånvaro av broskskada förklarade 6 % av ett gott resultat mätt med en-bens längdhoppstest.

Konklusion: De studerade preoperativa mätvariablerna kunde endast delvis predicera tillfredsställande 'outcome' efter främre korsbandsrekonstruktion. Frånvaro av eller liten grad av främre knäsmärta visade sig vara de starkaste prediktorerna för *Funktion, fritid och idrott* – KOOS och *Livskvalitet* – KOOS 12 månader efter främre korsbandsrekonstruktion. Eventuella framtida studier bör även inkludera andra utvärderingsinstrument, där förslagsvis psykologiska faktorer beaktas.

Studie IV

Titel: Rehabilitation and recovery after anterior cruciate ligament reconstruction: patients' experiences. Annette Heijne, Karin Axelsson, Suzanne Werner, Gabriéle Biguet
Submitted to Scand J Med Sci Sports, December, 2006

Syfte: Syftet med föreliggande studie var att utforska patienters erfarenheter av rehabiliteringsprocessen efter främre korsbandsrekonstruktion.

Metod: Tio strategiskt valda patienter deltog i studien. Semistrukturerade intervjuer genomfördes med fokus på förväntningar och utmaningar från själva skadan till ett år efter främre korsbandsrekonstruktion.

Resultat: Fyra teman kunde urskiljas. (1) Valet mellan operativ och icke-operativ (konservativ) behandling uppfattades inte som något faktiskt val. Endast operation symboliserade möjligheten till full återgång till idrott samt den enda möjligheten att bli ”en komplett fungerande människa”. (2) Huvudanledningen till frustration var att tiden för rehabilitering varade mycket längre än vad någon hade kunnat föreställa sig och att rehabiliteringsprocessen inte motsvarade deras förväntningar. (3) Tre olika sätt att möta utmaningen i form av en utdragen rehabilitering beskrevs. Dessa var '*go for it', 'to be ambivalent'* och '*give in*'. De som inte antog utmaningen karakteriserades av en oförmåga att motivera sig själva, att sätta nya mål samt att mobilisera egna inre krafter. (4) Tankar om framtiden som ett ofrånkomligt ställningstagande lyftes fram. Rädsla för återgång till idrott var ett vanligt beskrivet fenomen. Några av deltagarna beslöt dock att ej återgå till idrott av andra orsaker än fysiska hinder eller rädsla.

Konklusion: Deltagarna uppgav att utökad preoperativ information vad gäller innehållet i och omfattningen av rehabiliteringen, skulle ha varit till hjälp liksom handledning och vägledning i att kunna sätta upp realistiska mål genom hela rehabiliteringsprocessen. Rehabiliteringspersonal bör beakta att vissa patienter omvärderar sina mål under rehabiliteringsperioden, t ex att ej återgå till tidigare idrottsliga aktivitetsnivå. Om detta beror på rädsla att skada sig igen eller på andra faktorer bör utredas individuellt. Ytterligare studier med adekvat studiedesign för att undersöka effekten av sådana insatser bör genomföras.

List of Original Papers

This thesis is based upon the following original papers, which will be referred to in the text by their Roman numbers (Studies I-IV).

I. **Annette Heijne, Braden C. Fleming, Per A. Renström, Glenn D. Peura, Bruce D. Beynnon, Suzanne Werner**
The strain on the anterior cruciate ligament during closed kinetic chain exercises.
Med Sci Sports Exerc, 2004, 36 (6):935-941

II. **Annette Heijne, Suzanne Werner**
Early versus late start of open kinetic chain quadriceps exercises after ACL reconstruction with patellar tendon or hamstring grafts. A prospective randomised outcome study.
Knee Surg, Sports Traumatol, Arthrosc, Published on-line, January 2007

III. **Annette Heijne, Björn Äng, Suzanne Werner**
Predictive factors for the 12 months outcome after anterior cruciate ligament reconstruction. *In manuscript*

IV. **Annette Heijne, Karin Axelsson, Suzanne Werner, Gabriéle Biguet**
Rehabilitation and recovery after anterior cruciate ligament reconstruction – patients´ experiences. *Submitted to Scand J Med Sci Sports, December 2006*

Abbreviations

In the present thesis, the following abbreviations were used

ACL	Anterior Cruciate Ligament
AKP	Anterior Knee Pain
ANOVA	Analysis of Variance
BMI	Body Mass Index
BPTB	Bone-Patellar Tendon-Bone
CI	Confidence Interval
CKC	Closed Kinetic Chain
DVRT	Differential Variable Reluctance Transducer
ICC	Intraclass Correlation Coefficient
IKDC	International Knee Documentation Committee
KOOS	Knee injury Osteoarthritis Outcome Score
OKC	Open Kinetic Chain
ROM	Range Of Motion
SEM	Standard Error of Measurements
TAS	Tegner Activity Scale

Definitions

In the present thesis, the following abbreviations were used

ACL-graft	The biological substitute used for reconstruction of a ruptured Anterior Cruciate Ligament
Anterior Knee Pain	A syndrome based on unspecific knee pain that aggravates during prolongued sitting with flexed knees or knee loading conditions
Anterior knee laxity	Anterior tibial displacement relative to the femur
Closed Kinetic Chain	Activities modelled as a closed linkages where a movement in one joint simultaneously produces movements in other joints of the extremity
Concentric muscle action	When a muscle shortens while producing force
Compliance	A patients collaboration with treatment directions
Eccentric muscle action	When a muscle lengthens while producing force
Electrogoniometer	A computerised device for measuring a specific angle between two extremities
In-vivo	An experiment performed on a living human being
Lachman test	A clinical test to detect an anterior cruciate ligament rupture
Muscle torques	A force that produces a rotation or torsion
Open Kinetic Chain	An exercise where the distal segment is free to move across one joint independently (e.g. kicking, active knee extension)
Postural sway	The interplay between destabilizing forces acting on the body and actions by the postural control system to prevent loss of balance
Qualitative thematic content analysis	A systematic process of identifying, coding and categorising patterns of regularity in data
Resistance Training	Training the muscles of the body to increase strength through moving a load or a weight
Strain	The ratio of elongation with respect to the original length
Training volume	The product of sets x repetitions x resistance during physical training

Work The product of the force and the distance through which the lower extremity moves, expressed in Newton Meter (Nm)

Introduction

Anterior cruciate ligament (ACL) rupture is one of the most common traumatic injuries among physically active individuals (64). The injury could, for some individuals, result in functional limitations, reduced quality of life and income, loss of specific social relations due to not being able to perform the sport he or she performed prior to injury, or in worst case, not being able to exercise at all.

The immediate problem for the athlete is usually functional instability (e.g. giving way) of the lower extremity. It is therefore the opinion of many authors, that an anterior cruciate deficient knee in an active individual whose functional goal is to continue stressful, pivoting sport or work, should undergo surgical reconstruction of the ACL (4, 31, 46). The natural history of the ACL deficient knee has not yet been characterized by a well-designed prospective study, but it appears as if an ACL injury increases the risk for early development of osteoarthritis in the knee joint regardless of whether reconstruction is performed or not (106). Based on present research, it is not clear which ACL deficient patient who benefits most from an ACL reconstruction. There seem to be a lack of rigid selection criteria for surgery and therefore knowledge of possible predictive factors for clinical outcome might play an important role in order to find out who will benefit from an ACL reconstruction or not.

The most optimal graft for ACL reconstruction still remains controversial (135). Each of the different grafts has certain strengths and weaknesses. Different authors have shown that the mechanical behaviour of the graft (2, 30, 40, 81, 95) and the type of fixation does not affect early nor late result of the stiffness in the ACL reconstructed knee. However, two independent meta-analyses published by Yunes et al (135) and Goldblatt et al (52) have shown that knees reconstructed with bone-patellar tendon-bone graft (BPTB) had anterior-posterior (A-P) laxity values that were closer to normal than those reconstructed with a 4-strand hamstring graft. In spite of these reports there is no real consensus concerning knee laxity after using either the patellar tendon or hamstring grafts.

One of the main goals of rehabilitation after ACL reconstruction is to regain normal thigh muscle strength (6, 8, 100). Particulary, the quadriceps muscle has been suggested as an important knee extensor and a dynamic knee joint stabiliser during closed kinetic chain (CKC) activities (23).

In order to protect the graft from detrimental strain CKC rather than open kinetic chain (OKC) exercises have been reported to play a primary role in rehabilitation after ACL reconstruction (28). Recent studies (59, 84) have, however, revealed that the use of OKC exercises in knees reconstructed with patellar tendon graft, do not influence the stability of the knee joint. Whether different rehabilitation protocols should be based on graft choice still remains unclear.

Most of the literature on sports injury rehabilitation has focused on the clinical aspects of diagnosis, prognosis and treatment plans. However, the interest of the psychological aspects of sports injury and rehabilitation has increased. Unrestricted participation in sports activities and return to the pre-injury level of sport is often reported as an indicator of the success of ACL reconstruction. The athletes' choice not to return to their pre-injury activity level could depend on impaired knee funktion. However, in the clinical setting it has been noticed that social reasons or psychological hindrances such as fear of re-injury (130) may influence the return to sports (69).

Theoretical framework

Sports medicine has its origin in traumatology (orthopaedics), and since 1996 it is possible for a physiotherapist to become a specialist within this subdiscipline. Sports medicine can be defined as ”*multidisciplinary medical discipline with focus on physical activity, exercise and sport. The most important sub disciplines are physiology, traumatology and internal medicine. The main focus is aspects related to exercise but experts in sports medicine will additionally handle questions concerning competitive sports on elite level”*(88). Further on, in this definition biomechanical aspects and prevention of injuries which are important factors are mentioned, and finally it is written *"…today sports traumatologists take care of injuries related to overuse and chronical injuries on athletes and recreational activity…"*(88). This definition does not entirely cover the area and need to be updated to include ‘rehabilitation’, where physical therapy is a key aspect. Orthopaedics and rehabilitation are today essential and integrated parts of sports medicine.

Rehabilitation can be defined as the multi- and interdisciplinary management of a person’s functioning and health. The goals are to minimize symptoms and disability (116). Within the field of rehabilitation and sports medicine, the physiotherapist’s distinct view of the body, knowledge and understanding of human movement and rehabilitation, is of high value. This description of physical therapy, will further state the natural role and the interaction of physiotherapists in sports medicine *'physical therapy is providing services to people and populations to develop, maintain and restore maximum movement and functional ability throughout the lifespan. Physical therapy includes the provision of services in circumstances where movement and function are threatened by the process of ageing or that of injury or disease. Full and functional movements are at the heart of what it means to be healthy. Physical therapy is concerned with identifying and maximizing movement potential within the spheres of promotion, prevention, treatment and rehabilitation'*(41).

International Classification of Functioning, Disability and Health (ICF)

For this thesis, The International Classification of Functioning, Disability and Health, can be used as a conceptual framework (Table 1). The ICF framework describes health and functioning as complex and multidimensional and has been developed in order to create a biopsychosocial model of health, approved by the World Health Organization (WHO) (126). ICF provides a standard language and a framework essential to successful inter professional collaboration to describe health and health-related states. It is a multipurpose classification intended for a wide range of uses, for instance a statistical tool, in the collection and recording of data; as a research tool to measure outcomes, quality of life or environmental factors and as a clinical tool (126).

It has been reported (29) that studies that contribute best to functioning and disability in patients' with rheumatoid, which most likely could be transferable to patients with sport injuries, are studies that 1) incorporate a comprehensive model to integrate different variables of interest 2) use a longitudinal model to examine the potential causal relationships among the variables and 3) use hierarchical regression analyses to study the relation among variables.

The overall perspective of the present thesis is that of rehabilitation, and both clinical and experimental studies were performed. The thesis can thus be understood from as well a biological as a psychological point of view, where the concept of regaining normal function after trauma from both a physiological and psychological aspect is considered. The outcome measurements are therefore of both quantitative and qualitative structure (Table 1). The outcome will be fully presented in the assessment section.

Table 1. Classification of the main outcome measures in this thesis according to ICF.

Paper	BODY FUNCTIONS AND STRUCTURE					ACTIVITY/ PARTICIPATION			
	Strain on the ACL	Strength (Nm)	Anterior Knee Joint Laxity (mm)	Postural Sway (arbitrual units)	Anterior Knee Pain Score	Questionnaires		One-leg hop test (m)	Semi-Structured Interview
						KOOS	Tegners Activity Scale		
I	x								
II		x	x	x	x				
III		x	x		x	x	x	x	
IV									x

Background

Anterior cruciate ligament

Skeletal ligaments are well characterised as mechanical stabilisers of the knee joint (Figure 1). The motion characteristics of the articular surfaces of the tibia relative to the femur are complex and are guided by the ACL and the other primary ligaments such as the Medial Collateral Ligament (MCL) and the Lateral Collateral Ligament (LCL) that span the knee joint. Studies performed using cadaveric models have revealed that the ACL is the primary restraint to anterior displacement relative to the femur and acts as a restraint to internal-external rotation and varus-valgus angulation (63, 82). In addition, new evidence suggests that various sensory innervations within ligament tissue and neuromuscular reflexes contribute to motor control and affect ligament mechanical properties (26).

The muscles localised around the knee joint produce forces and moments to the knee joint. As the position of the knee joint is changed, the moment arms of the different muscles and tibio femoral joint contact forces also change, which, in turn affects ACL biomechanics. It is well known that the ACL is strained when quadriceps is contracted near terminal knee extension (21, 83).

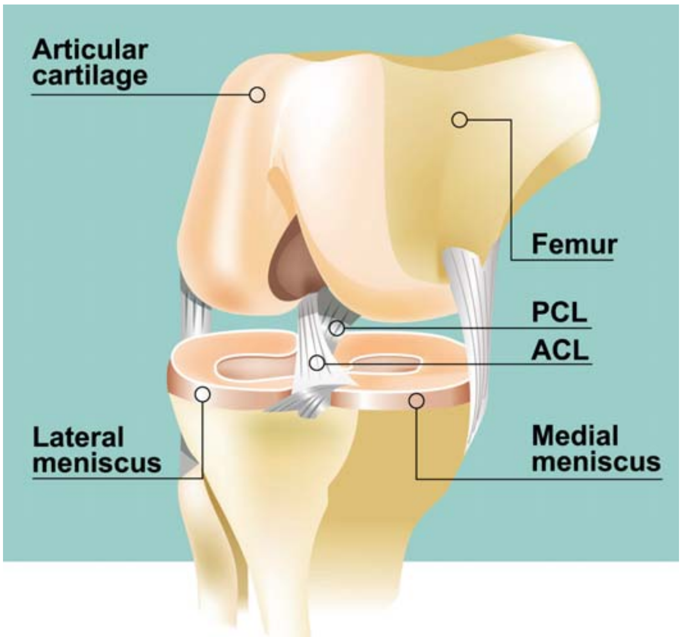

Figure 1. Anatomy of the knee joint

Anterior cruciate ligament injury

Approximately, 300.000 primary ACL reonstructions are carried out in USA every year. About 6000 ACL injuries occur in Sweden every year and approximately 50 % of these injuries are treated with reconstruction. Forty percent of the ACL reconstructions in Sweden are performed in females and subsequently 60 % in males (89). One reason for this is that a higher number of males than females participate in sports. However, several authors have reported an increased risk in sport injuries in female athletes compared to male athletes, especially injuries to the ACL (87).

It is well known, that ACL injuries more often occur in people active in sports than in the general population (31). The risk factors that predispose an individual to an ACL injury are multifactorial (anatomical, biomechanical, neuromuscular, environmental). Uhorchak et al (122) have reported that significant intrinsic risk factors leading to an ACL injury included a small femoral notch width and generalised joint laxity. Additionally, they reported for females that higher than normal body mass index and KT 2000 arthrometer measures of anterior-posterior knee laxity that were one standard deviation or more above the mean were suggested as risk factors. Furthermore, it has been reported in a biomechanical study (58) that females land from a jump with straighter knees than age- and height-matched males. Whether this can be considered as a risk factor for ACL injury is under debate and not yet scientifically proven. The influence of hormone levels in specific phases of the menstruation cycle as a risk factor has also been discussed in the literature (86, 87, 131). The exact mechanism of the increased risk for females to sustain an ACL injury or whether psychological attributes contribute to increase the risk for injury are not elucidated and is not in the focus of this thesis.

Strain and the anterior cruciate ligament

Strain can be defined as 'the change in length relative to the initial length' (38). The structural properties of the ACL are dependent on the geometry and mechanical response of the entire ligament-insertion site complex. They include the linear stiffness (the slope of the load-displacement curve), ultimate failure load (the greatest magnitude of load applied), and energy absorbed at failure (the area under the load displacement curve) (133). Using a cadaveric model, Woo et al (133) reported that the ACL ruptured at about 2000 Newton (N), which in his study was equal to 10-12 % strain. It remains unknown when a healthy/normal ACL rupture in man and it also remains unknown when an ACL graft ruptures in man. Although, muscle activity, body weight and joint motion could all affect the properties of a normal ligament, there is little consensus how these factors influence the biomechanical behaviour and the healing response in an ACL graft.

Reconstruction and the anterior cruciate ligament

History

In 1836, the Weber brothers of Göttingen in Germany described the abnormal tibial translation after cutting the ACL (123). Tecniques in ACL reconstruction have progressed over time. In 1917, Hey Groves (56) described the ACL reconstruction, using a part of the iliotibial band. His operative procedure was performed in many countries until the late 1960s. The use of patellar tendon as a graft was first reported in 1932 by zur Verth from Germany (129). In 1938, Palmer (97) published his thesis on injuries of the knee ligaments with detailed studies on anatomy, biomechanics, pathology and treatment. His studies opened new avenues in the field of cruciate ligament surgery. Broström and Eriksson (39) performed the first patellar tendon ACL reconstructions together in Sweden 1965-66. The use of the medial third and thereafter the central third of the patellar tendon creating a BPTB graft has been the most widely accepted graft choice since the 1960s. Lindemann (75) in Germany proposed the use of hamstring grafts for ACL reconstruction in the 1940s. In the early 1980s the first arthroscopy assisted ACL reconstructions were performed by Dandy (25) in the UK.

Bone-Patellar Tendon-Bone graft or Hamstring graft

During the last 30 years, an extensive evolution of the surgical procedures for reconstruction of the ACL has taken place. In terms of relative proportions of studies that have focused on surgical interventions, it appears that the graft material has received the greatest attention (1, 2, 9, 16, 40, 44). During recent years there has been a gradual shift towards the use of hamstring tendon as a graft for ACL reconstruction. Many orthopaedic surgeons are still hesitant about the use of the hamstring tendon because of some remaining unsolved issues about the fixation and the rehabilitation. Still there is a lack of consensus regarding the most optimal graft for reconstruction of the ACL (135).

To compare clinical outcomes with a single, or for that case, multiple particular techniques or grafts is a challenge due to the multitude of variables to control, such as activity level, sex, age, surgical technique, concurrent intra articular injuries as well as rehabilitation techniques. An extensive description of rehabilitation protocols in the literature are often sparse and yet it is commonly stated in the conclusions that the choice of graft appears to result in similar short and long term clinical outcome (1, 2, 9, 16, 40, 44).

Rehabilitation and anterior cruciate ligament reconstruction

It requires an excellent (e.g. normalised) knee function for a physically active individual to be able to go back to sports. The ultimate goal after ACL reconstruction and rehabilitation is to regain normal range of motion, knee joint stability, muscle strength and neuromuscular control, which all most likely contribute to normal functional performance, without jeopardising the healing graft. This puts high demands on the timing, the content and the variation of rehabilitation exercises.

Over the past decade, rehabilitation after anterior cruciate ligament reconstruction has been a subject of controversy and of intense research (11, 45, 61, 80, 91, 94, 112, 113). In the past the knee was immobilised during 6-9 weeks and the rehabilitation period lasted for at least one year. In the early 1990s, accelerated rehabilitation based mainly on CKC exercises, became popular (113). The long-term results of this rehabilitation technique are unfortunately not reported in the literature.

A CKC exercise can be described as a movement where the extremity is opposed by ”a considerable resistance”, either movable like a pedal or static like a platform. This creates a strict and closed system where movement in one joint produces movements in all other joints of the extremity (98). Conversely, an OKC exercise can be described as a movement when the distal segment is free to move, such as when the foot is kicking or the hand is throwing a ball (Figure 2).

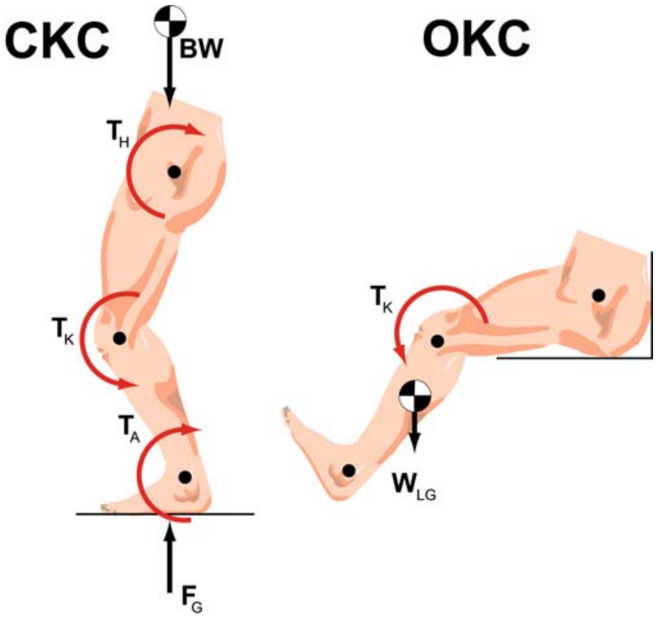

Figure 2. The difference between OKC and CKC. For OKC exercises, the resistive load (WLG) is applied to the tibia and transmitted to the knee (T_K). For CKC exercises, the ground reaction force (F_G) is transmitted to all the joints of the leg (T_A, T_K, and T_H).

Different types of movement put different strain on the ACL, depending partly on the load but also on knee joint angles. The use of CKC exercises in rehabilitation rather than OKC exercises have primarily been based on the following opinions: 1) CKC exercises simulate and replicate many functional movements in sports and daily life, and 2) with increased knee joint compression and increased co-contraction between hamstrings and quadriceps around the knee joint, the anterior tibial shear forces with respect to the femur decreases. This hypothesises that CKC exercises stabilise the knee joint and thereby minimize the stress on the ACL (42, 93, 98, 128). The use of CKC exercises or the OKC exercises during rehabilitation has been described in randomised clinical trials solely on patients reconstructed with BPTB graft (28, 57, 84).

There are numerous CKC exercises commonly used to rehabilitate the ACL reconstructed patient and several authors have analysed the relationship between CKC exercises and the intersegmental loads at the knee (76, 78, 93, 115, 128). The 'Vermont group' has in *in-vivo* studies recorded the amount of strain on the ACL during different CKC exercises, such as stair climbing, bicycling and squats, with or without resistance (19, 21, 48, 49). Stuart et al (115) analysed the muscle activity and the intersegmental forces about the tibiofemoral joint during two different squatting exercises and the lunge. Using an inverse dynamic model they determined that the net shear forces of the tibiofemoral joint for all three CKC exercises remained posterior throughout the flexion-extension cycle. This finding implies that the ACL, or ACL graft, would not be strained during these exercises. However, the distribution of the net joint loads between the structures of the knee remains unknown. Lysholm and Messner (78) showed in ACL deficient and in healthy knees that load bearing exercises, such as sitting down and standing up from a chair and walking upstairs, produced only *slight* amounts of tibial translation, measured with a goniometer linkage system. Different equipment and grading systems have been used, and it is therefore difficult to come to a consensus when comparing the outcomes of one approach to another. However, there is evidence to suggest that CKC exercises may not strain shield the healing ACL graft (21). It has been determined that the peak strains produced on the ACL during active extension (an OKC exercise) without external weight and squatting (a CKC exercise) were equivalent (21).

Bynum et al (28) reported that patients rehabilitated solely with CKC exercises for quadriceps had lower mean side-to-side differences in knee joint laxity measured with KT-1000 arthrometer and less patellofemoral pain. Furthermore, they were generally more satisfied with their end result, whereas Mikkelsen et al (84) found that an addition of OKC exercises from the sixth postoperative week on patients reconstructed with BPTB graft, was superior to CKC exercises alone leading to greater improvement of the quadriceps muscle torque without influencing knee joint stability six months after surgery. Recently, Isberg et al (59) reported that immediate active knee extensions following ACL reconstruction did not increase knee joint laxity. What effect early or late initiation of OKC exercises for the quadriceps muscle has on objective as well as subjective knee function in patients with hamstring tendon grafts remains unclear. Furthermore, it should also be pointed out that the issue of residual laxity regarding male versus female is not solved.

In particular, the quadriceps muscle has been suggested as an important knee extensor and a dynamic knee joint stabiliser during CKC activities (23). Since many daily life as well as sport activities consist of CKC exercises one could consider the quadriceps to be an ACL protagonist (23, 111). It has also been suggested that pain as well as weakness of the quadriceps muscle are the most common predictors of disability after an ACL reconstruction (101). On the other hand, it is known that co-contraction of the quadriceps and hamstring muscles are frequently altered in ACL deficient subjects (3, 100, 114). For instance, hamstring activity has been shown to increase in many ACL deficient subjects (3). An increase in hamstring activity would theoretically (due to insertion site on tibia) serve to decrease the shear forces and thereby minimize the strains on the ACL graft (115). Whether the differences in hamstring activity contribute significantly to reduce ACL loading during strenuous activities remain unknown.

Personality factors influencing rehabilitation and clinical outcome

Patient satisfaction and experiences during rehabilitaion after ACL reconstruction has not been well studied. Patient satisfaction in terms of the outcome of surgery or rehabilitation is a complex phenomenon, and contains multiple dimensions such as accessibility, functional health status, and quality of a patient-professional relationship, but also outcome expectations as well as expectations for and attitudes to rehabilitation (65). It has earlier been reported that some patients are not satisfied with their functional outcome after a surgical repair or postoperative rehabilitation (67, 92), despite good objective results such as normalized muscle strength, knee joint stability, and range of motion (67, 69).

Self-efficacy, that is, the belief about one's personal ability to successfully perform a task or a specific behavior has been suggested to play a major role for the outcome of rehabilitation (10, 121). Tailored instruments to assess self-efficacy in patients with ACL injuries have recently been developed (120). Furthermore, health locus of control has also been shown to influence the recovery process after injury and surgery (85) as well as coping strategies (62). Nyland et al. (92) reported that health locus of control has an important influence on the recovery process after injury and surgery among patients with ACL injuries. Patients with high internal health locus of control perceived fewer functional limitations, measured with Short Form health survey (SF-36), than those with a high degree of external locus of control.

High *internal* locus of control can be explained as believing that the progress and the results are directly related to individual factors, and high *external* locus of control as believing that the progress and results are controlled by other powerful factors such as luck, chance, or faith.

Coping can be defined as a cognitive skill/capacity on a psychological level and includes evaluation of a situation, strategy and the actual acting. Coping can be positive, which means that one has confidence in doing what one has decided to do in an active way. Coping can also be negative, which means that one stays in a certain state and feels passive and powerless (72). Johnson (62) found when studying coping strategies among long-term injured athletes that team-sport athletes coped more in terms of "passive acceptance" of help from others, whereas individual athletes actualised more "problem-solving" strategies in face of a stressor.

Empirically and in the literature, it has been recognized that some of the patients who have undergone ACL reconstructions avoid physical activities. A more specific fear of sport or physical activity, related to a feeling of a possible re-injury, has been noted (69). This phenomenon has earlier been studied in patients with low back pain, and is called "fear of movement/(re)injury".

Assessments

Measuring instruments are important in order to identify different functional problems but also to objectively evaluate results of an intervention. Several instruments and questionnaires are available to assess patients' subjective and objective outcome after an ACL injury or reconstruction.

Body functions and structure

Anterior knee laxity

Strain on the anterior cruciate ligament

ACL strain during activity can be measured in-vivo using a Differential Variable Reluctance Transducer (DVRT; Microstrain Inc., Burlington, Vermont, USA). The DVRT is a small highly compliant displacement transducer that can be arthroscopically applied to the anteromedial portion of the ACL. The method for application of the DVRT, for *in-vivo* strain measurement of the ACL, has previously been described (17, 114). The surgical and experimental procedure is performed under local anaesthesia, permitting subjects' full control of their muscles. It is currently very difficult to evaluate the strain in an ACL substitute *in-vivo* during dynamic activities that involve the leg musculature, since this would mean an unnecessary arthroscopy when the patient has recovered. Furthermore, additional variables that are associated with the reconstructive procedure would also increase the variability of the strain response. Therefore, it is advantageous to perform these measurements on the normal ACL. It is not possible, for ethical reasons, to do invasive surgery on healthy patients. Therefore the subjects included in investigations using the DVRT, are mostly patients with normal ACLs undergoing arthroscopic surgery for a partial meniscectomy, chondral debridement or plica excision under local anaesthesia. It seems reasonable, however, to extend these data to a properly positioned ACL graft. The elongation pattern of the BPTB graft during passive extension of the knee joint has been previously measured, *in-vivo*, and was found to be similar to the normal ACL (20). Thus, a loading condition that causes a decrease in normal ACL strain should cause a similar decrease in a properly positioned ACL graft.

KT-1000

The relation between objective laxity and functional activity has lately been debated in the literature (110, 114). An extensive knee joint laxity does not necessarily mean that the patient suffers from knee joint instability (101, 110). In spite of this, to measure anterior knee laxity can be valuable as a diagnostic instrument or in order to distinguish whether different interventions influence on anterior knee laxity.

Objective laxity (e.g. anterior tibial displacement relative to the femur in the sagittal plane) can, in a clinical setting, be measured with a KT-1000 knee arthrometer (MED metric, Corp., San Diego, CA, USA) (32). The KT-1000 is an instrument tested for reliability in healthy subjects (108, 134) and to distinguish a group of patients with ACL ruptures from a group without (108). The reproducibility of the KT-1000 measurements of anterior knee laxity between two experienced examiners was considered as fair (ICC=0.55) (108).

Muscle strength

Muscle strength can be defined as ’the magnitude of torque exerted by a muscle or muscles in a single maximum isometric contraction of unrestricted duration’(37). This definition does, however, not have a very functional approach having in mind that tests of muscular strength are commonly performed to assess functional performance, in both the sporting and rehabilitation fields. The number of published studies concerning the correlation between strength and functional performance is limited (6, 7, 100). It is not known whether muscle strength tests alone are sensitive enough to rate the success of rehabilitation after ACL reconstruction or predict future performance in terms of reducing the risk of re-injury. To measure strength is however valuable in terms of detecting whether the strength is normalised or not after ACL reconstruction. In ACL rehabilitation, it is often recommended to obtain a minimum of 85-90 % muscle strength in the operated leg compared to the non-operated leg, before returning to sport or physically demanded work (68, 96).

Muscle strength can be measured in an isometric, isotonic and isokinetic way. The Kin-Com® dynamometer (Chattecx Corp., Chattanoga, TN, USA) is one of the isokinetic devices used for measuring concentric and eccentric muscular torque in knee extensors and knee flexors. Research groups have reported high reliability coefficients (>0.90) for several isokinetic devices (127). Although the reliability coefficients for eccentric muscle actions appear to be slightly lower than those for concentric muscle actions, they remain high (43, 107).

Postural control

Modern ACL reconstructive surgery uses grafts with high initial strength in order to restore the mechanical behaviour in the knee joint. However, it is unknown to what extent an ACL graft reproduces the neural behaviour of the normal ACL. The innervation of ligaments originates from neighbouring muscular, cutaneous and articular nerve trunks (26). Postural sway reflects the interplay between destabilizing forces acting on the body and actions by the postural control system to prevent the loss of balance (99). Evaluation of postural control has several implications in sports medicine and has been used to identify subjects with increased risk of sport injuries and to evaluate rehabilitation interventions (102). Altered neuromuscular performance after ACL reconstruction have been reported during different exercises (3, 100, 118).

Determination of neuromuscular performance, balance or postural sway can be measured with highly developed instruments, for instance the stereoradiographic system which demands invasive procedures (118), but also with non-invasive, less expensive and more clinical applicable instruments such as force plates and the Kinesthetic Ability Trainer 2000 (KAT 2000™) (BREG Inc., CA, USA).

Anterior knee pain

Anterior knee pain (AKP) can be defined as a syndrome based on unspecific knee pain that aggravates during knee loading conditions. It is diagnosed based on symptoms and clinical signs (33). Anterior knee pain is reported as a frequent complaint after ACL reconstruction, especially after reconstruction with BPTB graft (9, 30, 40). Several knee scores have been used to determine the frequency of AKP among patients with ACL reconstructed knees (64, 125) which make comparisons and conclusions provocative. A knee score for functional evaluations of patients with AKP should consist of different categories of symptoms during valid physical performance. Whether the knee walking test is valid for this category of patients may be further discussed. The AKP score (64, 125) is a score tested for both reliability and validity after ACL reconstruction. It consists of different categories of physical performance where AKP can be detected. The score is a modification of Lysholm Knee Scoring Scale, which originally was designed to evaluate patients with ACL injury as well as meniscus lesions and those with chondromalacia patellae (77).

Activity/Participation

To define and to measure functional capacity after ACL reconstruction is a challenge due to the limitation of sensitive tests. Functional capacity includes several aspects, for example what a person with an ACL deficient or reconstructed knee can do as well as what they actually do in a sporting environment. Traditionally, measures of success following knee surgery have been based on physical examination and radiographic variables. In the past two decades, outcome assessment following orthopaedic surgery has increasingly focused on the patient's perspective. The activity level and the satisfaction therefore is an important prognostic factor for predicting future activity and participation in sports.

Function/Level of activity

Several scores and questionnaires have been constructed, for example, the Tegner Activity Scale, which is a score for evaluating the patients' level of physical activity before and after surgery and rehabilitation and the IKDC form for clinical evaluation (55) which consists of seven objective parameters relating to the knee including the one-leg hop test. Knee injury Osteoarthritis Outcome Score (KOOS) is another outcome score that represents subjective evaluation of knee function (103, 104). In KOOS, five separate scores are calculated for pain, symptoms, activities of daily living, sport and recreation function and knee-related quality of life. The reliability, validity and responsiveness were determined to be satisfactory for KOOS, in a cohort of 21 patients who underwent ACL reconstruction (104).

Hop tests

Several hop tests have been used to measure dynamic knee function in both patients with ACL deficient and ACL reconstructed knees (12, 90). The one-leg hop test for distance (12), seems to be the most common standard test in clinical practice and research. The ratio between the ACL reconstructed and the asymptomatic contra lateral knee is calculated. If the side-to-side symmetry is near or above 85 %, the patients' knee function is considered to be sufficient. However, the sensitivity for detecting functional limitation with this test has lately been shown to be low in patients with ACL reconstructed knees (7). When patients with no less than 90 % hop symmetry underwent a standardised pre-exhaustion exercise protocol before testing, 68 % of the patients showed abnormal hop symmetry. The one-leg hop test has several advantages though. It is for instance easy to set up, why it can be used in the clinical setting and it does not demand expensive equipment.

Even though hop tests can be considered to be more functional and challenging than walking and strength tests for a patient active in sports, it is still not known whether these tests provide us with information of future performance or if normal hop symmetry could predict re-injuries. Furthermore, it is not known how fear interferes with performance during the one-leg hop test. In the present thesis there were patients refusing to carry out this test early in the rehabilitation, why we decided to exclude this test from the five months follow-up assessments in study II.

Patients' expectations and experiences

Patient satisfaction in terms of the outcome of surgery or rehabilitation is a complex phenomenon and therefore challenging to study. Keith (65) made a conclusion about patient satisfaction; that *"Methods of measuring satisfaction must reflect the patient's experiences in such settings"*, and *"to understand the patients' subjective experiences it is necessary to use qualitative techniques to probe for the connections between that experiences and responses to satisfaction"*. To interview patients can be one way to gain deeper understanding of the patient's subjective experience of ACL injury, ACL reconstruction, ACL rehabilitation and belief in the future. The interview method is, however, not without hazards. Without the anonymous of a questionnaire, participants may answer what they believe to be socially acceptable. The advantages, however, is that it might be possible to achieve greater depth of response, maintain control over who actually responds and also may have greater response rate (34).

Rationale for this thesis

The use of hamstring tendon as a graft for reconstruction of the ruptured ACL has increased in popularity. Whether patients with hamstring ACL reconstructed knees can be rehabilitated similary as those patients that have undergone patellar tendon ACL reconstruction have not yet been extensively studied. The patients who have undergone ACL reconstruction are normally encouraged to return to pre-injury level of sports within 6-9 months postoperatively. How specific rehabilitation exercises, if the volume of training or if and to what extent different preoperative variables influence outcome in the early phase after ACL reconstruction remain unclear. Furthermore, there is a lack of knowledge in terms of experiences and expectations during the rehabilitation process from a patient perspective and to what extent this may influence the success of rehabilitation and thereby clinical outcome.

Aims of this thesis

Overall aim

The overall aim of this thesis was to improve the knowledge of appropriate exercises, the influence of preoperative factors for good clinical outcome as well as the patient's experience of the rehabilitation after anterior cruciate ligament reconstruction with patellar tendon or hamstring graft.

Specific aims

To evaluate the *in-vivo* strain on the anterior cruciate ligament during four closed kinetic chain exercises, commonly used in the early phase of rehabilitation after anterior cruciate ligament reconstruction (Study I)

To study the outcome in terms of physical variables after anterior cruciate ligament reconstruction with early versus late initiation of open kinetic chain exercise for the quadriceps in patients with either patellar tendon graft or hamstring tendon graft (Study II)

To investigate possible preoperative subjective and objective individual factors that predicts a successful clinical outcome as measured with the subscales *Function in sports and recreation* and *Quality of life* from the Knee injury Osteoarthritis Outcome Score, one-leg hop test and Tegner Activity Scale on an average 12 months after ACL reconstruction (Study III)

To explore patients' experiences of the rehabilitation process after anterior cruciate ligament reconstruction (Study IV)

Material and Methods

Patients

Study I

Patients scheduled for arthroscopic surgery of meniscus injuries or other minor knee injuries were asked to participate by sending written information. Nine patients (five males and four females) who were candidates for arthroscopic partial meniscectomy (n=6) or debridement (n=3) under local anesthesia volunteered for this study (Table 2). Their ages ranged from 20 to 49 years (mean age = 31 years). None of the patients had a history of a knee ligament injury nor did they show any evidence of an injury via clinical and arthroscopic examinations.

Table 2. The clinical data for the nine patients.

Subjects	Age	Sex	Involved Side	Surgical Procedure
1	20	Male	Left	LM
2	25	Female	Left	P
3	49	Female	Left	LM
4	34	Male	Left	PD, P
5	32	Male	Left	LM
6	30	Female	Right	MM
7	37	Female	Left	FD, PD
8	24	Male	Left	MM
9	30	Male	Right	LM

LM = Lateral meniscectomy
MM = Medial meniscectomy
P = Plica debridement
FD = Femoral chondral debridement
PD = Patellar chondral debridement

Study II and III

Between 1999 and 2005, 80 ACL injured patients, 42 males and 38 females met the inclusion criteria and were involved in preoperative physiotherapy at a Sport Rehabilitation Clinic Table 3). Six males and six females declined to participate due to (a) lack of time (n=8), (b) no ACL reconstruction was performed (n=3), and (c) transferral to another city (n=1). Sixty-eight patients, 36 males and 32 females were finally included as participants in Study II. In Study III, four of the 68 patients were missing for the 12 months follow-up. One patient did not show up at scheduled visits, one sustained a re-rupture of the ACL graft and two patients were excluded due to pregnancy (Figure 3).

Table 3. Demographic data (Study II) for patients with bone-patellar tendon-bone graft with early start of OKC exercises for quadriceps (P4), patients with bone-patellar tendon-bone graft with late start of OKC exercises for quadriceps (P12), patients with hamstring graft with early start of OKC exercises for quadriceps (H4) and patients with hamstring graft with late start of OKC exercises for quadriceps (H12).

	P4 (n=19)	**P12 (n=15)**	**H4 (n=17)**	**H12 (n=17)**
Males/Females	11/8	11/4	7/10	7/10
Age, years (M, SD)	31 (8)	27 (5)	30 (8)	31 (9)
Height, meter (M, SD)	1.73 (0.07)	1.78 (0.07)	1.73 (0.08)	1.72 (0.1)
Weight, kg (M, SD)	74.2 (10.7)	76.2 (9.4)	73.7 (11.5)	71.1 (12.5)
BMI, kg/m^2 (M, SD)	24.6 (2.7)	24.0 (2.1)	24.7 (3.33)	23.7 (2.4)
Injured Leg Left/Right	7/12	8/7	5/12	8/9
Median time between injury and surgery, months (lower and upper quartile)	8.5 (6-19)	5.5 (3-9.5)	9.0 (6-17)	7.5 (4.5-30)
Semitendinosus graft alone (n)			11	12
Semitendinosus + gracilis graft (n)			6	5
Medial meniscus injury	8	3	5	2
Lateral meniscus injury	2	4	4	4
Patella cartilage damage	3	0	2	2
Tibia cartilage damage	2	1	3	0
Femur cartilage damage	4	3	4	5
Medial collateral ligament injury	1	1	1	0

Inclusion criteria

The inclusion criteria were; age between 16-50 years and a symptomfree contralateral knee. Patients with a medial or lateral meniscus tear and/or a medial collateral ligament injury grade I in the index knee, where surgical repair was not indicated, were also included.

Exclusion criteria

The exclusion criteria were; injuries other than the above mentioned, uncorrected vision, a medial collateral ligament injury grade II or III, meniscus lesions suitable for fixation, and patients operated with patellar tendon or hamstring grafts harvested from their contralateral knee.

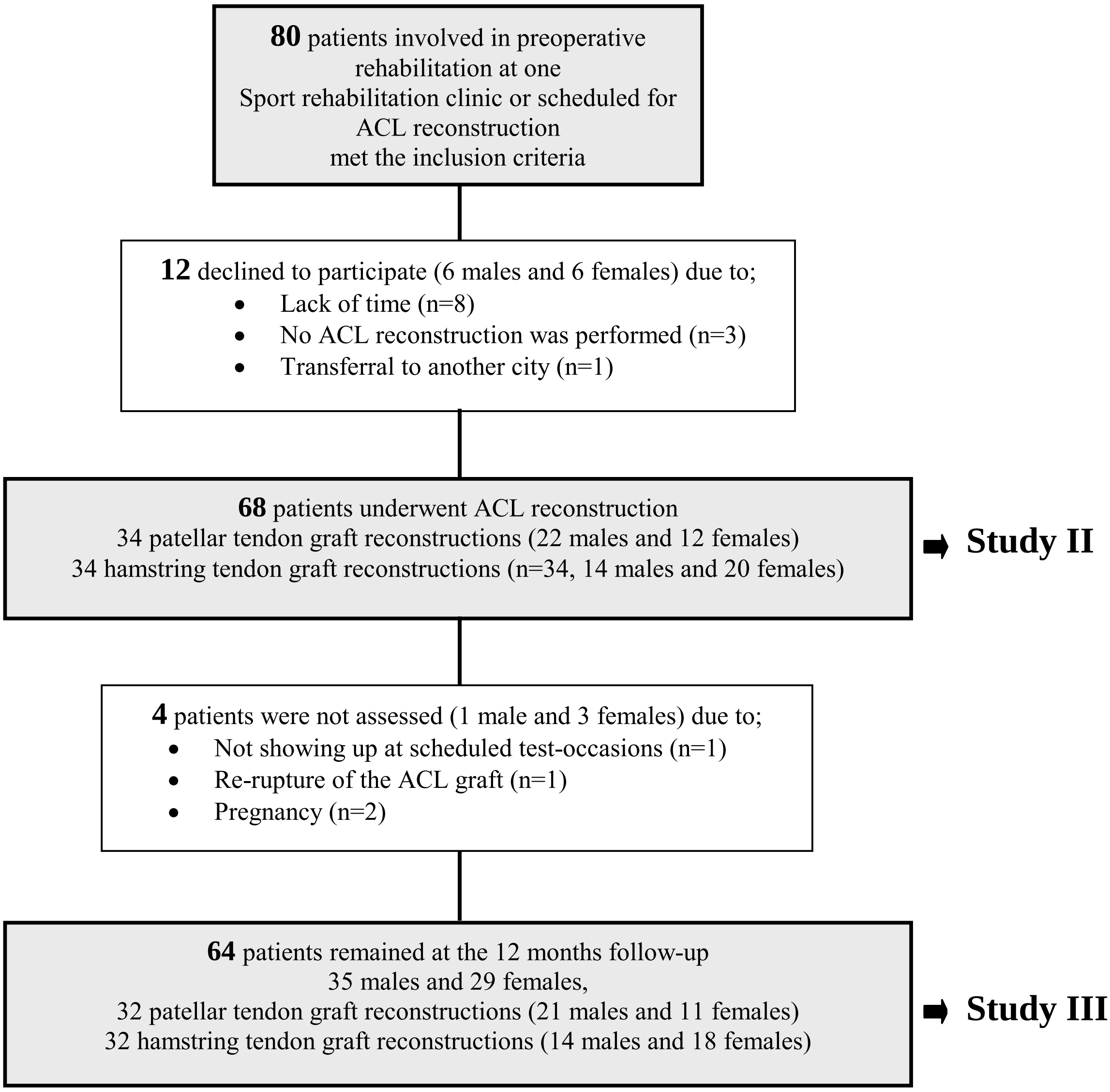

Figure 3. Flowchart of the patients in Study II and III

Study IV

Fifteen patients were asked to participate in the present study at their one-year postoperative follow-up at the clinic. Three patients declined to participate. Two interviews were excluded for technological problems. Ten patients, (nine males and one female), median age 29 (23-41) years, that agreed and granted their informed consent prior to participating were finally included in the study.

The patients were chosen strategically regarding age and gender and recruited from two different outpatient sports rehabilitation clinics in Stockholm, Sweden. All patients were involved in postoperative rehabilitation after ACL reconstruction at one of the rehabilitation clinics between November 2003 and October 2005 (Table 3). Furthermore, nine out of the ten patients also participated in a larger study on clinical outcomes after ACL reconstruction.

The inclusion criteria were: a) age between 16-50 years, b) the same type of patellar tendon or hamstring tendon ACL reconstruction, respectively, and c) an asymptomatic contralateral knee. Patients with a medial or lateral meniscus tear and/or a medial collateral ligament injury grade I were also included. The exclusion criterion was inability to speak or understand the Swedish language.

All patients went through an interview and the median time from surgery to the interview session was 14 months (12-21). The median preoperative activity level evaluated with Tegner Activity Scale (119) was 8 (8-10). For more detailed information, see Table xxx. At the time of the interview one patient was still involved in rehabilitation (nr 10).

Table 3. Demographic data of the participants included in the present study (N=10). Median and ranges are presented.

Participants	Age (Years)	Gender (M=male F=female)	Time between surgery and interview (months)	Preoperative Tegner Activity Scale	Postoperative Tegner Activity Scale (1 year postoperative)	Postoperative rehabilitation (months)
1	23	M	14	8	8	10
2	34	M	13	8	7	6
3	29	M	13	8	8	9
4	30	M	14	10	3	6
5	24	M	17	9	7	4
6	34	M	16	9	7	5,5
7	26	F	17	8	9	10
8	29	M	12,5	10	4	12
9	41	M	12	8	7	5,5
10	23	M	21	7	7	21
Median (Ranges)	29 (23-41)		14 (12.5-21)	8 (7-10)	7 (3-9)	7.5 (4-21)

Surgeons

One experienced surgeon performed the arthroscopic surgery in Study I. The surgery was performed prior to implanting the DVRT on the ACL. In Study II, twenty experienced orthopaedic surgeons performed the ACL reconstructions representing the average standard of ACL reconstructions in the Stockholm area (Table 4).

Table 4. Frequency of the different orthopaedic surgeons in each of the four rehabilitation groups (P4, P12, S4, S12).

Orthopaedic Surgeons	P4	P12	S4	S12
1	2	2	1	1
2	1	1		
3	1	1		
4	1			
5		1		
6	1			
7		1		
8	1	1	2	
9			3	3
10		1		
11	4	4	1	3
12		1		1
13	1		6	5
14			3	1
15			1	
16				2
17	1			
18	3	2		1
19	1	1		
20	1			

Table 5. Physiotherapists supervising the different rehabilitation programmes, early start (4 weeks) of OKC exercises for quadriceps and late start (12 weeks) of OKC exercises for quadriceps.

Physiotherapists	Early Start (n)	Late start (n)
1	3	2
2	7	8
3	11	5
4	1	2
5	4	3
6	1	1
7	2	2
8	4	3
9	1	3
10	2	3

Physiotherapists

Ten experienced physiotherapists at the same outpatient sport physiotherapy clinic, were involved in the rehabilitation (Study II and III) (Table 5).

Test leaders

Two experienced independent examiners evaluated all patients. None of these two examiners were involved in the rehabilitation. The same examiner followed the same patient at all his/her test occasions and the examiners were blinded to type of rehabilitation, but not to type of reconstruction.

Group randomisation for the rehabilitation programme (Study II and III)

Postoperatively, the patients were randomised into four different rehabilitation groups. The study was stratified for gender. At the first postoperative rehabilitation session each patient with patellar tendon graft or hamstring graft, respectively, was asked to choose one out of 50 closed envelopes (25 for males and 25 for females) for group randomization. At the end of the study there were three envelopes left for males and 13 for females with patellar tendon graft and 11 envelopes left for males and five for females with hamstring graft. The reason for using more envelopes than was calculated by the power analysis, was that patients included late in the study should have the same possibility to be randomized to either of the groups.

Rehabilitation protocol (Study II and III)

All patients started a standardized postoperative rehabilitation program within one week after surgery at the same outpatient clinic. Supervised physiotherapy was performed two to three times a week as long as the patient and the physiotherapist considered it necessary. The median number of training sessions was 41 (23-61) for the P4 group, 45 (24-55) for the P12 group, 40 (9-53) for the H4 group and 37 (14-48) for the H12 group. Ten experienced physiotherapists were involved in the rehabilitation. The rehabilitation protocol consisted of joint and muscle flexibility exercises, balance- and coordination training and strength training focusing mainly on the thigh muscles (Appendix 1). Patients from the H4 and the P4 groups were introduced to an OKC exercise of quadriceps consisting of a seated knee extension within the range of motion of 90°-40° with no external resistance starting at the 4th postoperative week, within 90°-20° of knee extension at the 5th week, and within 90°-0° of knee extension at the 6th week. Unlimited external resistance was allowed according to symptoms and tolerance of each patient. Patients from the H12 and in the P12 groups started with OKC exercises of the quadriceps muscle in a seated position at the 12th postoperative week. They were immediately allowed to start their OKC training at the 12 th postoperative week within 90°-0° of range of motion but with no external resistance during the first week. Bicycling was allowed for all patients of the four groups as soon as knee flexion of the reconstructed leg had reached ≥110°. No brace was used during the rehabilitation period. Immediate weight bearing according to tolerance was allowed after surgery. Based on muscle strength, balance/coordination and functional performance the patients were allowed to return to active, competitive sports six months postoperatively or later depending on their functional capacity.

Compliance (Study II)

Training volume

In order to control for type of exercises, sets, repetitions and external loading (kg), training volume was recorded for each training session between the 4th and the 12th postoperative week. For some of the exercises such as bicycling and stairmaster training (cardiovascular training) the duration was recorded in minutes. When analysing the data, CKC exercises such as one leg raising from a chair, step up and step down exercises, and functional training, such as slideboard exercises, jogging and different jumping exercises were grouped as one unit. Of the total number of 68 patients in this study, 58 were included in calculation of training volume (Appendix 2). The drop-outs were due to lost data sheets for training (n=4) and postoperative complications such as pain, infections or limited range of motion (n=6), which made the training volume with external resistance almost equal to zero.

The total training volume was calculated using the formulation sets*repetitions*resistance for each exercise at each training session and was then summarized for the studied training period, 4th to 12th postoperative week. An *Index* was then developed by dividing the training volume with each patient's body weight in order to make it possible to compare the training volume between males and females.

Evaluation

Study I

Strain on the anterior cruciate ligament

Displacement measurements of the anteromedial bundle of the ACL were performed using a Differential Variable Reluctance Transducer (DVRT; MicroStrain, Burlington VT) (18). The small displacement transducer was arthroscopically applied to the ACL through a lateral parapatellar portal as previously reported (18).

Because the surgery was performed under local anesthesia, a tourniquet was not used. The measurement axis of the transducer was aligned with the anteromedial bundle and attached to the ligament midsubstance (Figure. 4). The electrical connection and removal sutures of the DVRT exited through the lateral portal to enable data acquisition and removal of the transducer after the experiment was completed.

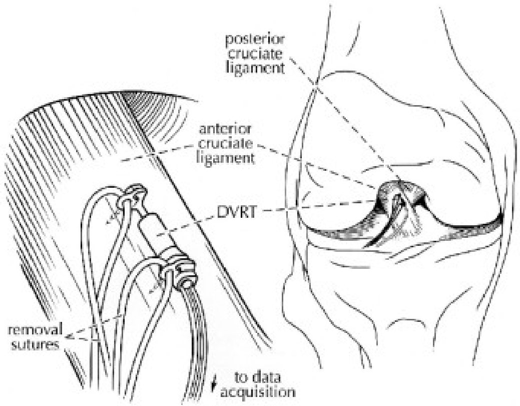

Figure 4. The DVRT was arthroscopically inserted on the anteromedial bundle of the ACL. The body of the transducer is approximately 5-mm in length.

Immediately following the routine surgical procedure, the DVRT was implanted on the ACL. The portals were sealed and an electrogoniometer (CA-4000; Orthopaedic Systems Inc, Hayward CA) was attached to the thigh and lower leg to record knee flexion angles. The patient was then escorted off the operating table to perform three repetitions of four CKC exercises. The exercise testing order was randomized. The outputs of the DVRT (the ACL displacement response) and the electrogoniometer (the knee flexion angle) were recorded as each subject performed the exercises.

A physiotherapist was in the operating room to provide instruction and supervised the performance of each exercise. For a lunge, the patients were instructed to position their upper body over the knee of the front leg (the instrumented knee) to align the torso center of gravity with the knee joint. The back leg served as a stabilizer to maintain balance. For a step-up, step-down and a one-legged sit to stand the subjects were instructed to move normally. All subjects practiced each exercise two to three times before data were collected.

An instrumented Lachman test was performed both prior to and immediately following the exercise testing protocol. Anterior-posterior directed shear loads, between the limits of –90 (posterior) and +130 (anterior) Newtons, were applied to the tibia while the knee was supported at 30^{o} of flexion while the femur was aligned in the horizontal plane (18). The shear loads were applied perpendicular to the long axis of the tibia at the level of the tibial tuberosity. The patients were instructed to relax their leg musculature during the test. The data that were obtained during the repeated Lachman test served two purposes: 1) to determine the reference for the strain calculation (50), and 2) to serve as a "repeated normal" to ensure that the DVRT measurements were reproducible (18). After completion of the repeated Lachman test, the lateral arthroscopic portal was re-opened and the DVRT was removed by pulling on the removal sutures.

Study II and III

Range of motion

A universal goniometer was used to measure passive range of motion with the patient in the supine position (36). Knee flexion and knee extension were registered according to the IKDC form (55).

Anterior knee laxity

Anterior tibial displacement relative to the femur was measured bilaterally at approximately 20° of knee flexion with the KT-1000 arthrometer (MEDmetric, Corp., San Diego, CA, USA) at max manual. The difference in displacement between the operated and the healthy knee was expressed in millimetres (32, 134).

Pivot shift

Pivot shift was checked and recorded according to the IKDC form (55).

Postural sway (Study II)

Kinesthetic Ability Trainer 2000 (KAT 2000™) (BREG Inc., CA, USA) was used for measuring balance/postural sway when standing on one leg. This equipment has been found to be reliable for testing groups of individuals (54). The measurements were performed during standardized conditions by having the patient standing barefoot on one leg with that knee as well as the knee of the free leg flexed approximately 30°, and the arms crossed in front of the chest. Three tests, lasting 20 seconds each, were performed on both legs starting with the asymptomatic leg. The distance between the centres of the board to centre of pressure was measured in arbitral units. The best trial (least postural sway) was recorded.

Thigh muscle torques

The Kin-Com® dynamometer (Chattecx Corp., Chattanoga, TN, USA) (43) was used for measuring concentric and eccentric muscle torques of the quadriceps and hamstring muscles at 90°/s and within 10°-90° of knee flexion, always starting with the asymptomatic knee. At the three months test occasion, thigh muscle torques were tested within 90°-40° of knee flexion. The patient sat with the thigh supported, with 90° of hip flexion, a support for their lower back, a fixation girdle around the pelvis and their arms folded. The centre of motion of the lever arm was aligned as accurately as possible with the slightly changing flexion-extension axis of the knee joint and the resistance pad was placed just proximal to the lateral malleolus. Determinations were repeated at least three times and consecutive recordings for reproducibility were obtained while superimposing the last record on the preceding ones on the computer monitor. Solely closely similar recordings of the highest observed amplitude were accepted to exclude measurements at obvious submaximal effort. (66, 125). Torque values were corrected for gravitational force (53). The average muscle torque was recorded. Prior to the isokinetic testing the patients warmed-up on a stationary bicycle during 5-7 minutes. They were also allowed to perform 2-4 warm-up cycles during extension and flexion in the Kin-Com device before data were collected. The muscle torques were calculated as the ratio between the asymptomatic knee and the ACL reconstructed knee, reported in percents.

One-leg hop test (Study III)

The patients were standing on one leg and were asked to jump straight forward as far as possible. Free arm swing was allowed throughout the movement. The landing had to be steady for at least two seconds on the landing foot. The distance from the toe at the push-off to the heel mark at the landing was measured in metres. Three tests were performed on both legs alternatively. The patient decided which leg to start with (12). The best trial was recorded. The ratio between the ACL reconstructed and the asymptomatic knee were calculated and used as continuous data in the analysis.

Outcome questionnaires

Anterior knee pain (Study II and III)

An AKP score modified from an earlier version (124) was used to evaluate anterior knee pain. This score has been adjusted and specified for possible AKP in ACL injured patients. It has been tested three times under standardized conditions within a period of three weeks. The modified version showed a good reliability with an ICC of 0.969 of the total score. Test for sensitivity was performed by studying five subject groups: ACL injured and ACL reconstructed knees, hamstring tendon ACL reconstructed knees, postoperative meniscus lesions, and asymptomatic controls. The patients who had undergone ACL reconstruction and the patients with meniscus lesions were tested 4-6 months postoperatively. All groups answered the score at one test occasion. The total score that comprises 50 points showed the highest sensitivity for ACL injured patients (M=35.5±8.0 points) and the least sensitivity for asymptomatic controls (47.5±3.8 points). With regards to the total score there was a significant difference between asymptomatic controls and ACL injured patients (p=0.0001) (Unpublished data).

KOOS (Study III)

The KOOS is a knee-specific instrument, developed to access the patients' opinion about their knee and associated problems (103, 104). It holds 42 items in 5 separately scored subscales; Pain, other Symptoms, Function in daily living (ADL), Function in Sport and recreation (Sports/Rec) and knee related Quality of Life (QOL).

It has been proven reliable, responsive to surgery and physical therapy, and valid for patients undergoing ACL reconstruction (104). In Study III only the Sports/Rec and the QOL were used in the analysis.

Tegner Activity Scale (Study III)

The Tegner Acticity Scale (TAS) (119) was used describing a patient's activity level from 0 to 10. A high score means that the patient participates in sports such as soccer and floor ball, for instance, which are sports that place high demands on knee joint stability.

Study IV

Semi-structured interviews

Data collection was performed by semi-structured interviews conducted by one of the authors. The interviewer was a physiotherapist with long clinical experience of rehabilitation after ACL reconstruction, not involved in the interviewed participants' rehabilitation. Each interview lasted approximately one hour performed in a location chosen by the participant. All interviews were audio taped and transcribed verbatim. The interview guide was based on previous studies and clinical experiences of the authors (Table 6). The interview guide was tested on three interviewees and subsequently modified by three of the authors. The three test interviews were not included in the current study.

Table 6. The interview guide

- The occasion of the injury (Why? Other choices?)
- The operation/Surgery (Expectations? Challenges?)
- The rehabilitation process (Expectations? Challenges? Advantages and disadvantages? Advices to caregivers/other patient?)
- The present situation (Expectations? Challenges? Function? Activity level?)
- The future (Expectations? Challenges? Function? Activity level?)

Ethical approvals

Study I

The ethical committee at the Karolinska Hospital, dnr 99-090 and the Institutional Review Board at the University of Vermont approved this study.

Study II and III

The ethical committee at the Karolinska Institutet, dnr 99-091, approved this study.

Study IV

The ethical committee at the Karolinska Institutet, dnr 03-281, approved this study.

Statistical methods

Study I

The peak ACL strains produced during the four exercises for the flexion and extension portion of the cycle were compared using a two-way repeated measures analysis of variance. The two within subject factors were exercise type and cycle direction. The ACL strain patterns (i.e. ACL strain as a function of knee flexion angle) were compared using a three-way repeated measures analysis of variance. The three within subject factors were exercise type (step-up, step-down, lunge, and one-legged sit to stand), knee flexion angle (30^o, 50^o and 70^o) and cycle direction (flexion vs extension). Fisher's Least Significant Difference procedure was used to make pair-wise comparisons. The strain reference values that were obtained from the "repeated normal" Lachman tests were compared using a paired t-test to ensure that the DVRT measurements were reproducible (18). Statistical significance for all analyses were determined at α=0.05.

Study II

Prior to the study a power analysis was made based on anterior knee laxity. A difference of 1.5 mm side-to-side difference in anterior knee laxity of the reconstructed knee estimated a sample size of 15 patients in each group with 80% power, when $p \leq 0.05$. The power analysis was made as a "Two-group repeated measures ANOVA" (Greenhouse-Geisser correction) in the nQuery 4.0. The demographic data of the patients and the training volume were presented in means and standard deviations or medians and lower and upper quartiles. The result of the AKP score and range of motion were considered as non-parametric data and the Kruskal-

Wallis test was used when calculating these results. If general treatment effects were found, multiple comparisons of mean ranks for all groups were performed (Post Hoc test). In order to compare the ratio in thigh muscle torques, differences in anterior knee laxity and differences in postural sway between the ACL reconstructed knee and the asymptomatic leg over time, a mixed effect model analysis was used. The mixed effect model analysis is a method, which is more flexible than repeated measures ANOVA. It can take inhomogeneous variances and missing data into consideration, when data is missing at random (Table 7). These analyses included testing for a treatment effect and graft choice, the effect of concentric and eccentric muscle actions, a time effect and the effect of whether the ACL reconstruction was performed in the left or right knee. In situations in which a significant general treatment effects was observed, planned pair-wise comparisons were used. To adjust the significant levels of the planned comparisons, a Bonferroni correction was made. SAS PROC MIXED was used for these analyses.

Table 7. Missing data at random regarding muscle torque, sagittal knee laxity, postural sway and anterior knee pain of the four rehabilitation groups at each of the three test occasions. The Mixed Model analysis was used for muscle torques, sagittal knee laxity and postural sway.

		Muscle torque (Kin-Com)	**Sagittal knee laxity (KT 1000)**	**Postural Sway (KAT 2000)**
3 months postop	**P4**	1	1	2
	P12	1		4
	H4	1		
	H12	1		
5 months postop	**P4**	4	3	5
	P12	5	3	4
	H4	2	2	2
	H12	6	3	3
7 months postop	**P4**	5	3	4
	P12	2		
	H4	5	3	3
	H12	5	4	5

Study III

The four dependent outcome variables, studied 12 months after reconstruction, were Sport/Rec – KOOS, QOL – KOOS, one-leg hop test and Tegner Activity Scale. Correlations between listed pre-operative factors (independent variables) and the dependent post-operative outcomes were determined by Spearman rank-correlation coefficient analysis, where preoperative factors that were correlated at a p-level of 0.10 were included for further regression analyses. The Spearman rank-correlation coefficient analysis was in addition used to exam whether strong co-linearity (defined as $r > 0.8$) existed between the preoperative independent variables. A standard linear multiple regression analysis was used followed by a statistical forward step-wise regression procedure to reveal the most important preoperative factors for each dependent outcome variable. In the regression models adjusted R^2 and Beta were presented. The adjusted R^2 is the proportion of variation in the postoperative dependent variable that is explained by the present preoperative factors (independent variables), adjusted for number of variables included in the analysis. The regression summary for the dependent variables (Table 3) displays the standardized Beta and statistical significance. Here, the Beta value, explains the importance for each preoperative independent factor in *predicting* the dependent postoperative variable; it is normalized as if all of the independent factors had means of 0 and a variance of 1. Thus, the magnitude of these Beta coefficients allows you to compare the *relative* contribution of each preoperative independent factor in the prediction of the postoperative dependent variable.

Study IV

The transcribed interviews were analysed using a qualitative thematic content analysis, which could be described as a systematic process of identifying, coding and categorising patterns of regularity. To begin with, the interviews were read several times by two of the authors as a whole in order to obtain an overall understanding of what was important to discuss for the patients, followed by a phase of identifying meaning units consistent with the aim of this study. The units were condensed and sorted in categories for each interview. According to that, the categories were compared and related to each other and summarised in overarching themes right across all interviews, emphasised on the similarities and differences between the ten interviews. This process was done separately by two of the authors and interpreted for validation. The interviews were reread once more to refine and verify the overreaching themes. Alternative interpretations were discussed. Three of the authors took part in this process. Finally, each theme was labelled and specific quotations were chosen to illustrate the general implications.

Results

Study I

No significant differences were found between the peak ACL strain values produced due to exercise type ($p=0.25$) or by cycle direction ($p=0.34$) The average peak ACL strains produced during the step-up exercise were 2.5% (SEM = ±0.36) during the extension portion of the exercise cycle and 2.5% (SEM = ±0.31) during the flexion portion of the exercise cycle. The average peak ACL strains produced during the step-down exercise were 2.5% (SEM = ±0.34) during the extension portion of the exercise cycle and 2.6% (SEM = ±0.34) during the flexion portion of the exercise cycle. The average peak ACL strains produced during the lunge was 1.8 % (SEM = ±0.62) during the extension portion of the exercise cycle and 2.0% (SEM = ±0.50) during the flexion portion of the exercise cycle. The average peak ACL strains produced during the one-legged sit to stand exercise were 2.8% (SEM = ±0.23) during the extension portion of the exercise cycle and 2.8% (SEM = ±0.27) during the flexion portion of the exercise cycle. On average, the peak strains occurred when the knee was approaching extension (Figure 5).

No significant differences were found between the ACL strains produced during the four exercises when the knee was at 30^o, 50^o, and 70^o of flexion ($p=0.15$) (Figure 5a-d). No differences were found between the extension and flexion directions of the cycle ($p=0.18$). The strains produced when the knees were at 30^o (1.7 ± 0.22%; pooled mean ± 1 SEM) were significantly greater than those produced at 50^o (0.7 ± 0.19%) and 70^o (0.1 ± 0.24%) of knee flexion.

For the instrumented Lachman tests performed before and after the exercises, the mean difference in the reference strains across patients was equal to 0.0 ± 0.04 mm. Because the mean change in reference length before and after the exercise bout was not significant ($p=0.73$), and the interclass correlation coefficient of the reference lengths was high (ICC = 0.98), the output of the DVRT was considered reproducible over the exercise bout.

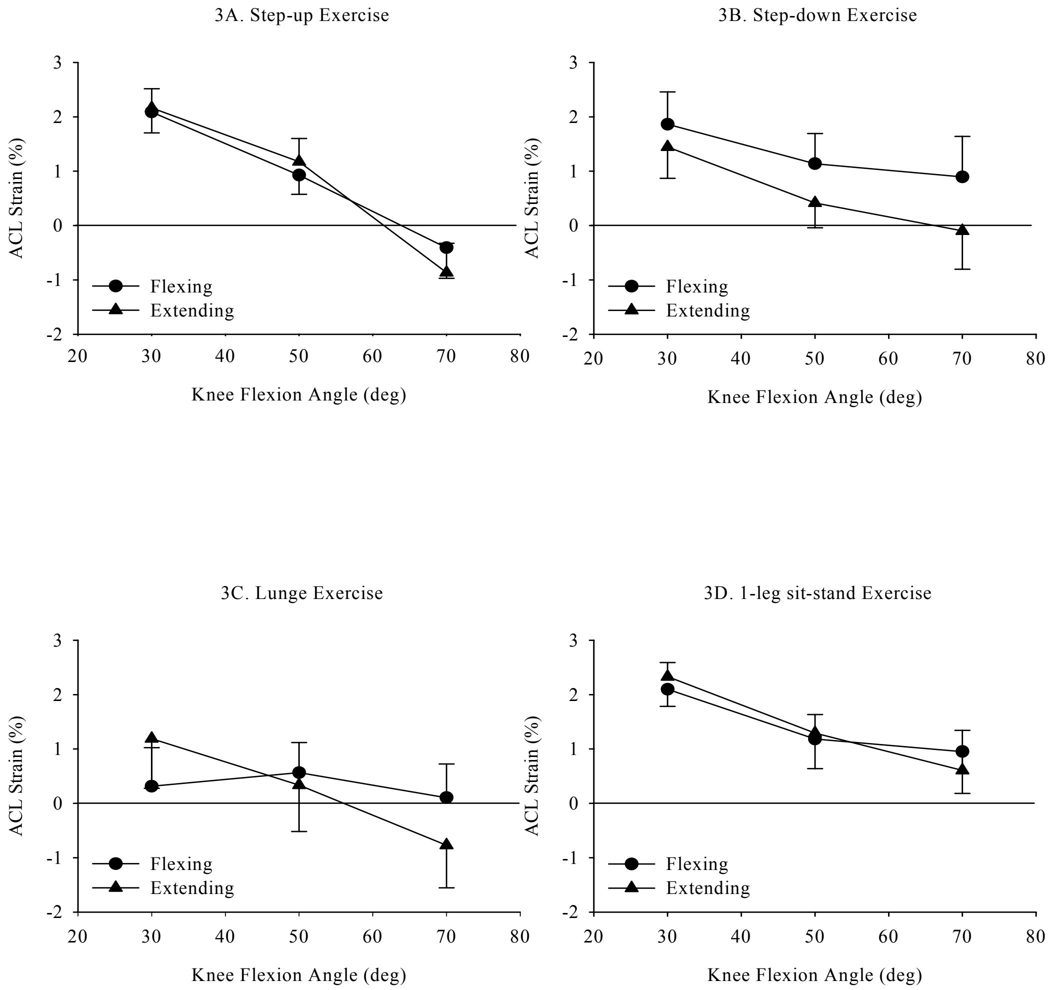

Figure 5. The mean ACL strains as a function of knee flexion angle for the four exercises: A) the step-up exercise, B) the step-down exercise, C) the lunge, and D) the one legged sit to stand exercise.

Study II

No significant differences were observed between the left and the right knee in terms of anterior knee laxity, thigh muscle torques and postural sway.

Range of motion

No significant group differences were found in terms of knee extension and knee flexion 3, 5 and 7 months postoperatively.

Anterior knee laxity

There was no statistical significant side-to-side difference (p=0.87) in anterior knee laxity at the preoperative assessment. The general treatment effects for all follow-ups showed a statistically significant difference (p=0.02) between the four groups. When comparing the P4 group and the H4 group (early start of OKC exercises for quadriceps) the H4 group showed a significantly higher mean difference over time of 1.0 mm (CI: 0.22-1.84) (p=0.04) (Figure 6). Within the same type of surgery (e.g. hamstring graft reconstruction), the H4 against the H12, the mean difference over time was 1.2 mm (0.37-2.04) higher in the H4 group (p=0.02).

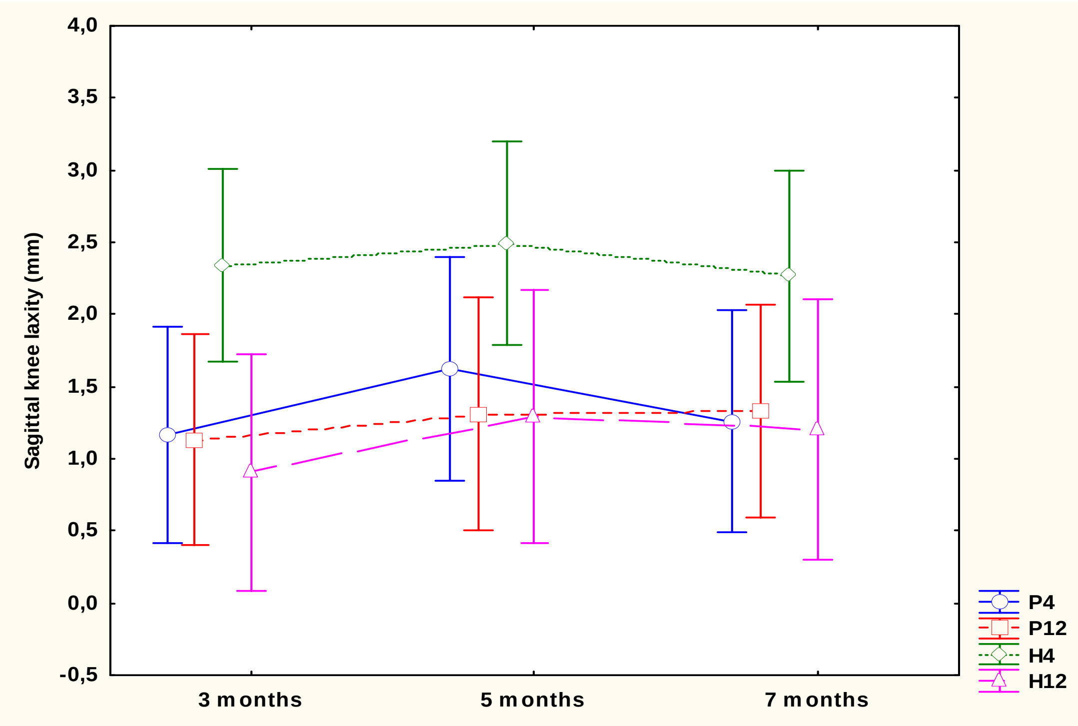

Figure 6. The difference in sagittal knee laxity (mm) (mean and CI) between the healthy and the reconstructed knee and CI at 3, 5, and 7 months follow-up for the P4, P12, H4 and H12 groups.

Pivot shift

Preoperatively, the pivot shift tests showed no significant group differences in terms of rotational instability (p=0.27). The pivot shift test showed significantly higher rotational instability in the H4 group compared with the P4 group at 3 months (p=0.04) and 7 months (p=0.04), but not at the 5 months (p=0.07) follow-up. At each follow-up there were no significant differences between any of the other groups.

Postural sway

The preoperative values were used as a covariate in this analysis. There were no significant group differences in terms of postural sway (p=0.23). No significant change was observed in postural sway (p=0.84) over time (at 3, 5 and 7 months postoperatively) in neither of the groups.

Thigh muscle torques

No significant differences in terms of type of muscle action, neither concentrically nor eccentrically were observed for either the quadriceps (p=0.62) or the hamstring muscles (p=0.13) at an angular velocity of 90º/s. Significant differences in changes over time were found when comparing the four groups, for both quadriceps (p<0.001) and hamstrings (p<0.001) (Figures 7 and 8).

Quadriceps muscle torque

General treatment effects were seen (p=0.004) in quadriceps muscle torques, why planned comparisons at each follow-up were performed. Specific p-values for each follow-up can be seen in Figure 7.

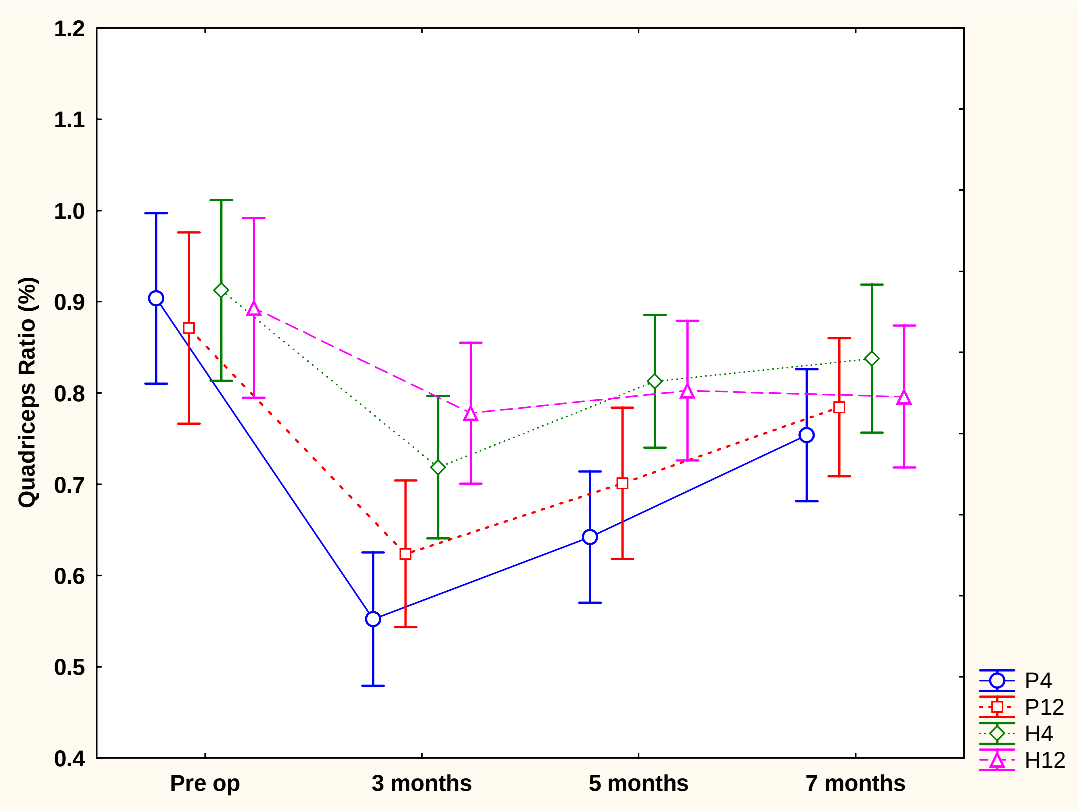

Figure 7. Quadriceps muscle ratio (reconstructed knee/asymptomatic knee) (mean and CI) preoperative, at 3, 5 and 7 months follow-up for the P4, P12, H4 and H12 groups.

P-values at follow-ups	Pre op:	for all comparisons = n.s	
	3 months:	P4 vs H4 = 0.012	P4 vs H12 = 0.0006
		P12 vs H12 = 0.04;	all other comparisons = n.s
	5 months:	P4 vs H4 = 0.005	P4 vs H12 = 0.012,
		all other comparisons = n.s	
	7 months:	for all comparisons = n.s	

Hamstring muscle torque

General treatment effects were found (p<0.0001) in hamstring muscle torques, why planned comparisons at each follow up were performed. Specific P-values for each follow-up can be seen in Figure 8.

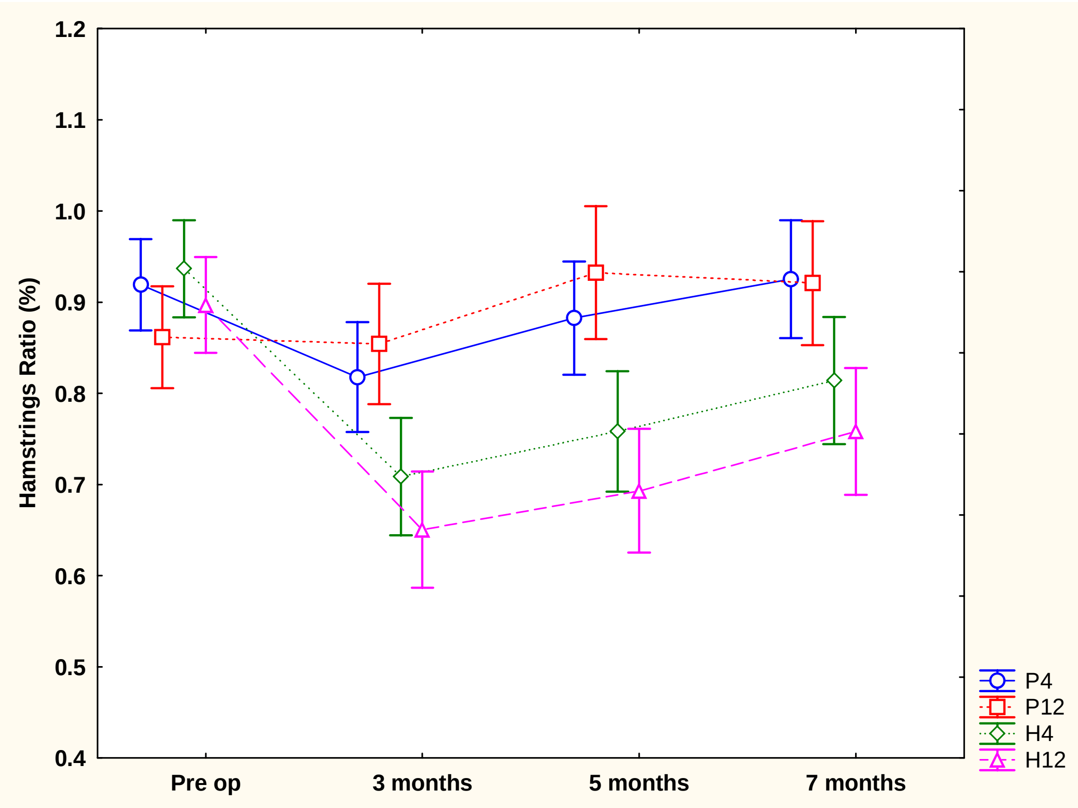

Figure 8. Hamstring muscle ratio (reconstructed knee /asymptomatic knee) (mean and CI) preoperative, at 3, 5 and 7 months follow-up for the P4, P12, H4 and H12 groups.

P-values at follow-ups:	Pre op:	for all comparisons = n.s	
	3 months:	P4 vs H12 = 0.01	
		P12 vs H4 = 0.01	P12 vs H12 = 0.0006
		all other comparisons = n.s	
	5 months:	P4 vs H4 = 0.04P4 vs H12 = 0.0006	
		P12 vs H4 = 0.003	P12 vs H12 = 0.0006
		all other comparisons = n.s	
	7 months:	P4 vs H12 = 0.003	P12 vs H12 = 0.006
		all other comparisons = n.s	

Anterior knee pain

There were no significant group differences in terms of anterior knee pain at the different test occasions, neither preoperatively (p=0.62), nor at 3 (p=0.49), 5 (p=0.39) or 7 months postoperatively (p=0.53). There were no significant differences in terms of AKP between the different grafts (P4 and P12 as one unit compared with H4 and H12 as one unit).

Study III

Co-linearity

There were no strong inter-correlations between the independent variables all combinations, r < 0.8. Thus all listed independent predictors were used in the analyses.

Bivariate analysis

The following six preoperative variables were significantly correlated with Sport/Rec – KOOS: AKP, knee function, knee flexion deficits, influence on activity level (IKDC), gender, cartilage damage. For the QOL - KOOS a correlation was found for knee flexion deficits, AKP, knee function, BMI, anterior knee laxity and eccentric quadriceps torques. For the one-leg hop test cartilage damage, correlated significantly with the outcome. The following four pre-operative variables were significantly correlated with activity level according to TAS: concentric quadriceps torques, graft, time between injury and reconstruction and anterior knee laxity.

The following independent variables were not significantly correlated with any of the dependent variables: rehabilitation, age, knee extension deficits, meniscus injury, medial collateral ligament injury, pivot shift sign or pre-injury activity level according to TAS.

Multivariate analysis

Sport/Rec - KOOS

The six variables entered, explained together 37 % of the clinical outcome in Sport/Rec - KOOS ($p<0.002$). Absence of or minor AKP were found to be a significant ($p\leq0.05$) pre-operative predictor for a high score in Sport/Rec - KOOS at the 12 months follow-up. When performing a forward step-wise regression analysis it was shown that pre-operative low knee influence on the patient's activity level (IKDC) in addition were independently associated with Sport/Rec – KOOS. Together they explained 31 % of this variable (Table 8).

QOL - KOOS

The six variables entered explained 44 % of the clinical outcome in QOL - KOOS ($p< 0.001$). High scores on the AKP, no loss of knee flexion, low BMI and low eccentric quadriceps torques were found to be significant preoperative predictors ($p\leq0.05$). These four variables remained significant predictors in the forward step-wise regression analysis. Absence of or minor AKP, no loss of knee flexion and a low BMI were shown to be the most important predictors (Table 8).

One-leg hop test

Cartilage damage only passed the initial bivariate analysis, and was solely entered for the one-leg hop test (p≤0.05). However, this variable did not receive significance when performing step-forward analysis. Absence of cartilage damage explained 6 % of good outcome as measured with the one-leg hop test (Table 8).

Tegner Activity Scale

The four variables entered explained 21 % (p=0.006) of the outcome. The use of patellar tendon graft was shown to be the strongest predictor in the forward step-wise regression analysis (Table 8).

Table 8. Multiple and Step-wise regression analyses for Sports/Rec – KOOS, QOL - KOOS, One-leg hop test and Tegner Activity Scale.

Outcome	**Multiple Regression**			**Step-wise Regression**		
	Significant Factors	**R^2**	**p**	**Important Factors**	**Cumulative adjusted R^2 by step**	**Beta**
Sport/Rec -KOOS (n=62)	AKP	0.37	0.0002	AKP	0.21	0.37
				Knee influence on activity level[1]	0.31	-0.25
QOL -KOOS (n=61)	AKP	0.44	0.00001	AKP	0.14	0.35
	Knee flexion deficit			Knee flexion deficit	0.26	-0.36
	BMI			BMI	0.34	-0.36
	Eccentric quadriceps torque, 90°/s			Eccentric quadriceps torque, 90°/s	0.38	-0.25
One-leg hop test (n=63)	Cartilage damage	0.06	0.05			
Tegner Activity Scale (n=63)	Graft	0.21	0.006	Graft	0.08	-0.28
				Time between injury and surgery	0.13	-0.23

[1] *How does your knee influence on your activity level?*

Study IV

The patients' experiences of the rehabilitation process after ACL reconstruction were grouped into the following four themes:

1. **Operative or non-operative treatment after injury – no personal dilemma**
2. **Time setting – a source of frustration**
3. **Struggling to attain goals – different responses**
4. **Outlook for the future – an unavoidable task**

1. There was no real choice between operative and non-operative treatment. Only surgery symbolized a full return to the pre-injury level of sport activity, and surgery was understood as the only way to become a completely restored "functional human being".
2. A major source of frustration was that the rehabilitation period lasted much longer than anyone could possibly understand before surgery. The implications and meaning of the rehabilitation process, and their progress during rehabilitation, did not match their expectations. All participants mentioned that they considered themselves not to be mentally prepared.
3. There were three different responses to the challenge of prolonged rehabilitation: "*going for it"*, *"being ambivalent"*, and *"giving in*". The group of patients who *accepted the challenge* ***("going for it")*** was convinced that they would succeed in returning to sports at their pre-injury activity level. They stayed active and goal-oriented. They seemed to be competitive and had a "fighting spirit", and never lost belief in the idea that they would be totally recovered. They also perceived themselves as capable of deciding whether or not they wanted to return to sport at the same activity level as before the injury.

   Those who were *ambivalent* ***("being ambivalent")*** seemed to lack goals, or had diffuse goals in terms of future sporting activity. On the other hand, ambivalence could also be related to re-evaluation of personal goals, personal identities, and social roles. The patients in this group described a loss of motivation and referred to not having given themselves an honest chance.

   Those who did not accept the challenges were able neither to motivate and guide themselves by setting realistic goals, nor to mobilise personal resources.

4. Finally, patients' outlook for the future was mentioned as an unavoidable task. Fear of re-injury was a common experience. However, some individuals decided against returning to their pre-injury level of sporting activity for reasons other than physical limitations or fear of re-injury.

Additional analysis

It is known from the literature that pain may inhibit muscle strength (5). Therefore, in the present thesis (Study II and III) pain rating was carried out using the Borg Pain Scale (24) during the isokinetic measurements. However, the patients´pain ratings were low during both the concentric and excentric muscle actions for the quadriceps muscle (Table 9).

Table 9. Pain rating (Borg Pain Scale) during concentric and eccentric isokinetic measurements for quadriceps at an angular velocity of 90º/s preoperatively, 3, 5 and 7 months postoperatively (Study II). Median and ranges are presented.

Pain	Preoperatively	3 months*	5 months	7 months
Concentric muscle action	0 (0-4)	0 (0-7)	0 (0-6)	0 (0-4)
Eccentric muscle action	0 (0-3)	0.5 (0-8)	0 (0-8)	0 (0-4)

* Measurements only performed within 90º-40º of knee flexion

Discussion

Anterior cruciate ligament rupture – a common injury

According to the Swedish National ACL-register (89) there are approximately 3000 patients every year in Sweden who are undergoing an ACL reconstruction. In 2006, 700 of these were performed in Stockholm. When taking the number of ACL reconstructions in Stockholm every year in consideration, there should be no difficulties to involve patients in research concerning ACL reconstruction and the following rehabilitation. However, the recruitment of the patients in Study II and III took six years, which could be considered as a long period of time. However, *all* patients undergoing preoperative rehabilitation at one specific clinic who met the inclusions criteria were asked to participate, but a large amount of these patients were already involved in other studies, which excluded them from the present investigation. In addition, Study II and III were stratified for gender and only one rehabilitation clinic was involved in the rehabilitation to secure the standardisation of the rehabilitation.

During the period of inclusion, a change in the referral system from the surgeons to the physiotherapists was noticed meaning that several patients were not referred to preoperative rehabilitation. Instead, the patients were only referred to the physiotherapist for postoperative rehabilitation. Therefore the strategy to recruit patients changed in Study II and III and the last third of the included patients were recruited by sending written information about the studies to the patients, who where scheduled for ACL reconstruction wherefter they were contacted. However, due to the randomisation procedure these patients were equally spread over the different rehabilitation groups.

Patients

Gender

There are approximately 1/3 more males than females who undergo ACL reconstruction every year. This might indicate that a higher number of males should be included in research concerning ACL reconstruction in order to make the results better generalised. However, when calculating the frequency of ACL injuries/hours of training it appears that females sustain an ACL rupture more frequently than men (87). Study II and III were stratified for gender, meaning that the intention was to involve an equal amount of both gender. When studying the literature concerning the outcome after ACL reconstruction there are more males included in several of the studies, which generally might influence the possibility of comparing the reported results from Study II and III with other investigations.

In Study IV, the sample was planned to cover a relatively heterogeneous group. However, a limitation of that study was that only one female ACL reconstructed patient participated. The result may also have been influenced by the fact that the patients were recruited from only two rehabilitation clinics and in some cases the patients were interviewed a relatively long time after the injury. Further studies should address gender differences in patients' experiences of and responses to challenges in the rehabilitation process after ACL reconstruction, particularly as the literature on coping strategies has shown that gender differences could be anticipated (62).

Additional knee injuries

The results of study I were based on subjects with normal ACLs undergoing arthroscopic surgery for a partial meniscectomy, chondral debridement or plica excision under local anesthesia. Although the subjects presented with minor cartilage or meniscal problems, the overall function of their knee joints were assumed to be normal. Cadaver investigations have shown that knee kinematics are not altered in the ACL intact knee following medial or lateral meniscectomy (13, 73, 74). Thus, it seems reasonable to assume that a partial meniscectomy would have a negligible effect on knee kinematics, and hence, ACL strain behaviour.

In Study II and III, 39 % of the patients underwent ACL reconstruction within six months after injury and 70 % within one year after injury. In Study II additional injuries such as meniscus and cartilage injuries were presented as background data, but not included in the data analysis. The presence of these cartilage and meniscus injuries was recorded, although not the date of injury or its severity.

As seen in Study III meniscus injuries did not influence the results on the subscales Sport/Rec - KOOS, QOL – KOOS, Tegner Activity Scale and the one-leg hop test. The absence of cartilage damage of the knee joint showed a positive correlation with the results in the one-leg hop test. However, it cannot be seen as a strong predictor by explaining 6 % solely. This might indicate that the cartilage and meniscus injuries of the involved patients´ knees most probably were acute and therefore these results should not be generalized to patients with chronic injuries and higher prevalence of osteoarthritis. In addition, if most of the cartilage injuries were sustained at the time of the ACL rupture it is unlikely that the present cartilage injuries would have affected the results of the used methods at the 7 months follow-up in Study II. Previous long-time follow-up studies (105, 132) have shown that patients with ACL injured knees and accompanying meniscus injury develop radiologic signs of osteoarthrosis (105) at an average of 10 years after injury. Furthermore, the injury irrespective of treatment provided to these patients, often results in knee related symptoms that severely affect the knee related quality of life by middle age (132). Whether the same can be seen in patients who have underwent ACL reconstruction remains unknown. In a prospective study, however, Daniel et al. (31) reported that patients with ACL reconstructed knees had a higher level of arthrosis verified with x-ray and bone scan than the patients who where conservatively treated. Their study was not randomised, though. Their more 'aggressive' patients selected surgery while the more sedentary patients selected non-operative treatment.

Generalisability

The group of patients who fulfilled the inclusion criteria was asked to participate in Study II and III. Those that denied participation and their reasons for this are described in a flowchart (Figure 3). The amount of meniscus injuries and cartilage damage observed in the patients´ knees (Study II and III) is similar with the findings reported by Laxdal et al (70) in their multicenter study involving 948 patients with ACL reconstructions. Age, time between injury and surgery as well as level of physical activity/sport (Tegner Activity Scale) are also comparable with the data from their study (70). Based on the information mentioned above we suggest our results to be generalisable. However, selection bias is a matter frequently discussed among clinicians. Who are those patients that accept and those that deny participation in research studies? Hitherto to our knowledge these are questions that lack answers and no consensus exists so far.

Evaluation

Strain on the anterior cruciate ligament

The DVRT was used for precise strain measurements of the anteromedial bundle of the ACL. Application of multiple DVRTs could potentially provide a detailed mapping of the strain distribution across the different bundles of the ACL. Due to the size of the DVRT and the location of the ACL with respect to the posterior cruciate ligament and the osseous walls of the intercondylar notch, the technique is currently limited to the anteromedial bundle using one transducer. Furthermore, due to the position of the DVRT in the knee joint the patients under study are not allowed to fully extend their knees during testing. We recognize that the ACL has a strain distribution about its cross section area (27). However, the measurements presented here may be sufficient since surgeons generally attempt to reconstruct the function of the anteromedial band when performing an ACL reconstructive procedure.

This investigation was performed on patients with normal ACLs to gain insight into the strains produced on an ACL graft during exercise following reconstructive surgery. It is currently impossible to evaluate the strain in an ACL substitute, *in-vivo*, during dynamic activities that involve the leg musculature because the surgical reconstruction should not be performed under local anesthesia. It is possible that the local anaesthesia could influence the strain response because it eliminates sensory perception within the joint capsule. Local anaesthesia, however, has not been shown to alter knee joint proprioception (14, 73, 74). Furthermore, additional variables that are associated with the reconstructive procedure would also increase the variability of the strain response. Therefore, it is advantageous to perform these measurements on the normal ACL. It seems reasonable to extend these data to the knee with a properly positioned ACL graft, though. The elongation pattern of the BPTB graft during passive extension of the knee joint has been previously measured, *in-vivo*, and was found to be similar to the normal ACL (20). Thus, a loading condition that leads to a decrease in normal ACL strain should cause a similar decrease in a properly positioned ACL graft. Most likely, the strain patterns for other graft types would be similar. However, this has not been verified.

The variability inherent to the strain measurements is most likely related partly to the variation in exercise performance. The repeated normal test (i.e. the instrumented Lachman test) ensures that the variability due to the measurement technique is minimal. It is important to note that the subjects were instructed by a physiotherapist how to perform each exercise as they would in the clinic. The subjects were allowed several trials of each exercise before data was collected to eliminate any potential learning effects. However, the position of the torso relative to the knee was not formally controlled or documented. The location of the center of gravity relative to the knee joint has been shown to influence the net shear loads across the knee (93). It is possible that location of the center of gravity was different across patients and this may account for some of the variability. The variability might also have been smaller if the patients had met the physiotherapist before surgery for instructions and practice of the four investigated exercises.

Anterior knee laxity

The principle findings of Study II were that early start of OKC exercises of quadriceps in patients operated on patellar tendon graft did not differ from those with late start of OKC exercises in terms of anterior knee laxity, measured with the KT 1000. This is in agreement with Beynnon et al (22) and recently, Isberg et al. (59). However, the patients reconstructed with hamstring tendon graft and early start of OKC quadriceps exercises, had a significant increase in anterior knee laxity compared to late initiation of OKC quadriceps exercises and also to those reconstructed with patellar tendon graft. We used the KT-1000 arthrometer (134) for assessing anterior knee laxity. It has recently been reported that the KT-1000 arthrometer revealed a significant increase in laxity measurements of the right compared to the left knee. This difference was found both preoperatively and postoperatively in ACL injured patients (109). In Study II the statistical analysis of anterior knee laxity included testing for the effect of whether the ACL reconstruction was performed in the left or right knee. Even though reproducibility of the KT-1000 measurements of anterior knee laxity between two experienced examiners is considered fair (108) its value when judging the function of the knee is questionable. Isberg et al (60) have recently compared the KT-1000 with Radio Stereometric Analysis (RSA) and they concluded that the KT-1000 recorded significantly smaller side-to-side differences than did the RSA in ACL reconstructed patients. With this in mind the significant but relatively small side-to side difference of 1 mm measured with the KT-1000 may play a significant role for the patients, especially for those involved in specific sports, where high precision and knee stability is of utmst importance.

Postoperative laxity values were not measured directly after the surgical procedures. Thus information whether the surgical procedure itself may have influenced anterior knee laxity cannot be verified. In Study II, 20 orthopaedic surgeons were involved in the surgical procedures. The high number of surgeons may be considered as a weakness of the study. On the other hand, out of these 20 surgeons, two were more involved than the others by performing 50 % of the reconstructions in the hamstring tendon groups. Their patients were equally spread between the two groups with hamstring tendon reconstructions. The surgeons, performing the other 50 % of the reconstructions, were well experienced surgeons wherefore we still suggest, that the increased anterior knee laxity in the patients with hamstring tendon reconstructed knees, introduced to early OKC exercises for the quadriceps can be explained by the exercises performed. We find the high number of surgeons to be a strength rather than a weakness, since this most likely reflect the reality.

Thigh muscle torques

The early introduction of OKC exercises for quadriceps did not increase the quadriceps muscle torques for neither patients operated with patellar tendon graft nor with hamstring tendon graft. There were no significant differences in terms of quadriceps muscle torques within the two patellar tendon groups (early and late start of OKC) or within the two hamstring groups (early and late start of OKC). However, when comparing ACL reconstructions with different grafts, patellar tendon and hamstring tendon, the quadriceps of the hamstring tendon group was significantly stronger over time than that of the patellar tendon group. This seems reasonable since the patellar tendon is the tendon of the quadriceps muscle and therefore it is likely that this muscle is especially vulnerable after patellar tendon ACL reconstruction. In contrast, Mikkelsen et al. (84) showed that OKC exercises introduced 6 weeks after patellar tendon ACL reconstruction led to significantly greater improvement in quadriceps torque than CKC exercises alone. It should, however, be pointed out that the OKC quadriceps exercises in their study were carried out using an isokinetic device. In Study II our patients were training in an ordinary leg extension device with isotonic training, where the external torque increases with decreased knee flexion. With such training the resistance of the quadriceps muscle is lower in the knee angles where the muscle is stronger. This might result in less effective strength training compared with isokinetic training.

Anterior knee pain

It has been reported (9, 30) that patients, two years after patellar tendon ACL reconstructions, more often suffer from pain inhibition from the muscle-tendon complex than patients operated with hamstring tendon. Moreover, there are suggestions that patients operated with patellar tendon grafts suffer from more AKP than those with hamstring reconstructions (40, 64). The majority of these studies are retrospective, though. The few prospective studies have used the so called knee walking test as their criterion of AKP (35, 71). In Study II and III we used a validated AKP score answered under supervision of one test leader. This specific AKP score does not include the knee walking test, but pain during more functional movements. This might explain that we did not find any difference in AKP between patients operated with patellar tendon or hamstring tendon grafts in Study II.

In Study III, no or less AKP symptoms appeared to be the strongest predictive factor for the 12 months outcome after ACL reconstruction in KOOS. It explained 21 % of good outcome in the subscale Sport/Rec – KOOS and 14 % of good outcome in QOL – KOOS. These findings could be seen as rather high percentages taking in consideration that, for example, presence of meniscus injuries and knee extension deficits did not turn out to be significant predictors for these outcomes in the regression model used. Still only 37 %- 44 % of the results were explained by the measured variables. In the literature (10, 121), it has been suggested that psychological parameters should be taken into account when deciding which individual who would benefit from surgical reconstruction or not. A new instrument has recently (120) been developed to assess patients degree of self-efficacy, and Nyland et al (92), when studying health locus of control, conclude that patients perceiving preoperative pain and functional limitation to be excessive may have low tolerance for the stressors associated with surgery and postoperative rehabilitation. Unfortunately, in Study III we did not assess any psychological parameters, which is a limitation of this study.

Postural sway

Previous authors (15, 79, 136) have shown that proprioception is affected by injury to the ACL. Determination of the amount of postural sway has been suggested as a method for functional testing of balance ability and the neuromuscular control system. In Study II the KAT 2000 was used to measure postural sway (e.g "one-leg static balance test"). No learning effect or significant group differences at different follow-ups were found, which has been reported earlier in healthy subjects (54). This learning effect may not stand for injured patients, though. The functionality and the sensitivity of this instrument to investigate disturbances and changes following ACL reconstruction might be too low compared with other methods. However, when Study II started, the only instrument available was the KAT 2000. We have not found any publications dealing with reliability nor the validity of the KAT 2000 in injured patients.

Rehabilitation

Study II had a short-term design consisting of several occasions for evaluations of clinical outcome. The repeated test occasions were chosen to make it possible to provide information about similarities and/or differences in clinical outcome measures during a "normal" rehabilitation period after ACL reconstruction. Except for the addition of OKC exercises for quadriceps in this thesis, the prescribed rehabilitation protocol used in Study II and III is based on, 1) earlier research in terms of how much strain different exercises put on the ACL (19, 93), 2) the early 90s reported success with the use of CKC exercises in rehabilitation (112) and 3) empirical knowledge in the sports physiotherapy area. This protocol has been regarded as 'golden standard' in many sport rehabilitation clinics in the Stockholm area, Sweden and is based on the theory that CKC exercises do not stress the ACL in a harmful way, why exercises like mini squats, weight shifts and balance training in standing position are introduced in the very early phase of the rehabilitation. This is however, in contrast to what Beynnon et al (19) reported in 1995. They concluded that exercises that produce low or unstrained ligament values and thereby not endanger a properly implanted graft, involve quadriceps muscle activity with the knee flexed at ≥ 60°, or involve active knee motion between 35 - 90° of flexion. For both CKC and OKC exercises the strain on the ACL increases when the knee moves towards knee extension (19). Mini squats, for example, are usually performed within 0-10º to 30-40º of knee flexion, indicating that this exercise would for safety reasons, be contraindicated in the early phase after ACL reconstruction. However, although the strain magnitudes produced during CKC exercises are similar to an active knee extension exercise without external resistance (21), there is evidence to suggest that increasing the resistance to the lower leg during the active extension exercise (i.e. quadriceps sets performed on a weight bench) will increase the peak strain values (51). Increasing the resistance during CKC exercises does not produce this increase (51). These reports strengthen the conclusion in Study II, in terms of increased laxity after early introduction of OKC exercises for quadriceps in the hamstring tendon reconstructed knees. Furthermore, it seems like the mini squats and weight shifts introduced early, that is, CKC exercises close to terminal knee extension do not strain the ACL graft in a harmful way. These results are in contrast to the literature, where it has been reported that the choice of graft appears to result in similar short and long term clinical outcome (1, 2, 9, 16, 40, 44). However, the description of the rehabilitation protocols in these studies are sparse and therefore difficulties arise when comparing the results.

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To strengthen the design of this study the rehabilitation was performed at one outpatient sport clinic. Threats to internal validity, concerning diffusion or imitations of treatment could therefore arise. As seen in Appendix 2, there are indications that some or one patient did not comply with prescribed exercises (eg leg extension with and without external resistance) even though they were supervised of physiotherapists. Even so, we did not use the *Intention to treat* approach when analysing these data. However, these patients were in the hamstring graft group (H 12) with late start of OKC exercises for quadriceps and the difference in anterior knee laxity compared with the H4 group was already shown to be significant and it would therefore have increased the difference in anterior knee laxity between the H4 and the H12 group, but also the difference compared to the P4 and the P12 groups. Furthermore, this imitation of treatments might have had an impact on the average quadriceps muscle torques for the H12 group, but the difference was not even near significance level at none of the four test occasions (P=0.28-0.85) which indicates that this threat to internal validity probably do not have a clinical relevance in terms of regaining strength.

Compliance with rehabilitation after ACL rehabilitation has not extensively been described in the literature. If it is mentioned, it is usually in the form of frequency of weekly or all visits in total to the physiotherapist during the postoperative rehabilitation period (1, 2, 9, 30). This presentation of information does not provide the reader with sufficient knowledge concerning the external resistance, type and duration of exercises involved in the rehabilitation. However, in a recent study by Beynnon et al. (22), compliance was shown as the proportion of exercises completed to the number of exercises that were prescribed. In the literature regarding strength training on uninjured, healthy persons the duration of exercises and the amount of external weights in weight lifting is normally described as percentage of one Repetition Maximum (RM) or calculated in volume (e.g. the number of sets*repetitions*external weight) (47). However, one should not test 1 RM of the thigh muscles in the early phase of rehabilitation after ACL reconstruction since this might interfere with the surgical outcome. Therefore, recording the training volume during different exercises might be a better way of describing what each patient actually has been able to perform during the rehabilitation, which was what we did in study II. Unfortunately, it was more females then men who underwent reconstruction with hamstring tendon grafts so, in order to decrease the risk of differences in training volume due to gender we divided the training volume for each person with that individuals body weight.

Qualitative methodology

In this thesis several assessments and different approaches of both qualitative and quantitative structure in order to study and evaluate ACL rehabilitation were used. Qualitative and quantitative research should not be in opposition but instead be suitable for different purposes or problems. The traditional perspective in quantitative research is claimed to describe and/or explain how things are from a first-order perspective whereas in qualitative research the perspective can be seen as second-order. In contrast to experimental research, non-experimental research does not involve manipulation of variables. This design may be appropriate: 1) when little is known about the topic, 2) when outcomes are not easily quantified, 3) when ethical issues preclude experimental approaches, and 4) when the purpose of the research is something more than determination of treatment effectiveness. The aim of qualitative research is to provide categories for the description and explanation of, for example human phenomena. In qualitative analysis both description and interpretation is always used and the focus can be either on similarities or differences of a human phenomena (117).

The ‘semi structured interview´ is one way of structuring a qualitative research project and it is appropriate when information of somewhat abstract nature is sought. Semi structured interviews are based on pre constructed questions, and the format permits the interviewer to clarify questions to help the participant provide more information for the study (34). The result in qualitative research cannot be generalized like quantitative results, but can serve as a description of a problem in a specific context.

When evaluating psychosocial outcomes concerning injury, recovery, and rehabilitation, it is necessary to know what really matters for an individual or a group of individuals with a certain injury. In Study IV, the intention was not to study the relationship between physical and psychological outcomes, but to highlight the patients’ experiences, choices, and challenges during the rehabilitation process. In general, a qualitative approach does not attempt to generalise the findings to the whole population group. Nevertheless, it is likely that the different themes in Study IV, which emerged and were described, could be identified in other patients with ACL reconstruction. To facilitate transferability, clear characteristics of the participants and the rehabilitation protocol were provided in Study IV. To better integrate qualitative studies with quantitative studies may be a suitable perspective for the development of the sports rehabilitation in the future.

Statistical considerations

Power analysis

The power of the analysis of variance used to compare the peak strain values between exercises was relatively low (approximately 30 %), if we assume a minimal detectable difference of 1 % strain and alpha equals 0.05 (Study I). The power could be increased to 80

% if we were to triple our sample size. The mean peak strains that were recorded for these exercises were less than those measured previously for the simple squat and the passive Lachman test (18, 21). Furthermore, the sample size was similar to those of our previous studies of ACL rehabilitation where significant differences were found. Considering the invasiveness of the experiment, the clinical relevance of the small differences observed between the exercises evaluated in this study is at least questionable. However, the low power of the analysis may be considered as a limitation.

In Study II several parameters were evaluated. The primary outcomes were anterior knee laxity and muscle torque. A power analysis using muscle torque as the primary variable showed a need for 19 patients in each group. When using anterior knee laxity as the primary variable a number of 15 patients were needed. For the studied parameters postural sway, knee extension and knee flexion deficits and AKP respectively, we did not reach statistical significance, where one reason might indicate a low power.

Study IV was conducted with a small sample of 10 patients, which allowed focusing on detailed descriptions and their meanings. However, caution in interpreting the findings is essential as the study is exploratory and is not necessarily generalisable. An important question in qualitative research concerns the determination of an adequate sample size in connection with data saturation. The decisive criterion was the point where variation ceases. The inclusion of participants continued until the authors considered that they had “heard the story before”, and the emerging themes could be described in a meaningful way.

Regression analysis

In order to investigate independent associations with good outcome, as defined in Study III, a standard linear multiple regression analysis was applied using a forward step-wise approach. Variables which had a correlation at a p value < 0.10 with the dependent variables in simple bivariate analysis were further included in the multiple regression analysis to reveal such independency. Important predictors were checked for co-linearity before entering into the regression model since strong inter-correlation may eliminate true effects from such variables. No strong linearity was found in the present data. While the present analysis approach was considered to be a strength of this study, the statistical power may be considered rather low. However, forward and backward elimination procedure gave largely the same results, indicating stability in the present analysing models.

Conclusions

- Study I shows that the step-up, step-down, lunge and one-legged sit to stand exercises did not produce greater strain on the ACL than the traditional two-legged squat exercise. Furthermore, the step-up, step-down and the one-legged sit to stand exercises are performed standing on one leg, which indicate that higher external resistance is present during these movements when compared with a normal squat. These findings may point out the possibility of performing these exercises at the same time as the two-legged squat exercise without significantly increasing the strain response of the ACL.

- Study II introduces new findings in rehabilitation after ACL reconstruction by showing that early start of OKC quadriceps exercises results in greater anterior knee laxity than late start in patients with hamstring ACL reconstructed knees as well as in those patients with patellar tendon ACL reconstructed knees. The early introduction of OKC quadriceps exercises did not influence quadriceps muscle torques in any of the patient groups. Furthermore, no differences in terms of postural sway and anterior knee pain were found between the groups.

- In Study III we found that the evaluated subjective and objective preoperative variables only partly could predict clinical outcomes after ACL reconstruction. Absence of or minor anterior knee pain before surgery was the strongest predictor for Sport/Rec – KOOS and QOL – KOOS 12 months after ACL reconstruction. Patellar tendon graft in favor of hamstring tendon graft and a short time (< 6 months) between injury and ACL surgery partly explained a higher level of activity. Preoperative cartilage damage was positively correlated with the one-leg hop test performance.

- In Study IV all patients experienced that they had no real choice between surgery and non-operative treatment. The surgery seemed to symbolise not only a full return to pre-injury level of sports but also to become a completely restored functional human being. The patients stated that preoperative information in terms of the meaning and extent of rehabilitation would have been helpful as well as guidance in realistic goal setting and coaching throughout the entire rehabilitation process. Some patients re-evaluate their goals during the rehabilitation period, including the thought of not returning to pre-injury level of sports.

Clinical relevance

- The step-up, step-down and one-leg sit to stand exercises can be used at the same time as the traditional two-legged squat during the rehabilitation after ACL reconstruction. This suggests that the clinician could treat the patient with more challenging resistance in terms of muscle strength training relatively early in the rehabilitation process. It should be pointed out, however, that it is still not known whether the amount of strain produced during a two-legged squat is detrimental to the ingrowing graft. (Study I)

- We suggest that the rehabilitation for patients with hamstring ACL reconstructed knees should not include early start of OKC exercises for quadriceps. Our results can, however, not determine the appropriate time when OKC quadriceps exercises should be started. The patients with hamstring reconstructed knees who started with OKC quadriceps exercises at the 12th postoperative week showed similar anterior knee laxity as those patients reconstructed with patellar tendon graft. Early OKC quadriceps training was not superior to late in terms of regaining quadriceps muscle strength. (Study II)

- Minor or absence of AKP preoperatively can partly predict future outcome after ACL reconstruction evaluated with Sport/Rec – KOOS and QOL – KOOS. We suggest that further parameters, for instance methods revealing personality characteristics are to be included in future studies. (Study III)

- From a patient perspective, there seems to be a need for extended information about operative or non-operative treatment in terms of the meaning and extent of rehabilitation, and the expected outcomes. There is also a need for improved guidance and goal-setting throughout the entire process. Health professionals should keep in mind that patients could re-evaluate their goals during the rehabilitation period, for instance not returning to their pre-injury level of sport. Whether this is due to fear of re-injury or other factors should be addressed explicitly. (Study IV)

Future studies

- It is not clear which ACL injured patient may benefit the most from surgical treatment. Therefore, future studies on large samples using analyses that have potential to control for independency between variables, may be conducted. Such studies may include multidimensional instruments for both subjective and objective evaluation (Figure 9).

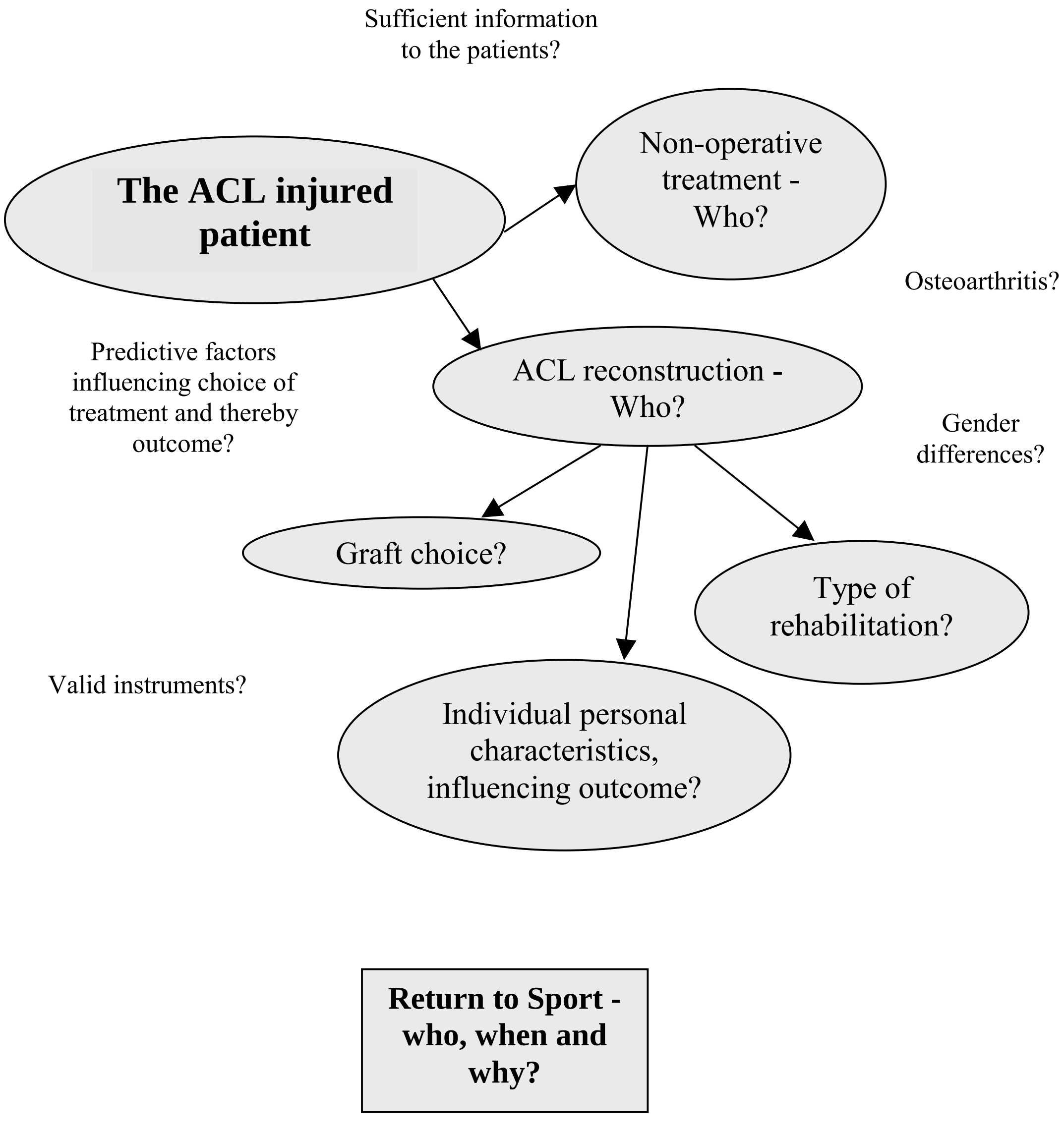

Figure 9. Future studies

- Males and females differ in a number of aspects. However, it is still not known whether males and females should be treated differently, above all with respect to type of graft and rehabilitation.

- There is very little documentation in terms of what psychological reaction strategies and challenges that occur during the postoperative rehabilitation after sport injuries. How to identify patients with extra need for support as early as possible should be paid more attention to as well as how to best support these individuals. Whether different personality characteristics influence rehabilitation and a successful outcome remain unknown.

- There is still a lack of long-term follow-ups concerning patients´ satisfaction and functional performance after ACL reconstruction with different grafts, in particular the hamstring tendon graft.

- There is a need for more randomised controlled trials in terms of osteoarthritis and whether there is a difference between the non-operative ACL injured patient and the patient that have undergone ACL reconstruction.

- There is a lack of valid instruments for measuring functional performance after ACL reconstruction. Should the measurements be individualized and tailored for age, gender and sport, for instance?

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Appendices

Appendix 1. Goal oriented rehabilitation protocol after ACL reconstruction with BPTB or hamstring grafts.

Time	Exercises
Day of surgery	pain control
Day 1	instructions from the inpatient clinic physiotherapist: ankle pumps passive terminal knee extension, no hyperextension active assisted knee flexion exercises instructions for home training
Day 2-2 weeks	patella mobilization passive terminal knee extension gait training in correct/normal pattern active knee flexion/hamstrings curl, 3x10 reps balance and proprioceptive exercises mini-squats, 3x10 reps calf raises hip extensions with legs on a Bobath ball
2-5 weeks, add	stationary bicycling when 110° knee joint flexion is reached calf raises on a step, 3x10-15 reps leg press in a device, 3x10 reps leg curl in a device, 3x10 reps
for the P4 and H4 group, add 3x15 reps:	- week 4 active knee joint extension 90°-40° - week 5 active knee joint extension 90°-20° - week 6 active knee joint extension 90°- 0° - week 7 active knee joint extension with gradually increased external resistance
6-8 weeks, add	active short arc, terminal knee joint extension, no external weight (30-0 º) step ups and step downs, 3x10 reps one leg calf raises, 3x10 reps lunges with weights, 3x10 reps one leg raising from chair, 3x10 reps squats in a device, 3x10 reps two leg trampoline exercises slide board stair master gait training different steps overall stretching
9-11 weeks, add	different movements on a trampoline functional training; different jumps on the floor running on even surface, straight line one-leg trampoline exercises
3-4 month, add	open kinetic chain quadriceps exercises, full range of motion (P12 and H12), 3x10-15 reps continued balance drills initiated plyometric training sport specific exercises and activities individually adjusted to each patient's capability
4-6 months, add	gradually increased running program and cutting acceleration-deceleration sport specific training

Appendix 2. Training volume (e.g. set*repetitions*weight) divided with body weight (index) for each of the four rehabilitation groups during the 4th and 12th postoperative week.

Type of exercises	P4		P12		H4		H12	
	median	lower and upper quartile	median	lower and upper quartile	median	lower and upper quartile	median	lower and upper quartile
Leg curl both legs	68.2	39.5 – 97.5	77.3	49.5 – 116.4	64.3	54.4 – 102.1	36.7	20.3 – 83.9
Leg curl operated leg	13.6	0 – 38.5	11.15	0 – 31.6	1.6	0 – 10.9	0	0.0 – 22.4
Leg extension 90-40º	0	0 – 0.0	x	0 - 0	0	0 – 0.7	x	0 - 0
Leg extension 90-20º	0.5	0 – 1.3	x	0 - 0	1.3	0.7 – 1.5	x	0 - 0
Leg extension 90-0º	0.9	0 – 1.3	x	0 - 0	1.2	0.6 – 2.1	x	0 – 1.1
Leg extension with external resistance	10.3	6.5 – 17.5	0.7	0 – 9.5	7.9	2.7 - 19	1.45	0 – 12.2
Calf raises both legs	4,7	4.1 – 7.6	4.1	3.3 – 6.1	3.9	2.5 – 5.5	3.7	2.5 – 4.7
Calf raises operated leg	0	0 – 2.3	1.1	0 – 3.9	0.6	0.0 – 2.8	0.6	0 – 2.6
Step up/down/one leg raising from chair	3.1	0.0 – 4.9	2.6	0.9 – 5.7	2.1	0.6 – 3.5	1.9	0 – 3.9
Squats	16.8	7.9 – 36.6	20.9	12.8 – 58.2	17.6	5.6 –23.3	13.2	4.6 - 21
Lunges	0.9	0 –2.8	0.4	0.0 – 2.8	0.3	0 - 1	2.4	1.3 – 4.6
Seated legpress both legs	124.1	83.5 – 185.3	117.2	36.3 – 208.2	57.9	0 – 120.4	33.8	0 – 176.6
Seated legpress operated leg	0	0 – 32.5	0	0.0 - 51	0	0 – 13.8	0	0 – 4.5
Balance training on non even surface (min)	59	33.5 - 77	59.5	29 - 108	45	25 - 64	36.5	23.5 - 78
Jogg and jump (min)	0	0 - 10	0	0 - 0	0	0 - 9	0	0 – 0.4
Stairmaster	6	0 - 30	15	3 - 40	2	0 - 20	12.5	0 - 43
Active short arc extension (30º-0º (min)	150	0 - 330	224,5	110 - 435	180	120 - 390	180	120 - 240
Number rehab sessions 0-3 months postop	19	16.5-23,5	22	19-23	18.5	15-24	17	16-21

Appendix 3. Anterior knee pain score

Functional knee score for
Anterior Knee Pain after ACL reconstruction

Please, circle what usually applies to your knee problem(s)!

Pain

None	5
Slight & infrequent	3
Constant pain	0

Occurrence of pain

No activity related pain	15
During or after running	12
After > 2 km walk	9
After < 2 km walk	6
During normal walk	3
During rest	0

Walking upstairs

No problems	5
Slightly impaired	4
Difficulties	2
Unable	0

Walking downstairs

No problems	5
Slightly impaired	4
Difficulties	2
Unable	0

Sitting with flexed knees > 30 min

No problems	5
Slightly impaired	4
Difficulties	2
Unable	0

Squatting

No problems	5
Slightly impaired	4
Difficulties	2
Unable	0

Kneeling

No problems	5
Slight pain	4
Moderate pain	2
Unable	0

Arretations - Catching

Never	5
Sometimes	3
Frequently	0

Sum of points: ____________

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