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Knee function, movement pattern and knee osteoarthritis in males 14-16 years after an anterior cruciate ligament injury

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av

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Title and subtitle

Knee function, movement pattern and knee osteoarthritis in males 14-16 years after an ACL injury

Abstract

The overall aim of this work was to study knee function movement pattern and knee osteoarthritis in males 14-16 years after anterior cruciate ligament (ACL) injury.

In the first study self-reported knee function and radiographic signs of osteoarthritis were assessed. Most of the subjects (122/154) underwent knee radiographs, 78% of which showed radiographic changes. The prevalence of tibio-femoral knee osteoarthritis was 41%. The self-reported knee function was worse than in healthy subjects.

In Study II, the kinematics and kinetics of three functional tests: gait, step activity and cross-over hop, of 12 ACL-injured subjects and 12 matched reference were compared. The self-reported knee functions of the two groups were also compared. No detectable differences were found in the kinematics and kinetics of the ACL-injured subjects and their matched reference. The self-reported knee function among ACL-injured subjects was, however, worse than that among non-injured subjects.

In the third study, an intervention programme consisting of knee-specific exercises, once a week for twelve weeks, was applied to the subjects with an ACL injury. After twelve weeks of training, both under supervision and at home, motion analysis of the injured subjects showed results closer to those of the healthy controls, and self-reported knee function had improved.

The fourth study was carried out to determine the reliability and validity of five functional performance tests. Four physiotherapists assessed the knee function of the subjects with an ACL injury before and after the training period using video sequences. The reliability between the physiotherapists was relatively good and the validity of the functional performance tests when compared with the motion analysis data was acceptable.

Based on the results presented in this thesis, it can be concluded that the prevalence of tibio-femoral knee osteoarthritis, 14 years after an ACL injury, is high, and that self-reported knee function is affected, despite the long time since injury. No differences in motion analysis results could be seen between injured subjects and references; however a type II error could not be ruled out. Knee-specific training decreased knee stiffness and improved self-reported knee function. The moderate to good reliability and the acceptable validity found indicate that the presence of knee stiffness in subjects with an ACL injury can be determined by visual observation of more demanding functional tests.

Key words: ACL injury, males, moment analysis, functional performance, neuromuscular training, reliability, validity

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Knee function, movement pattern and knee osteoarthritis in males 14–16 years after an anterior cruciate ligament injury

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Thesis 2007

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To Didrik
and our daughters
Maria and Camilla

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I. von Porat A, Roos E M, Roos H.
High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: A study of radiographic and patient-relevant outcomes.
Annals of the Rheumatic Diseases 2004; 63 (3): 269-73.

II. von Porat A, Henriksson M, Holmström E, Thorstensson C, Mattsson L, Roos E M.
Knee kinematics and kinetics during gait, step, and hop in males with a 16-year-old ACL injury compared with matched controls.
Knee Surgery, Sports Traumatology, Arthroscopy 2006; 14 (6): 546-54.

III. von Porat A, Henriksson M, Holmström E, Roos E M.
Knee kinematics and kinetics in former soccer players with a 16-year-old ACL injury – The effects of twelve weeks of knee-specific training.
BMC Musculoskeletal Disorders 2007; 8: 35.

IV. von Porat A, Holmström E, Roos E M.
Reliability and validity of videotaped functional performance tests in ACL-injured subjects.
Submitted.

This thesis at a glance

Paper	Question	Answer	Outcomes
I	Are knee joint structures and knee function affected 14 years after an ACL injury?	Yes, 41% of patients have radiographic osteoarthritis and 63% are symptomatic 14 years after an ACL injury.	Knee radiographs, KOOS, SF-36, Lysholm knee scoring scale.
II	Do knee kinematics and kinetics differ between ACL-injured subjects and matched references?	There were no significant differences in kinematics and kinetics, however, a type II error could not be ruled out.	Three-dimensional motion analysis, KOOS, Tegner activity scale.
III	Can neuromuscular training influence knee kinematics and kinetics?	Yes, neuromuscular training can influence knee kinematics and kinetics positively.	Three-dimensional motion analysis, KOOS.
IV	How good are the inter-observer reliability and the validity of five functional tests?	The inter-observer reliability between physiotherapists and the validity of the functional tests were acceptable.	Videotaped functional tests, 3-dimensional motion analysis.

Description of contributions

Paper I

Study design:	Anette von Porat Harald Roos
Data collection:	Anette von Porat Harald Roos
Data analysis:	Anette von Porat
Manuscript writing:	Anette von Porat
Manuscript revision:	Ewa Roos Harald Roos

Paper II

Study design:	Anette von Porat Ewa Roos Marketta Henriksson
Data collection:	Anette von Porat Louise Mattsson
Data analysis:	Anette von Porat
Manuscript writing:	Anette von Porat
Manuscript revision:	Ewa Roos Marketta Henriksson Eva Holmström Carina Thorstensson Louise Mattsson

Paper III

Study design:	Anette von Porat Ewa Roos Marketta Henriksson
Data collection:	Anette von Porat Louise Mattsson
Data analysis:	Anette von Porat
Manuscript writing:	Anette von Porat
Manuscript revision:	Ewa Roos Marketta Henriksson Eva Holmström

Paper IV

Study design:	Anette von Porat Ewa Roos Eva Holmström
Data collection:	Anette von Porat
Data analysis:	Anette von Porat Jan-Åke Nilsson
Manuscript writing:	Anette von Porat
Manuscript revision:	Ewa Roos Eva Holmström

Definitions and abbreviations

ACL Anterior Cruciate Ligament

ADL Activity in Daily Living

Copers Subjects who were able to return to pre-injury activities without knee instability or the need for surgery on the ACL [130].

Functional performance
Tasks that resemble conditions in daily life and/or more strenuous activities; in this thesis, gait, climbing stairs, knee-bending and various hop tests.

Gait cycle The equivalent of one stride, consisting of a stance and a swing phase [108].

ICC The Intra-class Correlation Coefficient

ICF The International Classification of Functioning, disability and health

IKDC The International Knee Documentation Committee

Isokinetic muscle strength
Refers to a muscle strength performed at a constant angular velocity [27].

Kinematics
The science of a system of movements without considering influencing forces [161].

Kinetics The science of a system of movements, taking influencing forces into consideration [161].

Knee function
In this thesis, *knee function* is either self-reported or observed.

KOOS Knee injury and Osteoarthritis Outcome Score [123, 124]

Moment Turning effect of a force about a point; the product of the force and the perpendicular distance from its line of action to that point [161]. *Internal moments* were calculated and interpreted as muscles and ligaments counteracting the external moments produced by the ground reaction force [46].

Movement pattern
Characteristic dynamic organisation of the body or a body part [15].

Neuromuscular control
The ability to produce controlled movement through coordinated muscle activity [159].

Non-copers
Subjects who report instability during activities of daily living and are thus scheduled for reconstructive surgery of the ACL [130].

OA Osteoarthritis

Power The product of joint net moment and joint angular velocity [46].

Power absorption
The ability of the muscles to perform work (negative power) during the eccentric phase of a movement [161]. Power absorption of the quadriceps muscle, for example, occurs when walking down stairs.

Power generation
The ability of the muscle to perform work (positive power) during the concentric phase of a movement [161]. Power generation of the quadriceps muscle, for example, occurs when walking up stairs.

Proprioception
The acquisition of stimuli by peripheral mechanoreceptors, and the conversion of these mechanical stimuli into neural signals that are transmitted along afferent pathways to the central nervous system for processing [73].

Reliability
Reliability is a measure of the reproducibility of a test [140]. The *inter-observer reliability* was assessed as a measure of the variation between several observers.

Self-reported knee function
In this thesis, the subject's self-assessed knee function, according to the KOOS questionnaire and the Lysholm knee scoring scale.

Symptomatic according to KOOS
In this thesis, a definition of a symptomatic knee created from the patient's self-report of the KOOS questionnaire was used. The definition required that the score for the KOOS subscale QoL and two of the four additional subscales should be equal to or less than the score obtained as follows: at least 50% of the questions within the subscale were answered at least one level below the best response [33].

Type II error
When the statistical conclusion is that there is no difference between the groups when in reality there is a difference [30].

Validity Validity determines that the test is measuring what was intended [140]. *Criterion-related validity* is the extent to which one measure is systematically related to other measures or outcomes [30].

VGRF Vertical Ground Reaction Force: the force recorded by a force plate generated by falling body weight or muscle action as the person walks across the force plate [108].

QoL Knee-related quality of life, one of the subscales in the KOOS questionnaire [123, 124].

Quadriceps index
Calculated as [(injured side peak torque/non-injured side peak torque) x 100]. In this thesis, a quadriceps index of 90% was required for the affected leg to be categorised as having good knee extensor strength.

Introduction

Sports injuries

Participation in sports is a popular form of recreation. Sports activities afford the participants personal satisfaction, relaxation and competition, as well as improved fitness and health. However, sports activities expose the individual to the risk of certain injuries. The overall injury incidence increases as the number of participants grows [68, 71, 78, 137], and the number of injuries increases with age, up to the age of 20–24, before levelling out [71, 78, 137]. In Sweden, the annual incidence of injuries during sports activities is about 34 per 10,000 inhabitants aged up to 17 years, 39 per 10,000 among boys and 29 per 10,000 among girls. Thirty per cent of the injuries among the boys and 26% of the injuries among the girls had occurred while playing or practising soccer [137].

The majority of all injuries incurred in soccer affect the leg, with knee injuries being one of the most common [34, 49, 52, 53, 65, 147]. The overall injury incidence in connection with soccer is 3–7 injuries per one thousand training hours and 14–30 injuries per one thousand match hours [7, 32, 104]. A previous injury is an important risk factor for soccer injuries [49].

ACL injuries

Anterior cruciate ligament (ACL) injuries continue to be a source of major concern for the injured subjects, clinicians and researchers, due to their high incidence and the long and expensive rehabilitation required [40]. In Sweden, the annual incidence of ACL injuries is about 8 per 10,000 inhabitants aged between 10 and 64 years [45] and the risk of a new knee injury is increased on return to elite soccer after an ACL injury [150]. Rehabilitation is often followed by a relatively high frequency of symptoms and detrimental effects on the sporting and social life of the injured subject (for example, reduced contact with work, school and other team members, and restriction of social activities), as well as socio-economic consequences [34, 71, 127]. Approximately 40% of all knee injuries sustained while playing soccer are ACL injuries [125].

Ligaments are composed of closely packed collagen fibre bundles oriented in a parallel fashion to provide stability of the joints in the musculoskeletal system [162]. The ACL ligament is made up of type I collagen. It has greater elasticity than a tendon, and receives its blood supply from the insertion sites. The ACL ligament contains mechanoreceptors and free nerve endings that are thought to aid in stabilising the knee joint [138]. It originates from the tibia plateau, just medial and anterior to the tibia eminence. The ACL runs from the tibia superiorly, laterally and posteriorly to its insertion on the posterior aspect of the medial wall of the lateral femur condyle (Fig. 1). The ACL consists of two bundles, an anteromedial and a posterolateral bundle. The anteromedial bundle is thought to be important as a restraint to anterior-posterior translation of the knee, while the posterolateral bundle is thought to be an important restraint to rotational moments about the knee [163].

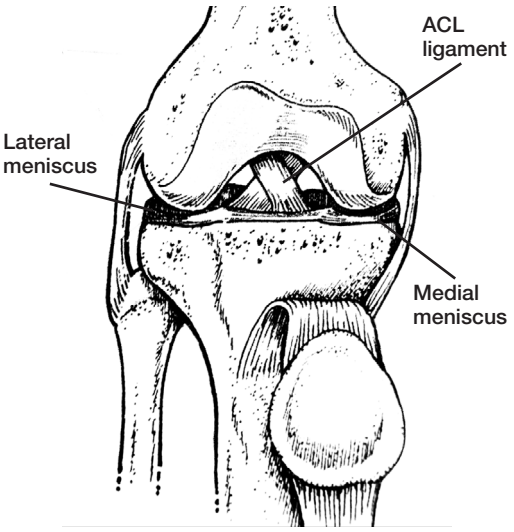

Figure 1. Anterior view of the knee, showing the anterior cruciate ligament, the medial and lateral meniscii. From [67], with permission.

The central nervous system receives proprioception information from the specialised nerve endings or mechanoreceptors in the ACL. Proprioception has been defined as an awareness of joint position in a space, as perceived by the central nervous system [73]. It encompasses the sensation of joint motion and spatial orientation [115, 116]. One of the most troublesome symptoms after an ACL injury is the sudden loss of control of the knee joint in a weight-bearing position, referred to as functional instability. Other effects commonly seen after an ACL injury include defective neuromuscular function with reduced strength and impaired functional performance, differences in movement and muscle activation patterns, proprioceptive deficiency, and impaired postural control [1, 13, 39, 44, 102, 106, 114].

Treatment after an ACL injury

For many years, ACL injuries have been treated by physical training in combination with surgery [55, 74, 79, 91] or by physiotherapy alone [20, 26, 41]. During the past two decades, rehabilitation programmes have gradually become more advanced. In the 1980s, ACL surgery was followed by immobilisation for 6-8 weeks, but today ACL surgery is followed by weight bearing to tolerance and early full-range of motion. The development of training programmes is based on theoretical models and clinical experience. The treatment usually emphasizes joint mobility, increased strength, functional activity, and neuromuscular control [85, 86, 98, 157, 165].

Knowledge concerning proprioceptive dysfunction after ACL injuries [13, 39, 44, 102, 106, 114], and studies showing that rehabilitation programmes including neuromuscular training have a greater effect on knee function and knee stability [9, 41, 165], have increased the use of neuromuscular training in rehabilitation. Successful treatment has been defined as the injured leg demonstrating a muscle strength and functional performance that is 85–90% of the uninjured leg [8, 120, 158]. The success of rehabilitation is assessed by functional tests, muscle strength tests and patient-relevant questionnaires. This thesis describes investigations of the effect on knee function, defined either as self-reported or observed, including neuromuscular control, of a knee-specific training programme.

Consequences of an ACL injury on knee function

The International Classification of Functioning, disability and health (ICF) is the first international classification of functioning, disability and health approved by the World Health Organization. It describes health and health-related states from the perspective of the body, the individual and society in terms of “Body Functions and Structures”, and “Activities and Participation”. The ICF uses the term “Functioning” as an umbrella term for the positive aspects of body function, activities and participation, whereas the previously used term “Disability” serves as a term for the negative aspects, such as impairment, activity limitation, or restrictions on participation (ICF 2001) (http://www.who.int). An ACL injury may result in consequences in the different ICF components. Functional instability, altered movement pattern and knee osteoarthritis (OA) are related to body structure and function, while functional performance tests are related to activities, and risk of reduced contact with work, school and team colleagues and limitation of social activities are related to participation. The self-reported knee function is related to all three aspects; body function and structures, activities and participation. The different outcomes described in this thesis relate to all the ICF components (Fig. 2).

Self-reported knee function

Measures suitable for self-reported outcome have become increasingly common in rehabilitation after knee injury. The use of self-reported outcome measures emphasizes the pivotal role of patients in the ongoing assessment and management of their condition [10]. Flanagan et al. recommend at least two subsequent validated functional outcome measurements, one disease-specific and one generic, to assist in measuring the progress of a patient in the long term. The process has three possible scenarios: patient improvement, patient dete-

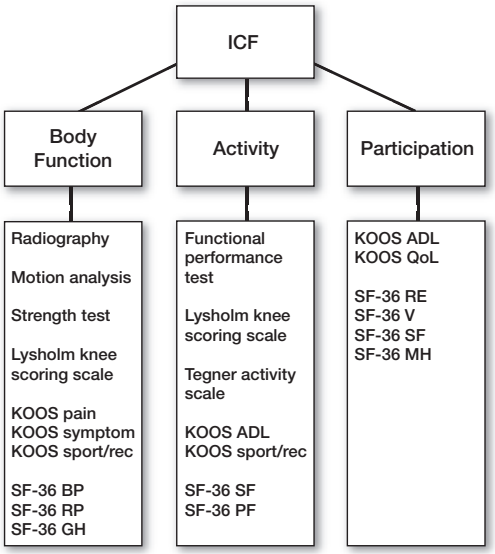

Figure 2. Distribution of methods used in this thesis into components according to the International Classification of Functioning, Disability and Health [113, 141]. Sport/rec = Sport and recreation function, BP = Bodily Pain, RP = Role-Physical, GH = General Health, ADL = Activities of Daily Living, SF = Social Functioning, PF = Physical Function, QoL = Knee-related Quality of Life, RE = Role-Emotional, VT = Vitality, MH = Mental Health.

rioration and patient stabilisation [42]. Measures widely used to assess the outcome of the treatment of knee ligament injuries include the Lysholm knee scoring scale [83, 143], the International Knee Documentation Committee (IKDC) system [54], the Cincinnati Knee Rating System [99, 100] and the Knee injury and Osteoarthritis Outcome Score (KOOS) [123, 124]. These measures include knee function, activity, functional limitations, symptoms and pain. The Lysholm knee scoring scale, the IKDC and the Cincinnati Knee Rating System are all observer-administered, while the KOOS is self-reported. Studies have shown that observer ratings report better results than the patient's own outcome ratings, [60, 77, 122], indicating that self-reported questionnaires are preferable to minimize bias in the assessment of patient-relevant aspects. In this thesis, knee function is studied by means of self-reported or as observed functional performance tests.

Observed knee function

Knee kinematics and kinetics

Increased or altered joint loads are a prerequisite for the development of OA [110]. An altered movement pattern often seen in ACL-injured subjects consists of less knee flexion during landing after, for example, a hop or stair climbing. Furthermore, the changes in movement pattern may consist of decreased internal knee extensor moment, often in combination with increased internal hip extensor moment in an attempt to avoid excess loading of the knee joint [12, 19, 23, 37, 63, 70, 76, 130]. Decreasing knee flexion angle and internal knee extensor moment define increasing knee stiffness [23, 76, 112, 129, 130]. Knee stiffness may lead to excessive joint contact force [130], as determined by an increase in vertical ground reaction force (VGRF) which, in turn, may lead to the development of knee OA. Changes in gait pattern may occur as a consequence of weakness of the quadriceps femoris muscle, knee joint swelling and joint tissue disorder, or muscle inhibition due to pain [35]. Another factor shown to influence the gait pattern is whether the ACL-deficient subject is classified as a non-coper (subjects who report instability during everyday activities and are thus scheduled for reconstructive surgery) [130]. On the other hand, some investigators report that ACL-injured subjects have almost normal gait [6, 19], indicating the need for more studies in this area.

Functional performance

The goal of rehabilitation is to restore knee function for everyday life and sports activities. Dynamic tests are increasingly being used for the evaluation of rehabilitation results [16, 41, 98, 117, 129, 166]. Commonly used functional performance tests are the one-leg hop for distance, vertical jump, triple-jump test, cross-over hop, running in a figure of eight and various balance tests [98, 144]. These are simple motor tests which quantitatively measure (e.g. time, height, and distance) the performance of the injured leg compared with the uninjured leg. Functional performance can also be assessed qualitatively. Examples of qualitative assessments are absence of knee flexion or excessive flexion during initial contact in gait [18, 31], and whether the push-off during gait is present, abnormal or

normal [89]. Other qualitative assessments may be related to the performance of various functional tests, such as running asymmetrically or limping, landing with knee stiffness in the one-leg hop test and less knee flexion of the injured knee when climbing stairs [14, 101].

Three-dimensional motion analysis has been used for quantitative assessments in this thesis. Qualitative assessment of knee function has also been studied, by means of videotaped functional performance tests.

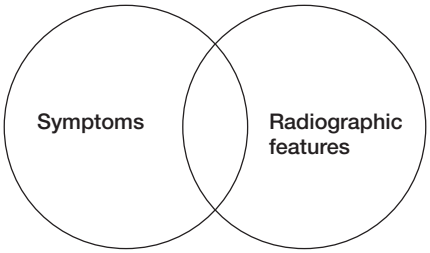

Figure 3. Osteoarthritis is associated with pain or radiographic changes or both.

Reliability and validity of knee function measures

Reliability is a fundamental way of reflecting the amount of error, random or systematic, inherent in any measurement [140]. Other terms similar to reliability are *accuracy, stability* and *consistency.* A measurement is said to be *reliable* if the error component is small, thus allowing consistent estimation of the true quantity of interest [30]. Reliability consists of various components: instrument reliability, intra-rater reliability, inter-rater reliability, and intra-subject reliability. Demonstrating the reliability of an instrument is the first step in providing evidence of the value of the instrument and demonstrating that measurements of individuals on different occasions, or by different observers, or by similar or parallel tests, produce the same or similar results [140]. In this thesis the inter-observer reliability between four physiotherapists in assessing knee function from videotaped functional performance tests was investigated.

Good reliability shows that a test measures something in a reproducible fashion, but says nothing about *what* is being measured. In order to ensure that the tool is measuring what it is intended to measure, more than peer judgment is required, empirical evidence must be produced. To this end, different types of validity are assessed, namely content validity, criterion validity and construct validity. *Content validity* is the extent to which a measure provides a complete representation of the concept of interest. *Criterion validity* is the extent to which one measure is systematically related to other measures or outcomes; it compares administrations of different measures. The correlation coefficient is often used to determine criterion validity. *Construct validity* is a measure of the extent to which questions are relevant to the respondents [30, 140]. In this thesis the criterion validity of functional performance tests was determined.

Knee osteoarthritis

Almost 50% of subjects with an ACL injury are affected by knee OA ten to fifteen years after injury [38, 47, 80, 82, 131, 136], regardless of whether they have been treated surgically or not. A combined ACL and meniscus injury leads to an even higher prevalence of OA [3, 38, 80, 90, 97, 131, 135].

An ACL injury in younger life can lead to OA within 15 years. However, a subject experiencing a knee injury after the age of thirty may exhibit OA after only five years [125]. As knee injuries are more common in younger age groups, it can be estimated that over approximately 3.5% of the population between 35 and 54 years of age have OA due to a knee injury [50, 56, 149, 160].

Osteoarthritis develops slowly. The time from the early changes, i.e. the first indication of cell and molecular changes, to the final stage, with symptoms of clinical OA and typical changes visible on radiographs, may be decades. The condition often exhibits fluctuating progress, with periods of improvement, and the correlation between typical OA symptoms and typical changes on radiographs is low (Fig. 3) [81].

Aims of the study

The general aim of the work described in this thesis was to study knee function, movement pattern and knee osteoarthritis in males 14–16 years after an ACL injury.

The specific aims were:

- to assess the consequences of an ACL injury with regard to tibio-femoral knee OA and patient-relevant outcomes such as pain, function, quality of life and activity level (Study I),
- to compare ACL-injured subjects with a reference group with regard to knee kinematics and the kinetics of gait, step activity, and cross-over hop, and self-reported knee function (Study II),
- to determine whether knee stiffness, defined by knee kinematics and the kinetics of gait, step activity and cross-over hop, could be reduced through a knee-specific 12-week training programme (Study III),
- to investigate the inter-observer reliability and the criterion-related validity of visual observation of knee stiffness determined from videotaped functional performance tests of ACL-injured subjects (Study IV).

Subjects and methods

Design of the studies

This thesis includes four studies. Knee function is the subject of all four studies. Studies I and II have a descriptive design and represent radiographic and biomechanical approaches. Study III describes a clinical trial and presents the effects of an intervention programme. Finally, Study IV is a methodological study, investigating the reliability and validity of observational assessments of videotaped functional performance tests.

Subjects

The ACL-injured subjects included in the four studies were selected in 1989 [127] (Fig. 4). In Sweden, all soccer players participating in league soccer have compulsory insurance through the same company (Folksam). A search in the Folksam database in 1989 identified a total of 937 knee injuries that had occurred while playing or practising soccer in 1986. Personal questionnaires and a search of hospital records revealed that 344 of the 937 injuries were ACL injuries. Sixty-nine per cent (238) of the ACL-injured subjects were male and 31% (106) were female [127] (Fig. 5).

Study I: The aim of this study was to identify the consequences of an ACL tear in a cohort of male soccer players 14 years after the initial injury, with regard to radiographic knee osteoarthritis and patient-relevant outcomes. In 2000, the male players were contacted for a 14-year follow-up. Of the 238 ACL-injured subjects 205 were available for follow-up. Of these, 154 answered the questionnaires. Eighty-nine of these had undergone ACL surgery while 65 respondents had been treated without surgery. The mean age of the study group 14 years after the index injury was 38 years (range 30–56) (Table 1, Fig. 5). The age of those choosing not to participate in the study did not differ from

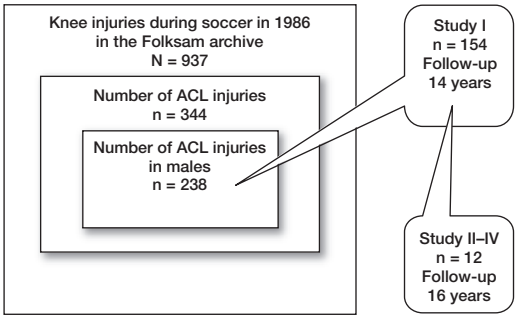

Figure 4. Description of the ACL-injured study population.

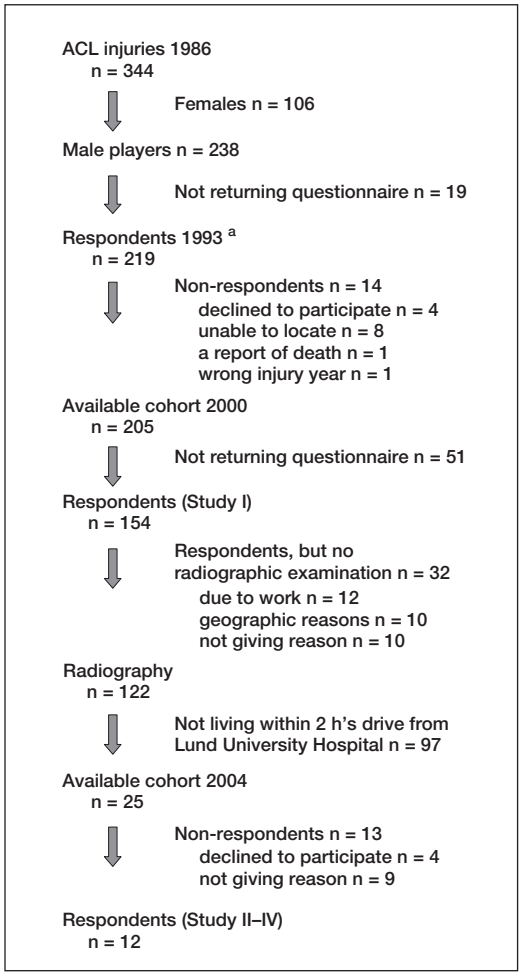

Figure 5. Flow chart of study population. [a] Previously reported [127].

Table 1. Subjects included in this thesis.

Study	Number of subjects	Age mean ± SD (range)	BMI mean ± SD (range)	Years since injury	ACL reconstruction n (%)	Meniscus tear n (%)	Radiographic examination n (%)
I	154	38 ± 5 (30–56)	26.0 ± 2 (21–34)	14	65 (42)	59 (38)	122 (79)
II–IV	12	40 ± 5 (32–53)	24.5 ± 2 (22–30)	16	6 (50)	6 (50)	12 (100)
II–III	12	39 ± 6 (32–53)	24.5 ± 2 (22–26.5)	Not injured	0	0	0

BMI = body mass index

those of those participating; mean age 37 years (range 29–48), p=0.7.

Studies II and III: The aim of these studies was to evaluate knee kinematics and the kinetics of gait, step activity, and cross-over hop in male soccer players with a 16-year-old ACL injury. The inclusion criteria; living within a two-hour drive of Lund University Hospital in the southern part of Sweden and having undergone a radiographic examination in Study I, produced 25 eligible subjects. Twelve agreed to participate, nine subjects did not reply to the invitation and four declined (Fig. 5). The mean age of the participating subjects 16 years after the initial injury was 40 years (range 32–53). The non-participants were younger than the participants; 38 years, p=0.05 (Table 1). There were no other differences in patient characteristics between participants and non-participants.

Study IV: The aims of this study were to assess the reliability and validity of videotaped functional performance tests, and involved the same subject cohort as Studies II and III.

Reference group (Studies II and III)

It was decided to use a reference group (Table 1), as other investigators have found that an injury in one knee may change joint loading and gait patterns, leading to overloading of the contralateral knee [133], and furthermore, because strength deficits are also seen contralaterally following a knee joint injury [59]. The reference subjects in Studies II and III were twelve healthy, uninjured male subjects matched for age, body weight, height, and activity level. For comparison between ACL-injured subjects and references, the injured side of the ACL-deficient subject was compared with the same side in the reference subject. For example, if the ACL subject had an injury to his left knee, we used the left knee of the ACL subject's matched reference for comparison.

Table 2. Outcomes used in this thesis.

Outcome	Study I	Study II	Study III	Study IV
Radiographic examination	•			
Motion analysis		•	•	•
Functional performance tests		•	•	•
Strength test		•	•	
KOOS	•	•	•	
SF-36	•			
Lysholm knee scoring scale	•			
Tegner activity scale		•	•	
Video analysis				•

In Study II, the reference group was used to reveal possible differences in knee kinematics and kinetics between ACL-injured subjects and non-injured subjects. In Study III, the reference group was used to determine if there was any improvement in kinematics and kinetics resulting from the intervention in the study group.

Self-reported knee function

Questionnaires (Studies I–III)

Three questionnaires were used to evaluate self-reported knee function; the Knee injury and Osteoarthritis Outcome Score (KOOS) (Studies I and II), the Lysholm knee scoring scale (Study I), and the Tegner activity scale (Studies II and III) (Table 2). In addition, data concerning the dura-

tion of knee problems and current physical activity level at work and during recreation were collected (Studies I–III). The subjects were also asked to report their current activity level (work & recreation) compared to that before the knee injury on a 5-point Likert scale ranging from "much lower" to "much higher". The subjects noted the reason(s) such as "knee problem," "other reasons" or "both," if a change in activity level was expressed (Study I). All questionnaires were self-administered.

Knee injury and Osteoarthritis Outcome Score: KOOS is a disease-specific self-administered questionnaire with 42 questions in five subscales: pain, symptoms, activity in daily living (ADL), function in sport and recreation (Sport/rec), and knee-related quality of life (QoL), and takes about ten minutes to complete [123, 124]. The KOOS ranges from 0 to 100 for each subscale, where 0 indicates extreme problems and 100 indicates no problems. If 50% or more of the questions in the KOOS QoL subscale and two of the four additional scales were answered at least one level below the best response, subjects were categorised as symptomatic, having sufficient symptoms in the knee to seek medical care. This cut-off was the result of consensus among the authors of a previous paper, two physicians and a physiotherapist [33]. The KOOS questionnaire is based on the WOMAC, Western Ontario and MacMaster Universities Osteoarthritis Index [11], proven to be valid for subjects with ACL injuries and early OA [123, 124].

The Lysholm knee scoring scale is an eight-item questionnaire, developed to assess symptoms and functional disabilities resulting from an ACL injury [143]. The scores from all eight items (pain, instability, locking, stairs, swelling, squat, limp and support) are aggregated into one score ranging from 0 to 100, where 100 indicates normal knee function. The Lysholm knee scoring scale is intended to be observer-administered and no patient instructions are provided in the original version. In Study I, the Lysholm knee scoring scale was self-administered and the subjects were instructed to consider the last week when filling in the questionnaire.

The Tegner activity scale is graded from 1 to 10 and covers activities in daily life and recreational and competitive sports. Tegner activity level 2 represents recreational golf, cycling or swimming, working with small children or working as a waiter, while Tegner activity level 9 represents competitive soccer and 10 indicates professional soccer. Activity levels 5–10 can be achieved only if the patient takes part in recreational or competitive sports [143].

Self-reported physical and mental health

Questionnaire SF-36

One questionnaire, SF-36 the Swedish Acute version 1.0 [142], was used to evaluate general physical and mental health status (Table 2) (Study I).

The Medical Outcomes Study 36-item short-form health survey (SF-36) is a widely used generic instrument for the evaluation of Health-Related Quality of Life (HRQoL). The questionnaire comprises eight multi-item subscales measuring different dimensions of physical and mental health status, such as the ability to perform various physical activities and participate in social activities, as well as emotional status [153]. The SF-36 has previously been used in studies of subjects with ACL injuries [134]. The SF-36 is self-explanatory and takes about ten minutes to complete. A score from 0 to 100 is calculated for each dimension, a higher value representing better HRQoL.

Radiographs (Study I)

For examination of the tibio-femoral joint in Study I, posterior-anterior radiographs with the knee at 15 degrees of flexion were taken in a weight-bearing position, the weight being equally distributed on both legs (Table 2). All radiographs were obtained with the same standardised technique. The frontal views of the tibio-femoral joint of both knees of the subjects were classified according to the recommendations of the Osteoarthritis Research Society [5]. A radiographic atlas was used to evaluate the appearance of the joint space and the presence of osteophytes and to grade these features on a scale from 0 to 3 [5]. Radiographic OA was defined as grade 1 joint space narrowing, combined with osteophytes, or grade 2 joint space narrowing or more [126]. This definition of OA corresponds to the Kellgren and Lawrence grade 2 knee OA [69]. The same reader evaluated all the radiographs. The

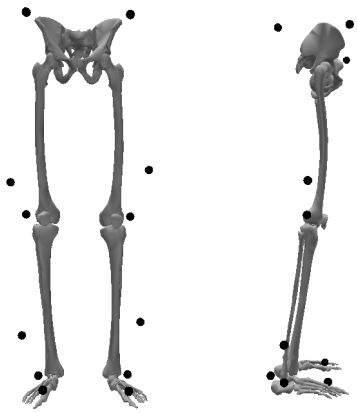

Figure 6. Lightweight surface markers were attached directly to the skin of the subjects at standardised landmarks. The marker positions were used to calculate the subject's 3-dimensional joint kinematics and kinetics in Studies II and III.

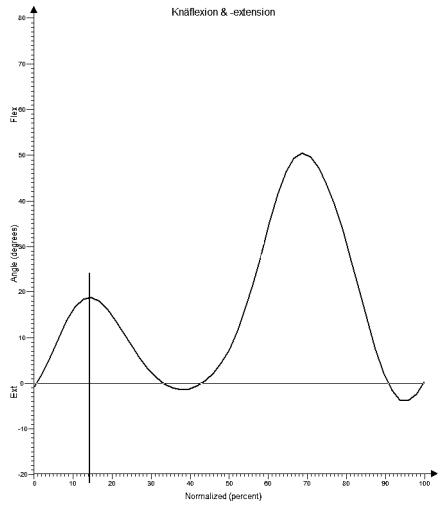

Figure 7. Knee flexion and extension during the gait cycle. The stance phase and swing phase together constitute a complete gait cycle, 100%. Peak knee flexion was assessed during loading response (the first 25% of the gait cycle), indicated in the figure by a vertical line.

reader was blinded with regard to the injured side in non-operated subjects. The bone tunnels were visible on the radiographs obtained from the ACL-reconstructed subjects.

Observed knee function

Knee kinematics and kinetics (Studies II–IV)

A three-dimensional movement analysis system (Vicon 612, OMG, Oxford, UK) was used to assess the kinematics and kinetics of the knee joint in Studies II and III (Table 2). This system consists of six cameras with a sampling frequency of 50 Hz, a data station and a PC where the information is stored and processed. VGRF data were collected from an AMTI force plate (OR6-7, Advanced Mechanical Technologies). The size of the force plate was 505 × 465 mm and the sampling frequency was 200 Hz.

Anatomical measurements of anterior superior iliac spine distance, femur epicondyle width, ankle width and leg length, from the anterior superior iliac spine to the medial malleolus, were made in a standardised way, by a technician with knowledge and experience within the area of motion analysis. Body weight and height were also measured.

Lightweight surface markers, reflecting the infrared light from the cameras, were attached directly to the skin by the same technician. Standardised landmarks were applied on anterior superior iliac spine, lower lateral third of the thigh, lateral epicondyle of the femur, lower lateral third of the calf, lateral malleolus of the fibula and over the second metatarsal head, on the posterior calcaneus at the same distance from ground level as the forefoot marker and one marker between the posterior superior iliac spine, according to the biomechanical model of Kadaba et al. [66] and Davis et al. [28] (Fig. 6). The marker positions were used together with estimates of the joint centre locations and data from the force plate for 3-dimensional joint kinematic and kinetic calculations. The methods of calculation and model assumptions have been described in detail earlier [28, 66, 111].

Kinematics and kinetics data were obtained concerning gait, step activity and cross-over hop. For gait, the stance phase and swing phase were normalised to 100% of the gait cycle. The kinematic and kinetic parameters of gait were studied during loading response, which occurs during the first 25% of the gait cycle (Fig. 7). Kinematic and kinetic data for step and hop activities were obtained during the stance phase and the stance phase was normalised to 100% (Fig. 8). Three measurements of each test were made on the right and left sides, and the mean value of the three tests was used for analysis. Calculated kinetic data were normalised

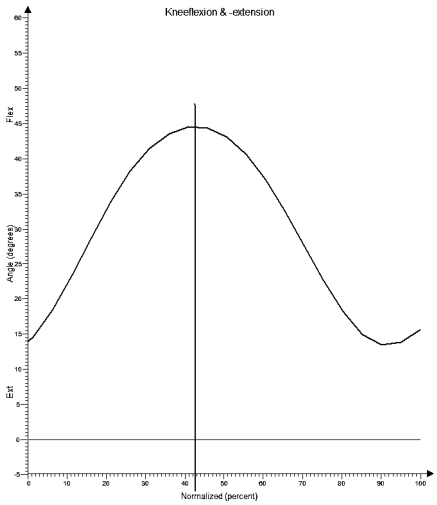

Figure 8. Knee flexion at landing during cross-over hop; 100% is equivalent to the stance phase. Peak knee flexion is indicated by a vertical line.

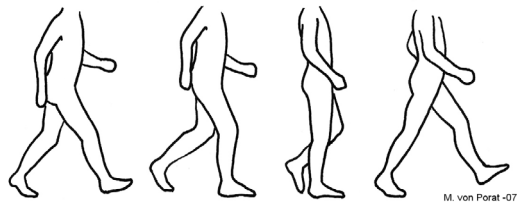

Figure 9. The functional test 'gait' used in Studies II–IV.

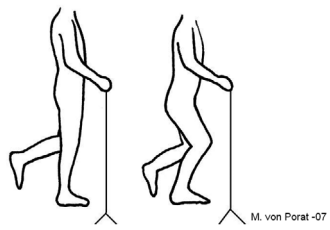

Figure 10. The functional test 'knee bending' used in Studies II–IV.

Figure 11. The functional test 'step activity' used in Studies II–IV.

to body weight in kilograms, and the step activity data were also normalised to leg length.

Peak knee flexion upon landing in the cross-over hop test was determined in Study IV to assess the criterion validity between the Vicon 612 system and the observations of the physiotherapists.

Functional performance tests (Studies II–IV)

Five functional performance tests, increasingly more provocative to the knee, were performed in Studies II-IV (Table 2): 1) gait, 2) knee bending, 3) step activity ascending and descending a 25 cm step, 4) cross-over hop test on one leg, and 5) one-leg hop for distance. In Studies II and III kinematics and kinetics were assessed during gait, step activity, and the cross-over hop test on one leg, and in Study IV videotapes of all five tests were used for the assessment of inter-observer reliability and criterion validity. The tests are described briefly below.

- *Gait:* The subjects walked at a self-selected, comfortable pace on a 10 m walkway (Fig. 9).
- *Knee bending:* Knee bending is a test in which the subjects perform five consecutive knee bends to 30-35 degrees of flexion with fingertip support. The subjects stood on one leg, with fingertip support on a rail and bent the loaded leg five times [17] (Fig. 10).
- *Step activity:* The subject stood facing the step at a self-selected distance and was told to step up with one leg and cross over the step with the contralateral leg [130] (Fig. 11).
- *Cross-over hop:* The cross-over hop test was performed on a 6 m long course where the subject hopped from side to side over a 15 cm wide centre strip on the floor. The subject hopped three times on one foot, crossing over the centre strip on each hop [98] (Fig. 12).
- *One-leg hop for distance:* The subjects stood on one leg, with their hands behind their backs, and performed a one-leg hop as far as possible with a controlled landing on the same foot [144] (Fig. 13).

All functional tests were performed three times on each leg and all subjects started all tests with the right leg.

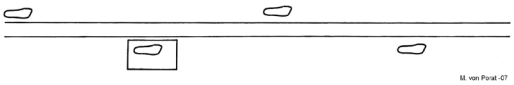

Figure 12. The functional test 'cross-over hop' used in Studies II–IV. Illustration of the right foot. The square indicates the force plate.

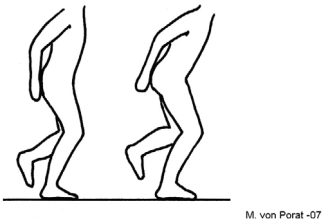

Figure 13. The functional test 'one-leg hop' used in Studies II–IV.

Muscle strength testing (Studies II and III)

In Studies II and III the isokinetic strength of both legs in the ACL-injured subjects and the references was evaluated with an isokinetic dynamometer (Cybex II Dynamometer 325, Lumex Inc., Ronkonkoma, NY, USA) (Table 2). The subject was secured to the apparatus with straps across the chest, pelvis, thigh and ankle, according to the Cybex manual [27]. The subject sat with the thigh supported, with 90 degrees hip flexion and the 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 approximately 3 cm proximal to the lateral malleolus. The range of motion of the knee joint was set from 0–100 degrees. To familiarise subjects with the operation of the dynamometer before formal testing began, they were allowed several sub-maximal practise attempts, after which three consecutive measurements of the maximum effort for knee extension and flexion at angle velocities of 60°/s and 180°/s were made. The peak torque (Nm) of extension and flexion muscle strength was recorded. When studying the impact of quadriceps weakness in Study II the expression [(injured side peak torque / non-injured side peak torque) x 100], was used and a result ≥ 90% was required for the categorisation of good knee extensor strength of the injured leg [8, 120, 158].

Video analysis of functional performance tests (Study IV)

All subjects were recorded from the front with a video camera simultaneously with the 3-dimensional motion analysis (Table 2). The original videos from 12 test occasions before the training programme and 12 test occasions after the training programme were edited with a computer program to provide video sequences of 3½ minutes for each occasion. The videos were used for observers' assessments of knee function during the five functional tests in Study IV.

Inter-observer reliability (Study IV)

Four physiotherapists participated as observers in Study IV. Their clinical experience varied from seven to twenty-four years. All had more than six years' experience of "knee functional assessment."

Based on the video recordings, the physiotherapists were asked to estimate the ACL-injured subject's right and left knee function separately, before and after a 12-week knee-specific training period, on an 11-point scale (Fig. 14), modified from McGinley et al. [89]. First, the video sequence of the five tests performed *before* the 12-week knee-specific training period by the first subject was shown to the four physiotherapists, who assessed right and left knee function separately. Then, the video sequence of the five tests for the same subject performed *after* training was shown to them and they again assessed the degree of knee stiff-

Right:	Loss of knee elasticity	0	1	2	3	4	5	6	7	8	9	10	Normal knee function
Left:	Loss of knee elasticity	0	1	2	3	4	5	6	7	8	9	10	Normal knee function

Gait __ Knee bending __ Step activity __ Cross-over hop __ One-leg hop __

Figure 14. The assessment form used by the observers in Study IV. The level of knee function was rated by marking a number from 0 to 10 for the right and left knees separately. Finally, the functional test of choice for assessing knee stiffness was indicated.

Figure 15. Examples of exercises in the neuromuscular training programme included in Study III. Knee control was emphasized during all exercises. A: Balance on one leg. B: Knee bending with rubber band. C: Knee bending on a step. D: Jumping. E: Rising from a chair on one leg. F: Core stability.

ness in the right and left knee separately. The same procedure was repeated for each of the 12 subjects. Knee stiffness, defined as reduced knee flexion [22, 62, 128, 130, 146], was used to estimate the quality of the knee function during the performance of each test. To determine the strategy used to arrive at their conclusions, the observers were finally asked which of the five tests to be the test of choice for assessing knee stiffness (Fig. 14).

Before the estimation started, the concept of knee stiffness, the five functional tests and the 11-point scale were explained. No further practice was allowed after the instruction session and all the observers carried out the assessment independently on the same occasion. Each observer made 48 assessments: 12 for the right and 12 for the left knee, before and after training, giving a total of 192 assessments for the four observers.

Neuromuscular training (Study III)

Because neuromuscular training has gained in importance and now plays a major role in the rehabilitation of ACL injuries, we used a knee-specific intervention programme focused on neuromuscular control (Fig. 15) (Appendix), to determine whether it was possible to influence the knee kinematics and kinetics in a positive way. Neuromuscular training can be defined as training enhancing subconscious

motor responses by stimulating both the afferent signals and central mechanisms responsible for dynamic joint control [120]. The training programme included balance exercises, dynamic joint stability exercises and core stability exercises. The aim of the programme was to make the ACL-injured subjects aware of knee movements and knee loading during functional activities. Each exercise was adapted to the individual subject's functional capacity. The difficulty was gradually increased from double- to single-leg exercises and from stable to unstable surfaces, when tolerated. During the supervised sessions patients were repeatedly encouraged to maintain symmetry in the double-legged exercises throughout the exercise, and to focus on foot and knee placement during balancing and jumping exercises. Furthermore, subjects were told to use more knee and hip flexion during landing and take-off when practising jumping. The knee control exercises were performed in front of a mirror to make the subjects aware of their knee position during the exercise. The core stability exercises were aimed at improving postural control.

The one-hour sessions were supervised by a physiotherapist (AvP) and took place once a week for twelve weeks. In addition to the group training, each person was given instructions for home exercises. The home exercises were almost identical to the supervised programme. Instead of using a step board for knee bending or jumping exercises, the subjects were instructed to use a staircase, and instead of using a pulley machine during knee control exercises they used a rubber band. All subjects were instructed to perform the home exercises once or twice a week. After the 12-week training period, all the subjects reported their compliance with the home exercise programme in a self-administered questionnaire.

Statistics

Non-parametric statistics were used in Study I. Kruskal-Wallis test was used to determine differences for each sub-scale of the KOOS between groups without or with radiographic OA grade 1 to grade 3. The Mann-Whitney U-test was used when comparing two groups.

The distribution of the populations in Studies II and III was approximately normal, and parametric statistics were thus used. In addition, no differences were found in the interpretation of the motion analysis when using parametric and non-parametric statistics. The paired samples t-test was used to determine levels of significance when comparing the groups.

Study III, Pearson's correlation coefficient was used to determine the correlation between knee extensor strength and knee extensor moment, and to determine the correlation between the changes in knee kinematics/kinetics and the change in self-reported sport and recreational function according to the KOOS questionnaire.

In Study IV, the Intra-class Correlation Coefficient ($ICC_{1,2}$) was used to investigate the agreement between the four observers, and was interpreted according to Altman: < 0.20 = poor, 0.21–0.40 = fair, 0.41–0.60 = moderate, 0.61–0.80 = good, and 0.81–1.00 = very good [4]. Finally, Spearman's correlation coefficient and scatter plots were used to determine the criterion validity. The observer's assessment of knee function on the rating scale was correlated to the knee flexion angle upon landing in the cross-over hop test obtained from the Vicon analysis (48 observations for each observer).

Significance levels of ≤0.05 were considered statistically significant in all four studies.

Ethics

The ethics committee of the Faculty of Medicine, Lund University, approved the studies (LU 403-99 and LU 581-00). Informed consent was obtained from all participating subjects.

Results

Knee osteoarthritis and self-reported function (Study I)

In the cohort of 122 ACL-injured subjects who underwent a radiographic examination 14 years after the initial injury the prevalence of radiographic changes was 78%. Tibio-femoral knee OA, equivalent to Kellgren and Lawrence grade 2 or worse, was found in 41% of those with radiographic changes. There were no differences in the prevalence of tibio-femoral knee OA between those treated with an ACL reconstruction and those treated without surgery. Radiographic changes were more prevalent in subjects with a concomitant meniscus tear than those without: 59% vs. 31% (p=0.002). Twenty-seven subjects (22%) showed no radiographic changes at all.

The most affected subscales in the self-reported knee function questionnaire were the sport and recreation function and QoL, while the least affected subscale was ADL (Fig. 16).

There were no significant differences in any of the five subscales of KOOS between the 154 ACL-injured subjects in Study I (whole cohort) and the 12 ACL-injured subjects in Studies II and III (subgroup) (p=0.2–0.9) (Fig. 16).

Sixty-three percent (97/154) of the ACL-injured subjects were defined as symptomatic according to the KOOS cut-off established by Englund et al. [33] (Fig. 17).

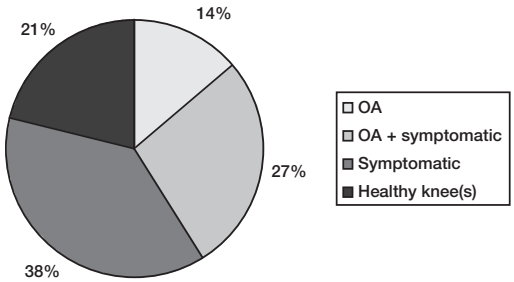

Figure 17. Distribution of radiographic OA, and/or beeing symptomatic according to KOOS and "healthy knee" (no radiographic changes or not beeing symptomatic according to KOOS) in percent, n=122.

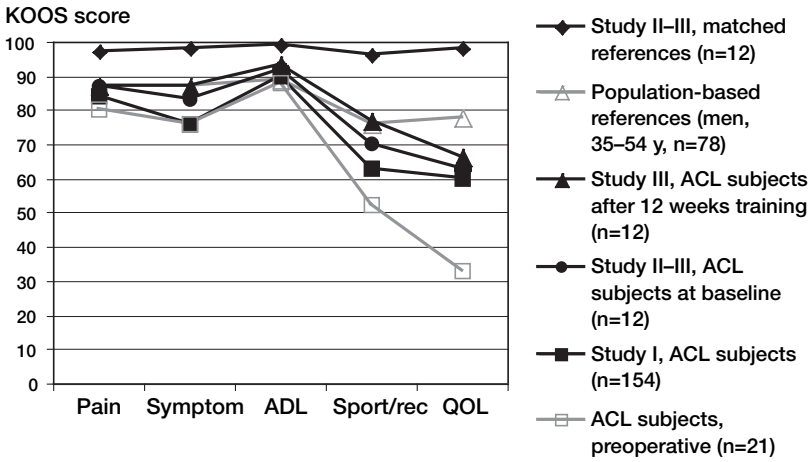

Figure 16. The Knee Injury and Osteoarthritis Score (KOOS) profile for the different study groups in this thesis compared to two reference groups not included in the thesis. Groups from top down: The matched references in study II–III, with no knee injuries or knee problems (♦), a population-based group of men, {Paradowski, 2006 #558}, in the same age as the subjects in this thesis (△), subjects in study II–III, after training (▲) and, at baseline (●), the subjects in study I (■), and ACL subjects on waiting list for surgery (□) [124]. ADL = Activities of daily living, Sport/rec = Sport and recreation function, QOL = Knee-related quality of life.

Knee kinematics and kinetics and self-reported knee function (Study II)

When comparing ACL-injured subjects to the reference group, no significant differences in gait, step activity or cross-over hop were found. The mean values of the internal knee extension moment and knee flexion angle were, however, lower and showed greater variability in the ACL-injured subjects during step and hop activity, and a type II-error could not be ruled out.

The ACL-injured subjects' self-reported knee function was worse than that of the reference, as indicated by significantly lower scores in all five dimensions of the KOOS (p=0.003–0.05) (Fig. 16). Seven out of twelve (58%) subjects were defined as symptomatic according to the KOOS cut-off established by Englund et al. (33).

The effects of neuromuscular training on knee stiffness and self-reported knee function (Study III)

When comparing the ACL-injured subjects before and after training, the cross-over hop was the most indicative test. The peak knee flexion during landing and internal knee extensor moment changed significantly (p<0.031). The mean peak knee flexion during landing increased from 44 degrees before training to 48 degrees after training, and approached that of the reference group which had a mean peak knee flexion during landing of 49 degrees. The internal knee extensor moment during cross-over hop increased from 1.28 Nm/kg before training to 1.55 after training (p=0.017), exceeding the mean internal knee extensor moment of the reference subjects/controls, which was 1.49 Nm/kg (Fig. 18).

The internal knee extensor moment during step activity and cross-over hop and the knee power generated during cross-over hop increased significantly after training in the subjects with a quadriceps index (injured leg divided by uninjured leg) of less than 90% (Table 3).

The mean KOOS scores improved after 12 weeks of neuromuscular training, indicating a better knee function related to sport and recreation (from 70 before to 77 after training, p=0.05) (Figs. 16 and 18).

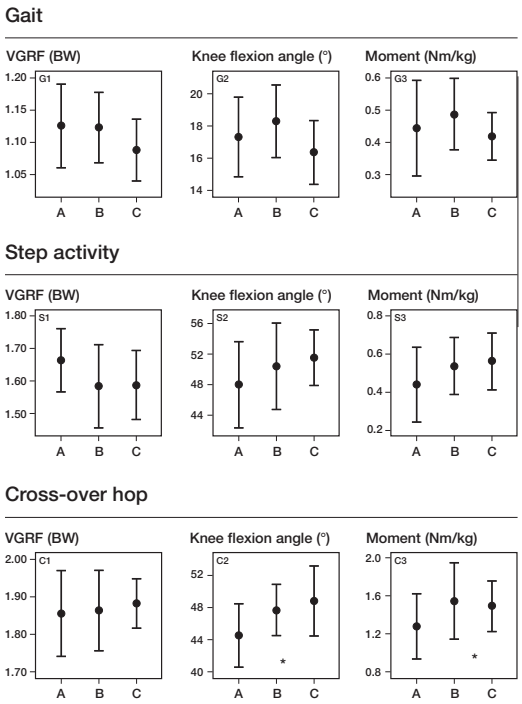

Figure 18. Mean values (and SD) of changes in vertical ground reaction force (VGRF), (G1, S1, C1), knee flexion angle (G2, S2, C2) and internal knee extensor moment (G3, S3, C3) during the three different functional performance tests, gait, step activity and cross-over hop, in the 12 ACL-injured subjects, at baseline and after training, and in the reference group at baseline. A = ACL-injured subjects before training, B = ACL-injured subjects after training, and C = reference group.

Inter-observer reliability and validity of functional performance tests (Study IV)

The inter-observer agreement was moderate to good between the four observers for the right and left knees before and after training, with ICC values ranging from 0.57 to 0.76 (p=0.001–0.032).

The relationship between the rating of knee stiffness on the 11-point scale by the physiotherapists and the knee flexion angle during landing in the cross-over hop test determined with the Vicon system was fair to good for each observer, with Spearman's correlation coefficients of 0.41, 0.46, 0.61 and 0.37 for the four observers (p=0.0001–0.008).

Hop tests were stated as being the preferred tests for assessing knee stiffness in 90% of the test

Table 3. Mean values (± SD) of the kinematic and kinetic variables during gait, step activity and cross-over hop tests for the ACL-injured subjects with a quadriceps index ≤90% and >90% at baseline and after neuromuscular training (Study III).

	Q-ceps index ≤90% (n = 6)		Q-ceps index >90% (n = 5)	
	Before training	After training	Before training	After training
GAIT:				
VGRF (BW) [a]	1.1 ± 0.2	1.1 ± 0.2	1.1 ± 0.2	1.1 ± 0.2
Peak knee flexion at loading response (degrees)	16 ± 4	18 ± 4	17 ± 4	18 ± 3
Knee extensor moment (Nm/kg), (internal moment)	0.34 ± 0.3	0.47 ± 0.2	0.54 ± 0.2	0.53 ± 0.1
STEP ACTIVITY:				
VGRF (BW) [b]	1.7 ± 0.4	1.8 ± 0.4	1.7 ± 0.3	1.8 ± 0.4
Peak knee flexion of supporting limb (degrees)	48 ± 8	50 ± 9	48 ± 12	52 ± 10
Knee extensor moment (Nm/kg), (internal moment)	0.23 ± 0.2	0.48 ± 0.2**	0.65 ± 0.3	0.65 ± 0.3
CROSS-OVER HOP:				
VGRF (BW) [c]	1.8 ± 0.2	1.8 ± 0.2	1.9 ± 0.1	1.8 ± 0.1
Peak knee flexion during landing (degrees)	44 ± 7	47 ± 5	45 ± 6	50 ± 5
Knee extensor moment (Nm/kg), (internal moment)	1.0 ± 0.6	1.26 ± 0.6**	1.64 ± 0.2	2.02 ± 0.4

[a] VGRF in gait was measured during the first 25% of the gait cycle.
[b] VGRF in step was measured during the initial contact with the force plate of the step over limb.
[c] VGRF in cross-over hop was measured during the initial contact with the force plate at the first hop.
** Significant difference between the group with quadriceps weakness before and after training.

Table 4. The number of times (%) each functional performance test was declared to be the test of choice for assessing knee stiffness by the physiotherapists in Study IV. The total number of assessments for each observer was 48.

Functional test	Observer A	Observer B	Observer C	Observer D
Gait	0 (0)	0 (0)	0 (0)	0 (0)
Knee bending	12 (25)	4 (8)	0 (0)	0 (0)
Step activity	0 (0)	2 (4)	0 (0)	2 (4)
Cross-over hop	26 (54)	32 (67)	9 (19)	27 (56)
One-leg hop	10 (21)	10 (21)	39 (81)	19 (40)

cases. The cross-over hop test was ranked as the most used test on 94/192 occasions (49%), and the one-leg hop test was ranked first on 78/192 occasions (41%) (Table 4).

General discussion

The risk of developing knee OA after an ACL injury was found to be high (Study I). The knee kinematics and kinetics, and self-reported knee function were influenced 16 years after the ACL injury (Study II). However, neuromuscular training improved both knee kinematics and kinetics, as well as self-reported knee function such that the injured subjects became more similar to the reference subjects (Study III). The inter-observer reliability between physiotherapists assessing knee function from videotaped functional performance tests was moderate to good, and the correlation between the physiotherapists' recorded ratings and the knee flexion angle during landing in the cross-over hop test was fair to good (Study IV).

Knee osteoarthritis and self-reported function (Study I)

Investigating the long-term consequences of an ACL injury involves studying subjects with different patient and knee joint characteristics, such as age, sex, BMI, years since injury, surgical reconstruction, meniscal injury, and presence of radiographic features of OA. The great variation in characteristics within a study group could be considered a limitation, but at the same time a strength of the investigation, as this is the reality many years after ACL injury.

Only 122 subjects of the 205 available agreed to have an radiograph taken. This may constitute a selection bias. However, the pain, function and activity level of the group who declined to have radiographs taken did not differ from the group undergoing a radiographic examination. The prevalence of tibio-femoral knee OA 14 years after an ACL injury was 41%. We used male soccer players injured during the same year. Posterior-anterior radiographs, taken in a weight-bearing position, the weight equally distributed on both legs, were used for the examination of the tibio-femoral joint. This radiographic technique has been used by several other investigators, with only minor changes in the knee flexion angles in the weight-bearing position [3, 38, 80, 90, 96, 97, 131, 132, 135, 136, 139], but the follow-up time, gender distribution, and use of radiographic atlas differ between the studies. The follow-up time in other studies ranges from 1½ years to 20 years, most with a variation of at least five years. Regarding gender distribution, mixed groups of males and females have been used in most studies [90, 96, 131, 132, 136]. Just one study examined females only and they used the same follow-up time for all the subjects in the study group, namely 12 years [80]. These women originate from the same cohort as the ACL-injured men described in this thesis [127]. When analysing the radiographs, the classification recommended by the Osteoarthritis Research Society was used. The appearance of the joint space was evaluated and the presence of osteophytes ascertained, and these features were graded on a scale from 0 to 3 [5]. This definition of OA corresponds to Kellgren and Lawrence knee OA grade 2 [69] and was the same classification as that used by Lohmander et al. [80]. The classification of Kellgren & Lawrence was used in two other studies when assessing knee OA [131, 132]. Lohmander et al. showed a prevalence of 51% tibio-femoral knee OA in females, while the other two studies reported prevalence rates of OA similar to that in Study I presented in this thesis, i.e. 41%.

A higher risk of knee OA was observed if the ACL injury was combined with a meniscus tear. Despite different classifications of knee OA, several investigators have reported an increasing risk of OA when concomitant meniscal injuries are present [3, 38, 80, 90, 131, 135]. In the only randomised study comparing primary repair and non-surgical treatment of ACL ruptures, Meunier et al. found knee OA in 2/3 of the subjects with an ACL injury combined with a meniscus tear, compared to 1/3 of the subjects with an isolated ACL injury [90]. In the present work, no difference was found in the prevalence of knee OA between subjects treated with surgery and subjects treated without surgery. This result is in line with those of other studies [3,

38, 80, 90, 96, 97, 131, 132, 135, 136, 139]. However, it was clearly shown in some studies that reconstruction of the ACL reduces the risk of a secondary meniscus tear, indicating an indirect preventive effect of reconstructive surgery [24, 90].

The group of ACL-injured former soccer players studied in this work reported similar symptoms in the KOOS questionnaire to patients on the waiting list for ACL reconstruction [124] (Fig. 16). A better score for the knee-related quality of life subscale for the ACL-injured subjects was the most noticeable difference, indicating possible adaptation to the injured knee with time, including reduced activity level. McAllister et al. reported that 52% of ACL-injured subjects scored abnormal or severely abnormal knee function according to the IKDC questionnaire 2–14 years after injury [88], which is similar to the results obtained from the KOOS questionnaire in this work.

Fifty of the 122 ACL-injured subjects who were radiographically examined showed tibio-femoral knee OA. Of these, 33 were symptomatic according to KOOS, and 46 were symptomatic without knee OA (Fig.17). These results support earlier findings of a low correlation between radiographic knee OA and symptoms in population-based samples [36, 51, 75].

Functional performance tests (Studies II–IV)

Five functional performance tests with increasing degrees of difficulty were chosen for ACL-injured subjects. Gait was chosen because it is the most frequently used performance test in combination with 3-dimensional motion analysis, and the reliability of kinematics and kinetics during gait and running are good [29, 43]. Other, more demanding tests were included, as it was thought that gait would not be sufficiently discriminating a long time after an ACL injury. The step activity is a commonly used test in studies where kinematics and kinetics are also assessed [128, 130, 145]. The hop and knee bending tests were chosen as they are commonly used during ACL rehabilitation. Both the hop and the knee bending tests have good reliability and validity when used to evaluate subjects with knee injury [17, 48, 98]. The results of Studies II and III showed that the most demanding performance tests were the most decisive tests, but further studies are needed to confirm the results. Since these performance tests are frequently used in the clinic, they were also well known by the physiotherapists used as observers in Study IV.

Strength and limitations of Studies II–III

Long-term follow-up is important, but a group larger than twelve subjects is necessary to carry out sub-group analyses and to be able to generalise the results. To avoid the risk of bias in Studies II and III during the data collection phase, the reader was blinded to the person, knee, and whether the image was obtained before or after the 12-week neuromuscular training period, which must be considered a strength of the studies.

The use of 3-dimensional motion analysis could be a limitation, considering the infinite number of parameters. This means that it is necessary, before starting, to determine which clinically relevant parameters should be used. Studies II and III covered a fairly large number of parameters due to the use of three functional performance tests, which could lead to type II errors. However, regarding the parameters that differed significantly with exercise the observations were concentrated, reducing the likelihood of statistical errors. A post-hoc analysis, based on a 15% difference between the groups, shows that more than 40 subjects would be needed in each group to avoid type II errors for the most provocative tests, and more than 500 subjects for the small differences in gait to be significant. This illustrates the difficulty in investigating movement patterns with 3-dimensional motion analysis many years after injury. Studies II and III must be thus regarded as pilot studies, and further investigations on larger groups are needed to verify the results.

As previous studies have shown that an injury to one knee may change the joint loading, gait pattern and muscle strength of the contralateral knee [59, 133], the use of matched references, as in Studies II and III, is preferable. The reference subjects in this work were not only matched with regard to body characteristics and age, but also to activity, according to the Tegner activity scale, which takes both work and recreation into consideration.

Knee kinematics and kinetics, and self-reported knee function (Study II)

It was found that 16 years after an ACL injury sustained while playing soccer males had a similar gait, step activity and cross-over hop pattern to uninjured references. These results are supported by Bulgheroni et al., who found gait pattern values of reconstructed ACL-injured subjects to be similar to those of normal subjects. The ACL-injured subjects in the study by Bulgheroni et al. were examined 17 ± 5 months after the surgical intervention. All of them had resumed their normal activities and there was no clinical evidence of instability [19]. Chmielewski et al. reported the opposite results. They found decreased peak knee flexion, knee moment and VGRF in ACL-injured subjects compared with un-injured subjects [23]. The subjects they studied had gone through a screening examination at an average of 24 days after injury, which ensured that all the subjects exhibited ≥ 80% of their un-injured leg on the timed hop test and ≥ 80% on the Knee Outcome Survey-Activities of Daily Living Scale. They were all classified as potential copers (subjects who could return to pre-injury activities without instability or surgery) and were compared with un-injured subjects during gait tests and jogging. Furthermore, Knoll et al. demonstrated changes in movement pattern up to 12 months after ACL reconstruction, and showed how the performance of the ACL-injured subjects approached that of un-injured subjects with increasing time [70]. The large difference in time since injury, 16 years for the subjects in this thesis and 1–9 weeks for the subjects in the study by Chmielewski et al., indicates that the time since injury plays an important role, and must be considered when comparing movement patterns in different studies. Differences in the methodology used for gait analysis also have to be considered when comparing the results of different studies. A 3-dimensional motion analysis system was used in the present work. This has also been used by several other investigators [19, 23, 63, 121, 130, 145, 154], while others have applied a simple linked segment model, which assumes that flexion and extension occur purely in the sagittal plane [12, 37]. An ultrasound-based system has also been used [70].

The results from the KOOS questionnaire show that the 12 ACL-injured subjects reported significantly worse results in all five subscales than the 12 matched references (Fig. 16). Five of the six subjects with knee extensor weakness were symptomatic according to the KOOS questionnaire, compared with only one of the five subjects with good knee extensor strength. This is in line with other studies showing that symptoms are more closely associated with knee extensor weakness than with radiographic features of OA [64, 87, 103].

The effects of neuromuscular training on knee stiffness and self-reported knee function (Study III)

Twelve weeks' knee-specific training focusing on neuromuscular control reduced the VGRF, and increased the knee flexion angles and the internal knee extensor moment, bringing the performance of the ACL-injured subjects closer to that of the reference (Fig. 18). Chmielewski et al. demonstrated that ten sessions with perturbation training of acutely injured, potential copers, caused the knee flexion during gait to become more similar to that of the un-injured controls [22]. They used perturbation training, i.e. balance on a moving surface, while we used balance training, hop training, knee control and core stability exercises. The exercises employed in the present work were based on clinical experience and a literature search [57, 84, 93, 94, 109]. The intention of the exercises was to make the subjects aware of their knee position during performance, to reduce avoidance behaviour and to improve postural control. Kinematics and kinetics were investigated using a Vicon system, to measure the effects of neuromuscular training. This method has also been used by others, who reported improvement in knee kinematics and kinetics of ACL-sufficient subjects and female athletes [22, 94], indicating that neuromuscular training positively effects knee function, by increasing knee flexion and decreasing internal varus and valgus moments, and that kinematics and kinetics are adequate measurements. In other studies, neuromuscular training has been used for knee injury prevention [21, 57, 58, 61, 95, 155, 156]. The results of neuromuscular training were evaluated in terms

of frequency of injury before and after training and/or between a group participating in neuromuscular training and a group that did not have access to this kind of training.

The poor correlation between quadriceps strength and knee extensor moment, seen in Study III, supports the theory that lower extremity kinematics and kinetics can be influenced by training focusing on neuromuscular control only, without special emphasis on improving lower extremity muscle strength. This theory is supported by results published by Beard et al. and Zätterström et al. [9, 165].

Twelve weeks of knee-specific training improved knee function, as measured by the KOOS. The subscale sport and recreation function improved significantly, indicating better control of, and greater confidence in, the injured knee (Fig. 16). The improvement in knee flexion angle during landing in the cross-over hop test, after knee-specific training focusing on neuromuscular control, was also positively correlated to the improvement in self-reported sport and recreation function. Houck et al. also found a positive correlation between knee flexion and knee function. They investigated ACL-deficient subjects divided into low- and high-functioning groups based on knee functional ratings. The group with low functional ratings had less knee flexion during step and cutting activity than the group with high ratings [63].

Due to the small number of randomised clinical studies comparing different types of rehabilitation programmes there is no clear evidence of the benefit of neuromuscular training. However, four studies have shown significantly better results following neuromuscular training than with muscle strength programmes or self-monitored training in ACL-injured subjects. Beard et al. compared strength training with a 12-week neuromuscular facilitation programme in ACL-deficient subjects and found significantly greater improvement in the neuromuscular group [9]. Ageberg et al. and Zätterström et al. compared self-monitored training, including exercises in non-weight-bearing positions to train isolated muscles selectively, with neuromuscular training, supervised by physiotherapists [2, 165]. Ageberg et al. examined the training results with stabilometry and one-leg hop for distance after 6 weeks and 3, 12 and 36 months, and observed restored functional performance at a follow-up examination after neuromuscular training [2]. Zätterström et al. found significantly greater improvement in the supervised group with regard to muscle strength, functional performance and the Lysholm knee scoring scale after 12 months [165]. Risberg et al. compared the effect of a 6-month neuromuscular training programme with that of a traditional strength training programme following ACL reconstruction. They reported significantly improved knee function according to the Cincinnati Knee Rating System and VAS, Visual Analogue Scale, but no significant differences between the groups regarding hop, balance, proprioception or muscle strength [118]. These results indicate the suitability of neuromuscular training, based on theoretical models and clinical experience, as the first choice in the rehabilitation of ACL injuries [119].

Inter-observer reliability and validity of functional performance tests (Study IV)

All four observers had previous experience of rehabilitation of ACL-injured subjects. They underwent training trial prior to performing the assessments. The functional tests used were all well known to the physiotherapists in their everyday clinical work. These aspects may improve the inter-observer reliability compared with inexperienced observers who have not undergone training. None of the physiotherapists had ever treated any of the subjects participating in the study.

Inter-observer reliability of the assessment of knee stiffness during the five functional performance tests was moderate to good. Observational analysis requires much practise, combined with an understanding of biomechanics [108]. This is reflected by poor to moderate reliability of gait analysis [18, 31]. The reliability of quantitative parameters [105, 148, 151, 152, 164] is often better than that of qualitative parameters such as knee stiffness [14, 18, 31, 89, 92]. The choice of variables to be assessed is another important factor. The variables selected, in this case knee stiffness, should have clinical relevance and be representative of the functional performance capacity of the study group in question [25]. We required the observers to determine the ACL-injured subject's knee func-

tion, defined as knee stiffness, on an 11-point scale. Zero was equivalent to loss of knee elasticity (i.e. maximum knee stiffness) and ten was equivalent to normal knee function (i.e. no knee stiffness) (Fig. 14). The scale was modified from McGinley et al., who used two 11-point scales, one abnormal and one normal, to assess push-off in gait after stroke. McGinley's approach may give the observers a more sensitive rating scale with better inter-observer reliability. It may, however, be questioned whether such precision is applicable in the assessment of knee stiffness in ACL-injured subjects. One of the four observers in Study IV used only the upper part of the rating scale with ratings from 5 to 10, and gave the best possible rating five times out of a total of 48 occasions for one observer. The other three observers, however, used the whole scale and gave the best possible rating only twice on a total of 144 occasions for these three observers, indicating that an 11-point scale is appropriate for the assessment of knee stiffness in ACL-injured subjects. A structured analysis form, listing the parameters to be assessed and describing how the parameters are to be assessed is more commonly used in reliability studies [14, 18, 31, 72, 92]. Despite the use of a structured analysis form, it may be difficult to assess several parameters simultaneously. We used only one parameter, knee stiffness, and no structured analysis form. Despite this, the inter-observer reliability in Study IV was higher than that in a study by Brunnekreef et al. (ICC=0.57–0.76 vs. ICC=0.38–0.60). They used a structured form with six parameters, each with one to four statements, making twelve statements to be assessed [18]. This may indicate that it is easier to focus on one specific body segment, in this case the knee, instead of several body segments simultaneously.

The acceptable correlation found in the comparison of observations of knee stiffness and knee joint angle indicates that physiotherapists could, without the help of laboratory equipment, assess knee stiffness ranging from complete loss of knee elasticity to normal knee function. McGinley et al. correlated push-off during gait assessed by physiotherapists and push-off obtained from 3-dimensional analysis in hemiplegic subjects [89]. The correlation coefficients between observed push-off and push-off obtained from 3-dimensional analysis ranged from 0.69 to 0.91, indicating better correlation than in Study IV in this thesis. This difference may be related to the subjects in the present study having a less obvious disturbance of their movement pattern than hemiplegic patients, and to the fact that only the frontal view was assessed using the videotapes for scoring. In the clinic, physiotherapists view the patient from different directions, which makes the assessment more difficult for the observers.

Conclusions

The major conclusions based on the results of the studies described in the papers (I–IV), listed according to the specific objectives, are given below:

- The prevalence of tibio-femoral knee osteoarthritis 14 years after an ACL injury was 41%.
- Almost two-thirds (63%) of the ACL-injured subjects were symptomatic 14 years after the initial injury.
- Self-reported knee function among the ACL-injured subjects, 16 years after the injury, was worse than among non-injured subjects.
- There were no detectable differences in kinematics and kinetics between the ACL-injured subjects 16 years after the injury and their matched references.
- Knee-specific training, 16 years after the injury, improved lower extremity kinematics and kinetics, indicating reduced knee stiffness during demanding hop activity.
- Self-reported sport and recreational function correlated positively with knee flexion, measured when landing in the cross-over hop test, and the knee extensor moment, which supports the clinical importance of the findings.
- The moderate to good inter-observer reliability and the acceptable criterion validity indicate that the presence of knee stiffness in ACL-injured subjects can be determined by visual observation of demanding functional performance tests such as the cross-over hop and one-leg hop tests.

Summary in Swedish — sammanfattning på svenska

En fysisk aktiv livsstil är viktig för alla åldersgrupper. Idrottsaktivitet utsätter dock individen för vissa skaderisker. Vissa skador, såsom främre korsbandsskador, är ett växande bekymmer. Den högsta frekvensen ses bland idrottare i åldern 15–25 år framförallt inom pivoterande idrotter som fotboll, basket, innebandy och handboll. Främre korsbandsskador är ofta förknippade med lång och kostsam rehabilitering. Rehabiliteringen följs ofta av en relativt hög omfattning av olika grader av försämring, med risk för den drabbade personens idrottande och sociala liv, till exempel risk för bristande kontakt med arbets-, skol- och lagkamrater, samt begränsad social rörlighet, likväl som samhällsekonomiska konsekvenser. Detta visar att en skada inte bara innebär problem under en kort tid, utan också kan leda till ett helt ändrat socialt liv för vissa individer. Studierna i denna avhandling visar att förekomsten av knäledsartros är hög 14 år efter en främre korsbandsskada, att de skadade individerna skattar sig själva sämre i knäfunktion än friska individer och att rörelsemönstret vid funktionella test är något mer varierat hos skadade individer. Undersökningarna visar också att träning kan påverka variationen i rörelsemönstret och den självskattade knäfunktionen samt att de funktionella testen var tillförlitliga vid bedömning av knäfunktion och att testerna även väl mätte vad vi ville att de skulle mäta.

I den första studien undersöktes förekomsten av knäledsartros och självskattad knäfunktion hos män, 30–56 år, med en 14 år gammal främre korsbandsskada. 122 män genomgick knäledsröntgen, varav 95 hade förändringar på röntgen och av dessa hade 50 knäledsartros. Endast 27 individer var helt ”knäfriska”. De korsbandsskadade personerna skattade sin knäfunktion sämre jämfört med friska kontroller.

I studie två och tre användes tredimensionell rörelseanalys. Individen utförde tester i ett laboratorium med reflexmarkörer fastsatta på huden över utvalda skelettpunkter. Sex höghastighetskameror registrerade markörerna under testmomenten och ett avancerat datorprogram beräknade belastningen och vinklarna över knäleden. Studie två var en undersökning med jämförelse av rörelsemönster hos 12 män, 32-53 år, med främre korsbandsskada 16 år efter deras skada, med 12 ”knäfriska” män, 32-53 år. Dessutom jämfördes självskattad knäfunktion. Alla individerna genomförde en rörelseanalys i laboratoriet där knäledsbelastningen och knäledsvinklarna mättes när individerna gick på plant underlag, gick ned för ett trappsteg och hoppade sicksackhopp på ett ben. Det var ingen statistiskt säkerställd skillnad i knäledsbelastning eller i knäledsvinklar mellan individerna med en främre korsbandsskada och ”knäfriska” individer. De korsbandsskadade individerna skattade sin knäfunktion som betydligt sämre än de ”knäfriska”. I den tredje studien fick de korsbandsskadade individerna träna ett knäspecifikt träningsprogram en timme i veckan under tolv veckor. De skadade individerna blev mer lika de ”knäfriska”, både när det gällde knäledsbelastning, knäledsvinklar och självskattad knäfunktion.

I den fjärde studien bedömdes tillförlitligheten av fem funktionella test: gång på plant underlag, knäböjning på ett ben, gång över ett trappsteg, sicksackhopp på ett ben och enbent längdhopp. Dessutom kontrollerades det om de fem testerna kunde användas för att mäta knäfunktion. Fyra sjukgymnaster bedömde knäfunktionen hos de 12 männen med främre korsbandsskada som ingick i studie två och tre genom att titta på videofilmer där individerna utförde de fem funktionella testerna. Därefter analyserades hur väl sjukgymnasternas bedömningar överensstämde och deras bedömningar jämfördes med resultaten från rörelseanalyserna. Sjukgymnasterna hade relativt god samstämmighet och det var även en acceptabel överensstämmelse mellan sjukgymnasternas bedömningar och rörelseanalyserna.

Baserat på resultaten av studierna drar jag följande slutsatser:

- Förekomsten av knäledsartros 14 år efter en främre korsbandsskada är hög.

- Den självskattade knäfunktion hos personer med en främre korsbandsskada är påtagligt sämre än ”knäfriskas” självskattning 16 år efter skadan.
- Det var inte möjligt att upptäcka några skillnader i knäledsbelastning och knäledsvinklar vid funktionella test hos individer med en 16 år gammal främre korsbandsskada jämfört med hos ”knäfriska” personer.
- Träning påverkar såväl knäledsbelastning som knäledsvinklar och självskattad knäledsfunktion i positiv riktning.
- Den relativt goda samstämmigheten mellan sjukgymnasterna och den acceptabla överensstämmelsen mellan bedömningarna och rörelseanalyserna indikerar att det är möjligt att bedöma knäfunktion genom observation av funktionella test.

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Appendix

Knee specific training with focus on neuromuscular control (patient instructions)

The training program is to be performed twice a week for 12 weeks. Each exercise is adapted to your functional ability and the difficulty level will be gradually increased as you improve, for example from double to single leg weight-bearing exercises and from stable to unstable surfaces.

Foot and knee alignment is very important in all the following exercises, that is, as you bend the knee forward it should stay in line over the great or second toe, the knee alignment should **not** deviate to the side. If possible, do the knee control exercises in front of a mirror to be fully aware of your knee position. Also as you jump/hop try to think about bending the knee and the hip during landing and taking-off.

Perform the exercises slowly in order to control the position of your knee.

Repeat each exercise in 3 sets of 10 (10x3) and you should train both right and left legs.

Warm up 10 minutes

A. Stationary bicycle;
B. Fast walking on a treadmill;
C. Jogging on a treadmill;
D. Jumping with skipping-rope.

Sit to stand

A. Both legs from a stool (50 cm);
B. Single leg from a stool;
C. Single leg from a stool (40 cm);
D. Single leg from a stool, while simultaneous bouncing a ball.

Explanation: Sit on a stool and bend your knee or both your knees, if possible, until your feet are under your body. Stretch your arms in front off you and rise up to a standing position. Then bend your knee slowly until you are in a sitting position again. Part D starts like B except bouncing a ball simultaneously.

Knee bending from a pulley machine or with rubber band

A. Both legs with the rope around and below the knee joints;
B. On one leg with the rope below the knee joint and with fingertip support;
C. On one leg with the rope below the knee joint and no fingertip support;
D. On one leg on a uneven surface.

Explanation: Stand side on to the pulley machine, the exercise leg furthest away from the wall. Place the rope from the pulley machine or the rubber band below your knee joint and stretch the rope or stand further away to feel the rope tension. You should start to feel that the knee will want to fall inwards towards the other leg as the rope pulls. The exercise is to allow your knee to bend forward keeping the alignment straight over your foot and resisting this inward draw. If possible, do this exercise in front of a mirror so that you can focus on holding a straight line between your hip, knee and foot.

Stair climbing forward and backward

A. Use a step 7 cm high;
B. Use a step 15 cm high;
C. Use a step 25 cm high.

Explanation: Stand on the step with one leg. Bend and straighten this leg while the other leg alternates from touching the floor in front of the step and then behind the step. Focus on holding a straight line between your hip, knee and foot of your loading leg.

Core stability

A. Both feet on the floor and a ball between your knees, arms by your side on the floor;
B. One foot on the floor, one leg stretched in front of you and a ball between your knees. Arms by your side;
C. One foot on the floor, one leg stretched out and a ball between your knees, arms in a cross over your body.

Explanation: Lie on the floor with your knee bent to 90 degrees and feet flat. Place a soft ball or a pillow between your knees, arms by your side. Lift your bottom so it makes a straight line with your knees. Hold for 10 seconds. To make it more difficult, stretch one leg out in front of you while

your trunk is lifted. Make sure that you can hold your hips in a straight line whilst lifted and do not drop the hip or allow the pelvis to rotate. Put your foot back on the floor and stretch the other leg out. To make it even more difficult, place your arms across your chest.

Balance

A. Double leg stance on wobble board;
B. Single leg stance on wobble board;
C. Single leg stance on wobble board, uneven surface;
D. Single leg stance on wobble board while you use a pulley machine with the other leg.

Knee bending with ball

A. Knee bending to 90 degrees on two legs;
B. Knee bending on one leg with toe support of the other leg;
C. Knee bending on one leg.

Explanation: Stand against a wall with a big ball behind your back. Sit down pressing your back against the ball until your knees reach a 90 degree angle (make sure the knee is straight over the foot). To make it more difficult, stand on one leg with toe support of the other foot and bend your knee as deep as you can and back up again. To make it even more difficult, stay on one leg with no support and repeat the same thing.

Jump

A. Jump with both feet together on the floor;
B. Single leg hop from the floor;
C. Single leg hop from an uneven surface;
D. Single leg hop down from a step of 15 cm;

Explanation: Make sure you bend the knees when landing and try to land with your knee position straight over your foot.