Long-term consequences of anterior cruciate ligament injury

Knee function, physical activity level, physical capacity and movement pattern

Eva Tengman
To my family
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Abstract

Rupture of the anterior cruciate ligament (ACL) is a common injury to the knee joint and occurs primarily in active young individuals involved in sports. An ACL injury has a negative impact on knee function and most athletes who sustain an ACL injury do not return to their pre-injury activity level despite treatment, which can be either physiotherapy in combination with surgery or physiotherapy alone. Regardless of treatment, reduction in knee function and physical activity level is evident in the short term and in a longer perspective. Knee function after more than 20 years post injury is however rarely described and none of the few follow-up studies have evaluated functional performance tasks. This thesis investigated self-reported knee function, physical activity level, physical capacity and movement pattern in the long-term perspective (on average 23 years) in persons who had suffered a unilateral ACL injury, treated either with physiotherapy in combination with surgery (ACL<sub>R</sub>, n=33) or physiotherapy alone (ACL<sub>PT</sub>, n=37) and compared to age-and-gender matched controls (n=33).

This thesis shows that regardless of treatment, there are significant negative long-term consequences on self-reported knee function and physical activity more than 20 years after injury. In comparison to the controls, the ACL<sub>R</sub> and ACL<sub>PT</sub> groups had lower self-reported knee function as measured by the Lysholm score and the Knee injury and Osteoarthritis Outcome Score (KOOS). The ACL injured individuals also had a lower knee-specific physical activity level (Tegner activity scale), while no differences were seen in a more general physical activity level (International Physical Activity Questionnaire, IPAQ) compared to healthy controls.

Regarding physical capacity, both ACL groups showed inferior jump capacity in the injured leg compared to the non-injured leg. However, compared to controls the ACL-injured had a relatively good jump performance. Knee extension peak torque, concentric and eccentric, was also lower for the injured leg compared to the non-injured leg for both ACL<sub>R</sub> and ACL<sub>PT</sub>. In addition, the ACL<sub>PT</sub> group showed reduced eccentric knee flexion torque of the injured leg. The non-injured leg, on the other hand, showed almost equal jump capacity and strength as controls. Balance in single-limb stance (30s) was inferior in persons with an ACL injury. This was true for both the injured and non-injured leg and regardless of treatment; 39 % of the ACL<sub>R</sub> and 50 % of the ACL<sub>PT</sub> failed to stand on one leg without occasional floor-supports with their contralateral foot. The controls did, however, manage to stand on one leg for 30s without any floor support. Amongst those who managed the single-limb stance, the drift of Centre of Pressure (CoP) was analysed, without indicating any further differences.

Movement pattern during the one-leg hop was analysed by a set of kinematic variables consisting of knee angles (flexion, abduction, rotation) and Centre of Mass (CoM) placement in relation to the knee and ankle joints. Both ACL<sub>R</sub>
and ACL\textsubscript{PT} displayed movement pattern asymmetries between injured and non-injured legs. In comparison to controls, the ACL\textsubscript{R} group had a similar movement pattern with the exception of larger external knee rotation at Initial contact and less maximum internal rotation during the Landing. ACL\textsubscript{PT} showed several differences compared to controls both regarding knee angles and CoM placement.

The ACL-injured persons with no-or-low radiological knee osteoarthritis (OA) had better knee function as reflected by higher scores on Lysholm and KOOS subscale 'symptom' compared to those with moderate-to-high OA. The degree of OA had no influence on reported physical activity level, jump capacity, peak torque or the kinematic variables.

In conclusion, this thesis indicates that persons with a unilateral ACL injury, regardless of treatment, have some negative long-term consequences e.g. self-reported knee function, knee-specific activity level, strength and balance deficits, when compared to age-and-gender matched controls. The results also indicate that the ACL-injured individuals can manage reasonably well in some jumps and general activity level but have an inferior performance in more knee-demanding tasks. The ACL\textsubscript{R} group had similar movement pattern with the exception of knee rotation, indicating that a reconstruction may restore the knee biomechanics to some extent. The ACL\textsubscript{PT} group on the other hand, seem to use compensatory movement strategies showing several differences in movement pattern compared to controls.
Svensk sammanfattning

Titel: Långtidskonsekvenser av en främre korsbandsskada. Knäfunktion, fysisk aktivitetsnivå, fysisk kapacitet och rörelsemönster.

Främre korsbandsskada är en vanligt förekommande knäskada som främst drabbar unga idrottsaktiva personer. En korsbandsskada har negativa effekter på knäledens funktion och trots behandling är det få av de skadade som kan återgå till samma aktivitetsnivå som innan skadan. En korsbandsskada kan behandlas antingen med fysioterapi i kombination med kirurgi eller enbart med fysioterapi. Endast få studier finns kring långtidseffekterna av en korsbandsskada och studier som utvärderar fysisk kapacitet 20 år efter skadan saknas helt.

Denna avhandling undersöker själv-rapporterad knäfunktion, fysisk aktivitetsnivå, fysisk kapacitet och rörelsemönster hos personer med en ensidig korsbandsskada och som är behandlad antingen med fysioterapi i kombination med kirurgi (ACLᵣ, n=33) eller med enbart fysioterapi (ACLᵫ, n=37) och detta i jämförelse med ålders och köns matchade kontroller (n=33). Studien utvärderar långtidseffekterna i medeltal 23 år efter skadan.

Avhandlingen visar att oavsett behandling finns det negativa långtidskonsekvenser på själv-rapporterad knäfunktion och aktivitetsnivå mer än 20 år efter skadan. I jämförelse med kontroller har korsbandsskadade (både ACLᵣ och ACLᵫ) en nedsatt knäfunktion mätt med Lysholm score och Knee injury and Osteoarthritis Outcome Score (KOOS). Korsbandsskadade visar också en nedsatt knäspecifik aktivitetsnivå (Tegner activity scale) medan inga skillnader sågs vad gäller en generell aktivitetsnivå (International Physical Activity Questionnaire, IPAQ).

Resultatet visar att korsbandsskadade, båda ACLᵣ och ACLᵫ, har en sämre hoppkapacitet i det skadade benet jämfört med det icke-skadade. Däremot i jämförelse med kontroller har de en relativt god hoppkapacitet. Även koncentrisk och excentrisk styrka i knäextensorer (mätt i vridmoment) var lägre för det skadade benet jämfört med det icke-skadade. Detta oavsett behandling. Personerna i ACLᵫ visade dessutom en nedsatt excentrisk styrka i knäflexorerna. Däremot fanns inga skillnader i hoppkapacitet och styrka vid jämförelse av icke-skadade ben och kontroller. I jämförelse med kontroller har de korsbandsskadade en nedsatt balans vid stående på ett ben. Detta gäller både skadat och icke-skadat ben. Alla kontroller klarade av att stå på ett ben i 30 s men 39 % av ACLᵣ och 50 % av ACLᵫ behövde sätta ner den andra foten. För de personer som klarade av att stå på ett ben i 30 s fanns det inga skillnader vad gäller förflyttning av tyngdpunkten.

Dessutom analyserades rörelsemönster under ett enbens-längdhopp via kinematiska variabler såsom knävinklar (flexion, abduktion, rotation) och placeringen av kroppstyngdpunkt (Center of Mass, CoM) i förhållande till
knä- och fotled. Oavsett behandling fanns det vissa skillnader i rörelsemönstret för skadat jämfört med icke-skadat ben. ACL₆ visade likande rörelsemönsler som kontroller, med undantag för en större utåtrotation i knäleden vid landningstillfället och mindre inåtrotation vid landning. ACL₇ visade flera skillnader jämfört med kontroller både vad gäller knävinklar och CoM, vilket tyder på kompensatoriska rörelsestrategier.

De korsbandsskadade med ingen-eller-lite röntgenologisk knäartros skattade bättre knäfunktion med högre poäng på Lysholm score and KOOS delskala symptom i jämförelse med de med moderat-till-hög grad av knäartros. Däremot verkar inte grad av knäartros påverka aktivitetsnivå, hopp kapacitet, styrka eller rörelsemönster.

Sammanfattningsvis visar denna avhandling att personer med en främre-korsbandsskada, oavsett behandling, har vid jämförelse med kontroller negativa långtidskonsekvenser vad gäller själv rapporterad knäfunktion, knäspecifik aktivitetsnivå, styrka och balans. Korsbandsskadade verkar däremot prestera bra vid test av hoppkapacitet och har en god allmän aktivitetsnivå medan de har en sämre prestation i mer knä-belastande aktiviteter. Vad gäller jämförelser med kontroller verkar ACL₆ ha liknade rörelsemönsler med undantag för rotationer i knäleden. Detta indikerar att korsbands-rekonstruktion till viss del återställer knäledens biomekanik. ACL₇ visade flera skillnader i rörelsemönster jämfört med kontroller vilket tyder på att de använder sig av kompensatoriska rörelsestrategier.
Abbreviations

ACL  Anterior Cruciate Ligament
ACL<sub>R</sub>  ACL-injured treated with physiotherapy in combination with surgery
ACL<sub>PT</sub>  ACL-injured treated with physiotherapy alone.
ACL<sub>TPP</sub>  In paper III this group is equivalent with ACL<sub>PT</sub>
ADL  Activity in Daily Living
BMI  Body mass index
BPTB  Bone-patellar-tendon-bone
CoM  Centre of mass
CoP-path  The total distance of CoP path
CoP-x  Standard deviations of CoP in the medio-lateral direction
CoP-y  Standard deviations of CoP in the anterio-posterior direction
H:Q ratio  Ratio between strength in Hamstrings and Quadriceps
Hc:Qc  H:Q ratio calculated on concentric contractions
He:Qc  H:Q ratio calculated on eccentric hamstrings and concentric quadriceps strength
ICF  International Classification of Functioning, Disability and Health
IKDC  International Knee Documentation Committee
IPAQ  International Physical Activity Questionnaire
Kinematics  The study of the position, velocity, and acceleration of bodies through space without regard to the forces that might be causing that movement
Kinetics  The study of movements and forces that causes them as well, because it is the dynamics in biomechanical systems
K & L  Radiological OA according to Kellgren & Lawrence
KOOS  Knee injury and Osteoarthritis Outcome Score
LSI  Limb Symmetry Index
na  Not available
NS  No significance
OLH  One-leg hop
OA  Osteoarthritis
ROM  Range of motion
SD  Standard deviation
TSK  Tampa Scale for Kinesiophobia
Sport/rec  Knee function in sport and recreation
QOL  Knee-related quality of life
Original papers

This thesis is based on the following papers, referred to in the text by their Roman numerals I – IV


IV  Tengman, E., Grip, H., Stensdotter, AK., Häger, CK. One-leg hop more than 20 years after ACL injury: kinematic analysis of persons treated with physiotherapy with or without surgery compared to healthy controls. (In manuscript)

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Introduction

Anterior Cruciate Ligament injury

Anterior cruciate ligament (ACL) injuries are a frequent injury to the knee joint and occur primarily in active young individuals involved in sports with pivoting movements (1-4). The ACL is an important structure in controlling knee joint laxity and a rupture leads to negative consequences for the knee function. The ACL consists of two bundles of fibres and restraints the tibia from anterior translation relative to the femur and limits excessive internal tibial rotation and thereby provides an anterior and rotational stability to the knee joint (5-7).

The incidence rate of ACL injuries in Sweden is 78 to 81 per 100,000 and year (3, 4) and about 75 % of all ACL-injuries occur in sports (3, 8). In 2012, soccer was the most common cause of ACL injuries for both females and males in Sweden, while the second most common activity was downhill skiing for females and floorball for males (1). About 70 % of ACL-injuries occurs in non-contact situations (8) when the athlete is landing from a jump, changing direction, in situations involving decelerations or side-cutting manoeuvres (8-11). Video analysis has shown that the injury often occurs when the knee is relatively straight and the tibia rotates inwards on the femur with an additional “valgus collapse” (8, 9, 11, 12).

Risk factors for sustaining an ACL injury are often dived into external and internal risk factors. External risk factors includes type of competition, footwear and surface, and environmental conditions (8). For example, the incidence rate of ACL injuries varies between different sports (8) and with a much higher incidence rate during a game than during practice (13-15). Internal risk factors includes, among others; gender (female), biomechanical factors, anatomical factors, hormonal factors, decreased neuromuscular coordination and prior ACL injury (8, 16, 17). Regarding gender, in a meta-analysis females shown to have about a 3 times higher incidence rate of ACL injuries in soccer compared to males (18). Biomechanical risk factors upon landing include; a high degree of valgus loading, less knee flexion, decreased control of the trunk, and Centre of Mass (CoM) placed outside the base of support (8, 17, 19-22). Also a low H:Q ratio (ratio between the strength of hamstrings and quadriceps) has been shown to be a risk factor for sustaining an ACL injury (23-25), indicating that a sufficient strength in both the quadriceps and hamstrings is important.

After an ACL injury, a major problem is the sudden loss of control of the knee joint in a weight bearing position (giving way episodes), referred to as functional instability. Other common symptoms include decreased strength, impaired functional performance, differences in movement and muscle activation patterns, proprioceptive deficiency and impaired postural control. In the first few years after injury the knee function regarding both self-
reported knee function and physical capacity seems to improve and the persons may function well (1, 26-30). However, despite rehabilitation, the majority of athletes who sustain an ACL injury do not successfully return to their pre-injury sport level and therefore quit their sports (2, 31-33). Also, in an even longer perspective of 5 years post injury, an RCT study by Frobell et al. (2013) showed that only 6-13 % of the ACL-injured individuals were active at pre-injury level, regardless of treatment (34). Fear of re-injury has been reported as a major cause for failure in returning to sport (32, 33, 35, 36) and McCullough et al showed that among persons not returning to sport, about 50 % cited that fear of re-injury or further damage was a main reason (37). Kvist et al. showed that the persons with an ACL-injury who did not return to the same level of activity as before injury, suffered from greater fear of movement/re-injury, which also had a negative impact on their knee-related quality of life (33). The level of fear of movement/re-injury seems however to decrease during ACL rehabilitation up to one year (38).

**Treatment**

ACL injuries are treated either with physiotherapy in combination with ACL reconstructive surgery, or with physiotherapy alone. To date, there is still controversy regarding the best treatment after ACL injury and there is insufficient evidence for which treatment, if any, that is superior in a long-term perspective (34, 39, 40). The goal of ACL rehabilitation is to reach the best functional level for the patient and to restore knee function to the same level as the non-injured leg.

Both surgery techniques and physiotherapy treatment have advanced since the mid-80’s. At that time, ACL reconstruction surgeries were often carried out with patellar tendon graft, single-bundle grafts and sometimes with a synthetic polypropylene braid (41) and with different techniques (42, 43). The surgical techniques have developed to only arthroscopic surgery and the use of double-bundled grafts (44, 45). In Sweden, 3410 reconstructive surgeries and 243 revisions were carried out in 2012. Both patellar and hamstring grafts were used but with a predominance of hamstrings grafts (1).

The physiotherapy treatment after an injury usually includes training of joint mobility, muscle strength, functional performance, and neuromuscular control (46-49), regardless of combination with surgery or not. The post-operative and conservative physiotherapy has also changed over the years to a more aggressive rehabilitation with earlier and strenuous training, shorter time unloading the knee, regaining full mobility sooner, and earlier return to sport (48-50). Regarding strength training, recent studies show that the use of both closed kinetic chain exercises and open kinetic chain exercises for the quadriceps muscle should be used in the rehabilitation programme (51, 52) and that eccentric training has shown greater improvements in strength and hop-performance than a rehabilitation program without eccentric training (53). Training of a movement pattern with a “knee over the foot” strategy (8, 22, 54) and proper landing techniques e.g. landing softly on the forefoot and
with larger knee flexion (8), is also recommended to be included in rehabilitation.

**Long-term consequences of an ACL injury**

The present thesis will focus on the long-term consequences after an ACL injury. In this context, long-term is referred to as 15 years or more after an ACL injury. A literature overview presented in Table 1 focuses on long-term results after treatment with reconstructive surgery (patellar graft) and treatment without surgery. The existing follow-ups report outcomes mainly from one treatment group and only a handful of studies report outcomes after both treatment with physiotherapy in combination with surgery and physiotherapy alone. The majority of studies present self-reported knee function and degree of radiological knee OA, while fewer studies report outcomes of functional performance tests. One-legged hop for distance (OLH) has been reported in about a third of the long-term follow-ups. To our knowledge only one study has assessed strength (55) and just one study reports outcomes for two jump tasks (56). There are only four follow-ups 20 years after injury, that we are aware of, (57-60) and none of those studies have evaluated physical capacity directly in terms of assessing, for instance, jump capacity or knee muscle strength.

**Self-reported knee function, physical activity level and fear of movement/re-injury**

In the present thesis, self-reported knee function is defined as outcomes of knee-specific scores such as Lysolm score and the Knee injury and Osteoarthritis Outcome Score (KOOS). The majority of the long-term perspective studies, indicate a quite good self-reported knee function (Lysolm score and KOOS, see Table 1). This applies both to ACL-injured treated with surgery (56-58, 60-66) as well as for those treated with physiotherapy alone (55, 58, 61, 62, 67). Regarding KOOS, the two subscales; sport/recreation and knee-related quality of life, seem to be most affected. This applies both for ACL-injured treated with surgery (56, 61, 62, 68-70) as well as for those treated with physiotherapy alone (55, 61, 62, 70). Knowledge about self-reported knee function beyond 20 years is however lacking since none of these studies have presented data on KOOS and only a few studies present Lysolm score (57, 58, 60).

Regarding knee-specific physical activity level (measured by Tegner activity scale), the long-term studies (55-58, 61-65, 67, 71) indicate either normal or slightly reduced knee-specific activity level when compared to controls of same age (72, 73). A more general activity level has not been evaluated in the long-run. The presence and impact of fear of movement/re-injury in the long-term after injury has neither been described earlier.
**Physical capacity**

Physical capacity in the long term after an ACL injury has been described by jump capacity and strength. The impact on balance in the long-term perspective has not been investigated, even though negative effects on postural control and proprioception have been shown in the shorter perspective (46, 74-76). To our knowledge, there is no study describing jump capacity or strength 20 years after the injury. Six studies have evaluated jump capacity 15-16 years after injury (55, 56, 62, 63, 65, 66). These studies show quite good jump capacity, with only 8-35% of those ACL-injured treated with surgery (56, 63, 65, 66) and 15% of those treated with physiotherapy alone (55) having an unsatisfactory jump capacity with a limb symmetry index (LSI) less than 90%. Stensbirk et al. (2013) (56) tested two jump tasks showing mean LSI of 92% for OLH and LSI of 87% for cross-over hop. Only one long-term study has reported knee muscle strength showing good results with mean LSI of 96.5% for knee extension and 101% for knee flexion (55). All studies regarding physical capacity have compared the results between the injured and non-injured leg with LSI and none of these studies have compared the performance of ACL-injured to data from matched controls. Regarding the use of LSI, there may however be a bilateral decrease of function following a unilateral ACL injury (74, 76-78) which may lead to a falsely high LSI. This is a major weakness of using the LSI measurement alone without comparison to absolute norm values for a gender and age matched control group.

**Osteoarthritis**

It is well established that knee OA is a common long-term consequence of an ACL injury. The prevalence of radiological knee OA after an ACL injury has been described as both quite low and high (values ranges between 11% and 90%, see Table 1). It is comparable of that 11% of a control group (mean age 43 years) showing radiographic changes but none had joint space narrowing (72). Several studies show that the prevalence is equal for those treated with reconstruction surgery and physiotherapy alone (61, 71, 79, 80). A systematic review by Øiestad et al. 2009 (80) has suggested that ACL reconstruction as a single factor would not prevent the development of knee OA. An important risk factor for OA, in addition to the ACL injury, seems to be meniscectomy (62, 80-82).
Table 1. Literature overview of studies 15 years or more post ACL injury. The abbreviations is described in page 11.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Groups, No of patients and type of surgery</th>
<th>Yrs</th>
<th>Tegner activity scale</th>
<th>Lysholm score</th>
<th>KOOS</th>
<th>Functional tests</th>
<th>Other measurements</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ageberg et al. 2007 (55) (party same population as in Kostogiannis et al)</td>
<td>ACL-PT 67</td>
<td>15 yrs</td>
<td>Median 4 (2-5)</td>
<td>Mean 86 (17)</td>
<td>Mean Pain 91 Symptoms 88 ADL 95 SportRec 77 Qol 76</td>
<td>OLIH injured leg 158cm, non-injured leg 167 cm. Mean LSI 94.8%, 85% had a LSI ≥90%. Isokinetic strength LSI conc knee extension 96.5%, knee flexion 101.7%, 71%, resp. 79% had a LSI ≥90.</td>
<td>Isometric strength and total work.</td>
<td>Conservative treatment after an ACL injury can achieve good performance and strength over time.</td>
</tr>
<tr>
<td>Bourke et al. 2012 (83)</td>
<td>ACL-R 314 BPTB</td>
<td>17 yrs</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>IKDC, graft survival, meniscectomy, family history.</td>
<td>Mean IKDC score was 85. Graft survival was 97%.</td>
</tr>
<tr>
<td>Drogset et al. 2006 (64)</td>
<td>ACL-R=22 ACL-R=54 ACL-R=36 1 primary repair 2augmentation device 3 BPTB</td>
<td>16 yrs</td>
<td>Mean R1=6.1 R2=5.2 R3=5.6 NS</td>
<td>Mean R1=88 R2=85 R3=90 NS</td>
<td>na</td>
<td>na</td>
<td>Knee stability (Lachman, pivot and KT1000), OA (in 11%), revision rate, ROM.</td>
<td>The authors concludes that participants have a good knee function and low rate of OA.</td>
</tr>
<tr>
<td>Gerhard et al. 2013 (65)</td>
<td>ACL-R 63 Patellar tendon</td>
<td>16 yrs</td>
<td>Median 6 (2-10)</td>
<td>Mean 91 (13)</td>
<td>A total score 84 (19)</td>
<td>OLIH, 92% had a LSI &gt;90%</td>
<td>IKDC (24% had a abnormal score), SF36, VAS for pain, OA (54% suspected, 9% minimal, 16% moderate, 7% severe).</td>
<td>Authors concludes that ACL-R shows good to excellent long-term results.</td>
</tr>
<tr>
<td>Hui et al. 2011 (66)</td>
<td>ACL-R 72 Patellar tendon</td>
<td>15 yrs</td>
<td>na</td>
<td>Median 95 (39-100)</td>
<td>na</td>
<td>OLIH; 65% had a LSI &gt;90% and 35% had a LSI 76-89%.</td>
<td>IKDC (Median 91), ROM, knee stability (Lachman, pivot shift and KT1000), OA (65%).</td>
<td>Authors concludes good long-term results.</td>
</tr>
<tr>
<td>Kostogiannis et al. 2007 (67)</td>
<td>ACL-PT 67</td>
<td>15 yrs</td>
<td>Median 4 (1-7)</td>
<td>Mean 86 (17)</td>
<td>KOOS profile figure.</td>
<td>na</td>
<td>Meniscal inuries, IKDC (mean 83).</td>
<td>Authors concludes that ACL-PT has a good long-term knee function and an acceptable activity level.</td>
</tr>
</tbody>
</table>
Introduction

<table>
<thead>
<tr>
<th>Authors</th>
<th>Groups, No of patients and type of surgery</th>
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<th>Tegner activity scale</th>
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<th>Functional tests</th>
<th>Other measurements</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maletius &amp; Messner 1999 (57)</td>
<td>ACL-R 56</td>
<td>20 yrs</td>
<td>Median 5 (0-7)</td>
<td>Median 90 (35-100)</td>
<td>na</td>
<td>na</td>
<td>Rate of additional surgery, ROM, Knee stability (Ludhman, pivot and KT1000), OA (84% has slight to moderate OA), SF36.</td>
<td>The study show high prevalence of knee OA.</td>
</tr>
<tr>
<td>Meunier et al. 2007 (61)</td>
<td>ACL-R 32 ACL-PT 36</td>
<td>15 yrs</td>
<td>Median ACL-R 6 ACL-PT 6 NS</td>
<td>Mean ACL-R 95 ACL-PT 90 p=0.0694</td>
<td>Mean ACL-R/C Pain 89/88 Symptoms 82/85 ADL 93/91 Sport/Rec 70/71 QoL 69/64 NS</td>
<td>na</td>
<td>Meniscus injuries, ROM, Knee stability (KT1000), OA (58% in ACL-R and 52% in ACL-PT had grade I)</td>
<td>A RCT study! ACL-R had a slightly higher Lysholm, less meniscus injuries and more stable knees. Besides that no differences between groups. One-third of the ACL-PT had a later surgery due to instability.</td>
</tr>
<tr>
<td>Mihelic et. al 2011 (58)</td>
<td>ACL-PT 18 ACL-R 33 BPTB</td>
<td>17-20 yrs</td>
<td>Median ACL-PT 4 (2-6) ACL-R 5 (2-9) p&lt;0.05</td>
<td>Median ACL-PT 53 ACL-R 84 p&lt;0.05</td>
<td>na</td>
<td>na</td>
<td>Knee stability, higher OA for ACL-PT, IKDC (ACL-PT=64, ACL-R=63)</td>
<td>The ACL-R had more stable knee, lower OA and better Lysholm/Tegner/IKDC compared to ACL-PT</td>
</tr>
<tr>
<td>Nebelung et al. 2005 (59)</td>
<td>ACL-PT 17</td>
<td>35 yrs</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>OA, meniscal and cartilage damage, total knee replacement (10 of 19 cases).</td>
<td>The study is on Olympic athletes. The injury lead to 95% cases of meniscal and cartilage damage, progressive OA and more than 50% risk of total joint replacement.</td>
</tr>
<tr>
<td>Neuman et al. 2008, 2009 (62, 84)</td>
<td>ACL-PT 72 (ACL-R 22 BPTB in a later stage)</td>
<td>15 yrs</td>
<td>Median All 4 ACL-PT 3.7</td>
<td>Mean ACL-PT 86 ACL-R 82</td>
<td>For all 94 patients Pain 90 Symptoms 88</td>
<td>OLH: Average distance on the injured leg was 145 cm.</td>
<td>Meniscal injuries, IKDC, OA (both tibiofemoral and patellofemoral), risk for meniscectomy, ROM, WOMAC. 68% had non-symptomatic knee. The primary risk factor for OA was if a meniscectomy had been performed. The prevalence of PF OA was relatively low.</td>
<td></td>
</tr>
</tbody>
</table>
Introduction

<table>
<thead>
<tr>
<th>Study</th>
<th>Methodology</th>
<th>Follow-up</th>
<th>KOOS Profile</th>
<th>LSI</th>
<th>Knee Stability</th>
<th>Extension Deficits</th>
<th>Graft Failure Rate</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stensbirk et al 2013 (56)</td>
<td>ACL-R 24 BPTB (Also 25 operated with iliotibialis)</td>
<td>15 yrs</td>
<td>Median 5.5 (2-9)</td>
<td>Mean 86 (12)</td>
<td>A figure with a KOOS profile is reported.</td>
<td>OLH had a mean LSI of 92 (17%) and cross over hop for distance had a mean LSI of 67 (13%)</td>
<td>Knee stability, extension deficits, graft failure rate.</td>
<td>Concludes good results of non-surgery treatment.</td>
</tr>
<tr>
<td>Strand et al 2005 (60)</td>
<td>ACL-R 81 (Primary repair - marshall)</td>
<td>15-23 yrs</td>
<td>na</td>
<td>Median 88 (16-100)</td>
<td>na</td>
<td>na</td>
<td>IKDC, Knee stability (KT1000), OA</td>
<td>The main aim was a comparison between BPTB and ITB reconstructed showing no differences between groups.</td>
</tr>
<tr>
<td>Streich et. al 2010 (71)</td>
<td>ACL-PT 40 ACL-R 40 BPTB</td>
<td>15 yrs</td>
<td>Mean ACL-PT 5.1 (1.9) ACL-R 4.7 (1.8) NS</td>
<td>Mean ACL-PT 75.5 (16) ACL-R 68 (20) NS</td>
<td>na</td>
<td>na</td>
<td>Knee stability (KT1000), IKDC (ACL-PT 75.9, ACL-R 69.9), OA</td>
<td>No differences between groups regarding Lysholm IKDC and OA.</td>
</tr>
<tr>
<td>Widuchowski et al. 2012 (63)</td>
<td>ACL-R 52 BPTB</td>
<td>15 yrs</td>
<td>Mean 6.9 (1.4)</td>
<td>Mean 86 (5.6)</td>
<td>na</td>
<td>OLH; 83% had LSI&gt;90%</td>
<td>ROM, IKDC (80.2), knee stability (Lachman, pivot shift and Rolfmeter), OA (67% had OA)</td>
<td>According to IKDC 75% of the patients had normal or nearly normal knee function. No correlations between OA and Lysholm/Tegner/IKDC. Author concludes a good overall clinical outcome.</td>
</tr>
</tbody>
</table>
Introduction

**Movement pattern**

Even if a person with an ACL injury performs in parity with healthy controls in clinical functional test like jump length, it cannot be assumed that the movement pattern is similar between limbs or in comparison to controls. Analysis of movement patterns may encompass aspects like movement quality and compensatory movement strategies. As described earlier, an ACL injury often occurs when landing during a jump or in situations involving decelerations or side-cutting manoeuvres. Many movements are very fast and it is difficult, if not impossible to analyse in detail simply by clinical observation. Movement patterns are therefore often measured by kinematics in movement laboratories. Kinematic analyses are measured by three-dimensional (3D) movement systems and include, for example; position displacements and associated velocities and accelerations/decelerations, joint angles and related changes and calculation of centre of mass (CoM). Longitudinal kinematic studies show that movement patterns, mainly in females, with a kinematic combination of larger hip adduction, larger hip internal rotation, large knee abduction and less knee flexion are associated with a higher risk for an ACL injury (19, 20). A higher risk of an ACL injury is also observed when the CoM of the body is placed outside the base of support (8, 21).

After an ACL injury there might be altered and compensatory movement patterns. In the short-term perspective there are asymmetries in movement pattern in the injured leg both measured by kinematic and kinetics. A low demanding activity such as gait shows kinematic asymmetries (e.g. less knee flexion, increased knee rotation) in the injured leg (85-87). The asymmetric kinematic pattern in low load activities, regarding gait, is suggested to become normalized over time (88-92), while the kinetic pattern such as moments and ground reaction forces seems to remain altered (89, 91-93). Also, for high demanding activities such as different jump tasks, there are altered knee kinematics and kinetics (e.g. less knee flexion, larger knee external rotation, less knee extension moment) in the short-term (94-98). The long-term kinematic and kinetic consequences during high load activities are much less investigated and so far with contradictory results. One study indicates, for instance, less knee flexion and increased knee abduction in the injured knee during a diagonal jump landing task four years post injury (99), while other studies (7-16 years) have found no differences in kinematics during jump landing and gait (88, 100).

**Measuring knee function**

Many individuals who have suffered an ACL injury experience impaired knee function as a consequence, which may be reflected by many different aspects such as instability, pain, swelling, joint stiffness, fear of movement/re-injury, reduced physical capacity and reduced activity both in daily life but also in sports and recreation activities. Therefore, an overall knee function needs to
be evaluated combining several different features like clinical examination, self-reported function and functional testing. To describe and classify the different consequences after an ACL injury the International Classification of Functioning, Disability and Health (ICF) is suggested by the World Health Organization (WHO) as a common framework to describe health and functioning of an individual (101). ICF’s dimensions are; body structure/functions, activity and participation. In the present thesis the aim was to evaluate all three dimensions. Contextual factors (personal and environmental factors) may also be considered in ICF. Figure 1 gives an overview of the different parts of the present thesis and the relation between the different measurements used in the present thesis to ICF. During recent years, ICF core sets have been developed for a dozen diagnoses (e.g. Stroke, OA, and diabetes) as a framework and classification to define typical problems of functioning within the different diagnoses (102-104). There is, however, no developed core set for ACL injury.

**Figure 1.** Overview of the present thesis different parts classified according to ICF.

When evaluating consequences after an ACL injury, both diagnose-specific and more general scores may be used. Regarding knee function, the most commonly used and established scores in ACL rehabilitation are the Lysholm score, International Knee Documentation Committee (IKDC), the Knee injury and Osteoarthritis Outcome Score (KOOS) and Cincinnati Knee Rating System (105). All four scores measure knee-specific function. In the present thesis, Lysholm score and KOOS were used. Lysholm measures outcome both in body function/structure and in activity e.g. pain, swelling, and stair-walk.
KOOS is utilized to measure all dimensions with questions regarding aspects such as pain, ability to jump and performing heavy house work (106).

One of the most common ways to assess physical activity level after an ACL injury is by using the Tegner activity scale (105), a score which grades how demanding the activities are for the knee joint. Estimates of a more general physical activity level are less common in studies after ACL injury. In the present study we have used the Tegner activity scale as a measure of a more knee-specific activity level and IPAQ as a more general activity level. We have also measured fear of movement/re-injury by using the Tampa Scale for Kinesiophobia (TSK) and interpret it as mostly fear of re-injury as is often assumed in the case of ACL rehabilitation. Fear is classified as emotional function in the dimension body function/structure, but of course it can be discussed if it is a way of coping and more of a personal factor.

The present thesis also focuses on physical capacity in the long-term perspective and several outcomes were used. Jump tasks are often used to evaluate the physical capacity and the OLH for distance is the most commonly applied functional test in clinics and for research (107, 108). One reason is that OLH is part of the commonly used IKDC. The use of three different types of jumps has been considered more decisive for evaluation of functional performance (109, 110) and the recommendation is to use both maximum jumps (e.g. vertical jump and one-leg hop) and hop tests that challenge endurance (e.g. side hop, triple jump and stair hop) (110). The single-limb stance was also applied in this thesis as a test of physical capacity for balance. In contrast to jump and balance, which are classified in ICF’s domain activity, knee muscle strength tested by isokinetic is classified as body function. To quantify an appropriate muscle balance around the knee joint the Hamstrings to Quadriceps ratio (H:Q ratio) may be used. The H:Q ratio is a ratio between the maximal knee flexion and knee extension torque (111). The outcomes of functional tasks are commonly valued with the Limb Symmetry Index (LSI, side-to-side difference). A LSI of <90 %, i.e. more than 10 % difference between injured and non-injured leg, has been regarded as unsatisfactory in terms of both strength and hop performance (108, 112).

**Rationale for this thesis**

An ACL injury is a common injury to the knee especially in young active persons leading to negative consequences for knee function, physical activity and physical capacity in the short-term perspective. Nevertheless, in the first few years after injury, knee function seems to improve and the persons may function well although many persons do not return to pre-injury activity level. Much less is known about the consequences in the long-term and the existing studies show contradictory results. There is still also debate about which treatment that should be used and the possible consequences in the long term of choosing physiotherapy with or without surgery and who would benefit specifically by either alternative. There are only a couple follow-ups more than 20 years after ACL injury with inconsistent evidence of long-term
consequences after injury. None of these studies examine physical capacity and movement pattern, which was aimed for in the present thesis.

Self-reported knee function in sport/recreation activities and knee quality of life (KOOS subscales) seem to be negatively affected in the long term after an ACL injury. There are, however, only a few follow-up studies as late as 20 years after ACL injury. Knee-specific activity level in the long term also needs to be further explored. In addition, from a health perspective in the long run, it would seem important to investigate a more general activity level, which has not previously been evaluated. Fear of re-injury has been described as a negative factor for return to sports or pre-injury activity level. However, the presence and impact of fear of movement/re-injury in the long term has not been described previously. To our knowledge, there are no long-term follow-up studies investigating physical capacity more than 20 years post injury, and even studies after more than 15 years post injury are few. There is clearly a need for research of long-term consequences on physical capacity. Kinematic asymmetries between the injured and non-injured leg have been shown in the short-term, while the long-term kinematic consequences are much less investigated and so far with contradictory results. There is clearly a requirement for increased knowledge of kinematic patterns and asymmetries after an ACL injury.

Altogether, the lack of knowledge of the long-term consequences after ACL injury and for persons treated with physiotherapy in combination with surgery or without surgery, and in comparison to controls, provides an excellent rationale for the present work. Moreover, the thesis contributes to the discourse on how to best evaluate knee function after ACL injury.
Aims of the thesis

General:
The overall purpose of this thesis was to investigate self-reported knee function, physical activity level, fear of movement/re-injury, physical capacity and movement pattern in persons more than 20 years after unilateral ACL injury treated with physiotherapy in combination with surgery or physiotherapy alone, and in comparison to knee-healthy controls.

Specific aims were:
• To investigate self-reported knee function, knee-specific and general physical activity level and fear of movement/re-injury (study I).

• To determine physical capacity (jump capacity, knee muscle peak torque and single-limb stance) in ACL-injured individuals compared to age and gender matched controls (study I, II, III).

• To correlate knee muscle strength (peak torque) with self-reported knee function (study II).

• To examine the movement pattern (kinematic), when performing a one-leg hop in the injured and non-injured leg of ACL-injured individuals compared to controls (IV).

• To relate self-reported knee function, physical activity level, physical capacity and kinematics to the degree of radiological knee osteoarthritis (Study I, II and IV).
Methods

Overview of the papers
This thesis and its four papers are based on a cross-sectional study on average 23 years after an ACL injury. The follow-up is a larger project with two parts; one part focusing on knee OA and orthopaedic parameters, and a part with functional performance tests. This thesis is based on the functional performance tests which took place at the movement laboratory UMotion lab at the Department of Community Medicine and Rehabilitation, Umeå University. Table 2 presents an overview of the four papers.

<table>
<thead>
<tr>
<th>Table 2. Overview over the four papers.</th>
<th>Paper I</th>
<th>Paper II</th>
<th>Paper III</th>
<th>Paper IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Participants (n)</td>
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<td>ACLa</td>
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<td>28*</td>
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</tr>
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<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
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<tr>
<td>OA</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Knee laxity</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Self-reported knee function, physical activity and fear of movement/re-injury</td>
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<tr>
<td>Tegner</td>
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<td>X</td>
<td>X</td>
<td></td>
</tr>
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<td>IPAQ</td>
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<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Lysholm</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>KOOS</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>TSK</td>
<td>X</td>
<td></td>
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<tr>
<td>Physical capacity</td>
<td></td>
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<tr>
<td>One-leg hop</td>
<td>X</td>
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<td></td>
<td>X</td>
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<tr>
<td>Vertical jump</td>
<td>X</td>
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<tr>
<td>Side hop</td>
<td>X</td>
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<td></td>
<td></td>
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<tr>
<td>Peak torque</td>
<td>X</td>
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<td></td>
<td>X</td>
</tr>
<tr>
<td>Single-limb stance</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Movement pattern</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Kinematics</td>
<td></td>
<td></td>
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</tbody>
</table>

*In this paper equivalent with ACLopp

Participants

Study sample
The 70 participants with an ACL injury, assessed in this thesis, are a part of a larger study consisting 113 persons with ACL injuries on average 23 years ago dived into two cohorts. The cohorts were treated at two separate hospitals in two different geographical regions of Northern Sweden (Västerbotten and Norrbotten). The cohort treated with physiotherapy in combination with reconstructive surgery comes from Västerbotten and the cohort treated with physiotherapy alone comes from Norrbotten.
Methods

Orthopaedic and radiology assessment 23 years post injury

- **ACL<sub>R</sub>**
  - n=62
  - Excluded due to; bilateral injuries, prosthesis, disease, n=20
- **ACL<sub>PT</sub>**
  - n=51
  - Excluded due to; bilateral injuries, disease, n=12

Functional performance tests

- **ACL<sub>R</sub>**
  - n=42
  - Declined n=9
- **ACL<sub>PT</sub>**
  - n=37
  - Declined n=2
- Controls
  - n=33

**Figure 2.** Flow chart of the two cohorts; ACL-injured treated with physiotherapy in combination with reconstructive surgery (ACL<sub>R</sub>) and ACL-injured treated with physiotherapy alone (ACL<sub>PT</sub>).

The exclusion criteria for the part with functional performance tests were: bilateral ACL injury, inflammatory or rheumatic disease or neurological pathology, re-injury to the ACL. From the orthopaedic/radiology part 32 participants were excluded. Further, 11 participants declined to participate in the functional performance test (Fig. 2). There were no significant differences in background variables between those eleven individuals who declined to participate compared to those who participated in the functional performance tests (see Appendix). 70 participants were included; 33 patients had been treated with physiotherapy in combination with ACL reconstruction (ACL<sub>R</sub>) and 37 patients had been treated with physiotherapy without surgery (ACL<sub>PT</sub>). An age-and-gender matched group of 33 non-injured healthy controls was also tested. Demographic data for the three groups are shown in Table 3. The control group had a lower weight compared to ACL<sub>PT</sub> and lower body mass index (BMI) compared to both ACL groups. In both ACL groups more than 90% of the patients displayed some form of radiological knee OA at the time of investigation, varying from Kellgren & Lawrence (113) stage 1 to 4. A more detailed description of OA will be described elsewhere (Brax Olofsson et al. in manuscript). OA was categorised to no-or-low OA (Kellgren & Lawrence 0-1) and moderate-to-high (Kellgren & Lawrence 2-4) respectively. For the injured leg, 7 persons in ACL<sub>R</sub> and 12 in ACL<sub>PT</sub> had no-or-low OA while 26 in ACL<sub>R</sub> and 25 in ACL<sub>PT</sub> had moderate-to-high OA. Paper III (single-limb stance) is based on a subsample consisting of 28 participants in ACL<sub>R</sub> (18 male, 44.7±4.4 yrs, 23.6±3.5 yrs since injury, BMI 27.1±3.3), 28 participants in ACL<sub>PT</sub> (18 male, 47.0±5.0 yrs, 22.4±1.2 yrs since injury, BMI 28.8±4.4) and 18 controls (12 male, 46.2±4.8 yrs, BMI 25.1±2.7)
Table 3. Participants’ characteristics of the three groups. Number and means [SD] are presented.

<table>
<thead>
<tr>
<th></th>
<th>Group</th>
<th>ACLa-</th>
<th>ACLEF -</th>
<th>ACLa-</th>
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<tr>
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<td>Controls</td>
<td>ACLa-</td>
<td>Controls</td>
</tr>
<tr>
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<td>33</td>
<td>37</td>
<td>33</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Male / female</td>
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<td>23 / 14</td>
<td>21 / 12</td>
<td>NS</td>
<td>NS</td>
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<tr>
<td>Height (cm)</td>
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<td>173.5 [8.0]</td>
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<td>NS</td>
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<td>Weight (kg)</td>
<td>83.0 [15.6]</td>
<td>87.1 [14.9]</td>
<td>77.4 [14.9]</td>
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<tr>
<td>BMI (kg / m²)</td>
<td>27.2 [3.3]</td>
<td>28.9 [4.6]</td>
<td>24.6 [2.5]</td>
<td>p=0.014</td>
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<td>Years since injury</td>
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<td>Years between surgery</td>
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<td>Injury side (%)</td>
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</table>

ANOVA’s with Bonferoni post-hoc test and independent t-test.

Treatment in the ACLa group

The participants in the ACLa group were injured in the period 1981-1993 and treated with ACL reconstructive surgery followed by physiotherapy between the years 1987-1993. The participants were operated upon with different surgical methods that were conventional during this time period. Nineteen participants received reconstructive surgery with a patellar tendon quadriceps autograft augmented with a synthetic polypropylene braid to shield the autograft during the first remodelling period (Kennedy LAD) (41). The LAD polypropylene braid was wrapped and covered by the biological autograft and placed over the top, as described by Marshall et al. (114). Nine participants received a graft placed through a femoral tunnel (42) using an aiming device (42). Finally, five participants who were surgically treated during the 1990’s received a bone-patellar tendon-bone autograft (116, 117). The postoperative intervention consisted of physiotherapy with activity modification and functional exercises according to a progressive design. During the first 14 weeks a knee brace was used 24 hours a day and thereafter only during daytime. Crutches were used to unload the knee during the first 6 weeks after surgery and weight bearing was progressively introduced during the following 3 weeks. Postoperative physiotherapy was performed with advancing levels of intensity and difficulty, and consisted of: regaining full range of motion, strength training, coordination exercises and balance training. Full return to sports activities was recommended no earlier than about 22 weeks after surgery in relevant cases.
Methods

Treatment in ACL\textsubscript{PT} group

Participants in ACL\textsubscript{PT} group were injured in the period 1983-1988. The rehabilitation was individually designed in close collaboration between the physiotherapist and the orthopaedic surgeon in charge. The treatment consisted of a tailored six goal-oriented programme involving activity modification (avoiding situations and movement that could cause give-way episodes) and progressively increased functional stability training. The physiotherapy was on one-to-one basis and with three sessions per week with the physiotherapist. The goal of the treatment was a minimum LSI of 90 % for strength and functional tests (118). The rehabilitation was regarded complete when the patient could perform the final step of exercises without instability, other symptoms and with good quality (119). The mean time to reach this level was 22 weeks (range 12–60 weeks). If the patients had reached the goal and the results in the functional test were considered normal, they were allowed to return to their sport. Return to high risk sports such as wrestling, soccer and floorball were generally advised against. Notice that in paper III this group is equivalent with ACL\textsubscript{TPP}.

Controls

Knee healthy controls without knee problems or other movement disorders were recruited through advertisement and convenience sampling via staff and acquaintances. The controls were matched to the ACL groups regarding age (maximum 3 years) and gender. The controls considered themselves to have healthy knees and a clinical examination was performed to exclude injury of the ACL, meniscus or other ligaments in the knees. Demographic data are shown in Table 3.

Test procedure

A number of questionnaires were filled in by the participants at home prior to the tests. Anamnesis and clinical examinations were then performed. Participants wore shorts, a training tank top and were barefoot. The test procedure started with a 6-minute warm-up on a bicycle ergometer at a moderate intensity (intensity of 11 on Borg Scale for ratings of perceived exertion (120)). Thereafter, the participants performed different functional tasks. Each task started on the non-injured leg for the ACL-injured and on the dominant leg for controls. The participants were asked which leg they preferred to use to kick a ball with and the leg chosen was considered to be the participants' dominant leg. Between each task there was a rest period of minimum 2 minutes or longer if so desired. After a longer break (15-30 minutes) with some coffee/fruit the test continued with isokinetic strength tests. The same physiotherapist (ET) tested all participants.
Methods

Assessment and data analysis

**Self-reported knee function, physical activity level and fear of movement/re-injury**

**Self-reported knee function**

The level of knee function was assessed (physician administered at the orthopaedic clinic) with the Lysholm questionnaire evaluating for instance; limp, support, pain, swelling, instability, locking, stair-walk, and squatting. (121). The score is reliable and valid (121, 122). Participants also rated their knee function on the Swedish version of the Knee injury and Osteoarthritis Outcome Score (KOOS) (123, 124). KOOS consists of 42 questions in 5 subscales, scored on a 0 to 100 (best) scale. The subscales are: pain, symptoms, function in activities of daily living (ADL), sports and recreation function (Sport/Rec), and knee-related quality of life (QOL). KOOS has shown to be a reliable and valid score (124, 125).

**Physical activity level**

Knee-specific activity level was assessed according to the Tegner activity scale (physician administered at the orthopaedic clinic). The scale is graded between 0 and 10; zero represents sick-leave due to the knee, and 10 represents practicing competitive sports on national or international level in sports that are demanding to the knee joint (121). The valid and reliable score provides a measure of knee-specific activity level (122). The short form of the International Physical Activity Questionnaire (IPAQ) was used for self-reported physical activity during the previous 7 days, with items for walking, moderate-intensity and vigorous-intensity activity. Computation of the total score requires summation of the duration (in minutes) and frequency (days) of the different activities. Each activity domain was weighted by its energy requirements defined in METs (Metabolic Equivalent of Task) to yield a score in MET-minutes/week. The amount of activity was classified into three categories: low, moderate or high physical activity level. IPAQ data was processed according to IPAQ’s guidelines; data cleaning and truncation of data (126).

**Fear of movement/re-injury**

The persons with an ACL injury assessed fear of movement/re-injury by the Swedish version of the Tampa Scale for Kinesiophobia (TSK) (127). The TSK consists of 17 items on a 4-point Likert scale with outcomes ranging from “Strongly disagree” to “Strongly agree.” A higher score indicating greater fear of movement/re-injury and the total score ranges from 17 to 68. The score is considered reliable for patients suffering from chronic low back pain (127). TSK has been used in studies of ACL patients (33, 38, 128) and is considered to be appropriate for an ACL injured population (129).
Physical capacity

Jump capacity

Paper I and IV are based on three jumps; One-leg hop for distance, vertical jump and side hop. These jumps have high test-retest reliability (ICC 0.93-0.97) and together these three jumps has a high test-retest reliability, sensitivity and accuracy, both for ACL-injured treated with or without surgery (109). **One-leg hop** for distance measures the maximal jump distance (108). The participants were instructed to stand on one leg in an upright position, arms crossed over the chest, and then hop forward as far as possible (without moving arms), land on the same leg, and maintain their balance. The test was performed until three jumps were approved on each leg. The hop distance was calculated by measuring the movement of the foot marker placed on the lateral malleolus from take-off to landing. The longest jump achieved by each leg was selected for analysis both regarding jump capacity and movement pattern. Good reliability and validity has been shown for the one-leg hop (130, 131). **Vertical jump** is a one leg jump that measures the maximal jump height. The participants were instructed to hold their arms crossed over the chest and jump upwards as high as possible. Upon landing the participants were instructed to keep their balance. The test was performed until three jumps were approved on each leg. The jump height was calculated by the distance of movement of CoM between normal standing and at the highest point of the vertical jump. The highest jump achieved by each leg was selected for analysis. **Side hop** is an one-leg jump where the subject is jumping side-to-side as many times as possible during a period of 30 s. Participants were instructed to stand on one leg with arms crossed over the chest then hop from side-to-side between two marked lines on the floor placed 40 cm apart. Numbers of hops were counted; any hops landing on the line, or on the inside of the area defined by the lines were not approved (109). The side hop was only performed once per leg. Individuals usually put their hands behind their back in these jump tests but in the present study the participants held their arms across their chest. The reason for this modification was to enable kinematic recording of markers placed on the pelvis.

Peak torque

Study II is based on knee muscle strength. Peak torque of concentric and eccentric knee flexion and extension was tested with a Kin-Com® dynamometer at 90°/s (Kinetic communicator 125 Auto Positioning, The Chattanooga group inc.). Isokinetic torque can be tested in different velocities; for this study 90°/s was chosen on the basis that the participants in ACL-R had previously been tested at this velocity (unpublished data). Participants were seated in the dynamometer with hips at 90° flexion, with arms resting on the lap and stabilisation straps applied across the chest, pelvis, and thighs. The seat of the chair was to accommodate the length of the femur and for the lever arm to align the axis of rotation of the dynamometer with the anatomical axis of rotation of the knee joint (lateral femoral condyle). A cuff was attached proximal to the malleolus. Depending on hamstring
Methods

tightness the range of motion was set from 0°-20° to 90° of knee flexion. Trial sessions with submaximal contractions were performed for familiarisation with the equipment. One set of 6 maximum repetitions was performed for each exercise starting with knee extension followed by knee flexion after a period of rest. The test was started with a concentric contraction followed by an eccentric contraction with about 6 seconds rest in between. Verbal encouragement was provided to facilitate maximal efforts. Raw data from isokinetic strength tests were exported from the Kin Com® to a software program MrD View (custom made, Dept of Biomedical Engineering and Informatics, Norrland’s university hospital, Sweden). To eliminate inertial effects close to the acceleration (start) and deceleration (end) of the movement, torque values for the initial and final 4° of ROM were excluded from the analyses (132, 133). The repetition that achieved the highest peak torque (normalised to body weight: Nm/kg) was used in the statistical analyses. H:Q ratios were also calculated for concentric knee flexion and knee extension peak torque (Hc:Qc) and for eccentric knee flexion and concentric knee extension peak torque (He:Qc) (111, 134). Isokinetic measurements for knee muscles strength has a high to very high reliability (132, 135-137) and validity (132). The KinCom dynamometer system reliability has been shown to be “very high” (ICC >0.95) for the functions of lever arm position, velocity and force measurement (138, 139). An isokinetic test protocol similar to ours has shown high reliability (140).

Single-limb stance

Study III is based on a single-limb stance test. The participants stood on one leg in the middle of a force platform (described below) for 30 s. The test was performed once per leg. The participants were instructed to stand an upright position with the arms crossed over the chest, looking forward and the uplifted foot was held apart from the stance leg. There were no further restrictions for leg positions. Moving the arms or putting the other foot down was counted as a failure and the numbers of failures (floor-supports) were counted and verified with video. CoP measurements were collected with a force-plate (custom made, Dept of Biomedical Engineering and Informatics, Norrland’s university hospital, Sweden). Force data were sampled with 1200 Hz and time synchronized with the motion analysis system (described below). Regarding CoP, 26 seconds of the trial were analysed because the first 2 and last 2 seconds were cut to avoid noise from initiation and ending of the single-limb stance. Outcome variables were 1) CoP path (m) expressed as the migration of CoP for the total distance travelled during a trial calculated as the cumulative sum of partial distances 2) Standard deviations of CoP (m) in the medio-lateral (CoP-x) and 3) In the antero-posterior (CoP-y) directions. Shorter path and smaller standard deviations indicates better performance.
Methods

**Movement pattern**

*Data acquisition*

Movements during one-leg hop were registered using a motion capture system (Oqus®, Qualisys Medical AB, Gothenborg, Sweden), consisting of eight cameras with a capture rate of 240 Hz. Infrared light was reflected from 42 passive reflective spherical markers (diameter of 12 and 19 mm) attached to the body on defined anatomical landmarks and 3-marker clusters were placed on thighs and shanks (see Figure at the left). Eight markers were removed after a stationary registration: trochanters, lateral/medial epicondyles, and medial malleoli.

*Data analyses*

The software Qualisys Track Manager (Qualisys Medical AB, Gothenborg, version 2.2) was used for capturing, construction of 3D marker coordinates, and for interpolation and identification of markers. The data was then exported to Visual3D software (Visual3D v.4.96, C-Motion Inc. USA) for further analysis. Data was low-pass filtered (Butterworth 6Hz) before further calculations. An eight-segment rigid body model consisting of feet, shanks, thighs, pelvis, and trunk was constructed, and joint centre calculations were based on a 6-DOF model (141). CoM was calculated based on this model and with an approximation of head and arms. The OLH was divided into three phases; 1) Take-off phase: 0.7 s before the foot was lifted from the force plate, 2) flight phase: between take-off and initial contact when the foot first touched the ground after the hop, and 3) Landing phase between initial contact and 0.7 s after. Outcome variables for the knee joint were flexion/extension, abduction/adduction and internal/external rotation. Maximum angles and range of motion (ROM) were derived for the Take-off and Landing phases and absolute angle at Initial contact. CoM in relation to knee and ankle joints in the medio-lateral direction in form of maximal values and range were also derived at these phases.

**Knee OA and knee joint laxity**

The radiological examination was carried out at the radiological department of Norrland’s university hospital. Knee OA was classified according to Kellgren & Lawrence (113). Knee joint anterior laxity was measured with an arthrometer KT1000 (Medmetric Corporation, San Diego, Ca, USA) at an anterior pull force of 30 pounds.
Methods

Ethics
All participants were presented with written and oral information about the study and gave their written informed consent according to the declaration of Helsinki. The project was approved by the Regional Ethical Review Board in Umeå, Sweden (dnr 07-115M and dnr 08-211M). Radiological examinations were not performed on the controls since that was not considered ethical.

Statistics
The Statistical Package for the Social Sciences (IBM SPSS Statistics) was used to analyse data. The level of significance was set at p<0.05. For demographic data, means, SD were calculated to characterize the study population. Lysholm score, KOOS and TSK were presented in mean (SD) and differences in group means were analysed with parametric statistics. IPAQ and Tegner were reported in median (range) and were analysed with non-parametric statistics. KOOS data was missing for one participant in each ACL group, and one participant in ACLR had a missing TSK-score. Eleven IPAQ questionnaires (4 ACLR, 5 ACLPT, 2 controls) were excluded because of insufficient or "don’t know" responses. When comparing ACL-injured with no-or-low knee OA to those with moderate-to-high independent t-tests were used for Lysholm and KOOS while Mann-Whitney U tests were used for Tegner and IPAQ.

Regarding physical capacity, the Limb Symmetry Index (LSI) was calculated by dividing the result for the injured leg by that of the non-injured leg (for the controls non-dominant by dominant leg) and multiplying by 100. Independent t-tests were used to compared jump capacity and peak torque between ACL-injured and controls. Chi-square tests were used for group comparison of number of floor supports in single-limb stance. For the participants without floor-supports (17 in ACLR, 14 in ACLPT, and all 18 controls), MANCOVA was used to analyse the differences between groups for the CoP-measures; CoP-path, CoP-x and CoP-y, with gender, BMI and age as covariates. Pairwise post-hoc Bonferroni corrected comparisons were made between groups.

For within-group comparisons of jump capacity, strength and kinematic, linear mixed models were used. Mix model is often used when data is hierarchical, e.g. when some variables are clustered or nested within other variables. Hierarchical data structures can be used in data as being nested within subjects (142). Outcome variables were distance in m (one-leg hop), jump height in cm (vertical jump), number of jumps (side hop), peak torque in Nm/kg, Hc:Qc, He:Qc and for the kinematics in degree and cm. Fixed factors considered in the models were leg (injured and non-injured), gender (men and women), knee OA (no-or-low OA, Kellgren & Lawrence 0-1 and moderate-to-high OA, 2-4). For the controls, leg dominance (dominant and non-dominant) and gender (men and women) were considered as fixed factors. Both legs were included in the analysis. All factors and two-way
Methods

Interactions were included in the first model. All non-significant interactions and factors were then successively removed to create a final model. “Participant” was included in the model as a random effect. For the CoP variables, comparisons between the injured and non-injured leg were performed with paired T-tests. Regarding the kinematic variables, due to hidden markers there were some missing data.

In paper I and II, Spearman’s rho correlation coefficient were used for correlations. In paper III, Pearsons were used when correlated CoP with gender, age, BMI, Tegner activity scale, Lysholm score, KOOS and with knee joint laxity.

A power analysis on data from a pilot study (5 ACL-injured and 5 controls) showed that 32 persons per group was needed for a power of 80 % to detect a significant difference in knee joint angle between groups (variance 10˚, alpha 0.05).
Results

Self-reported knee function, physical activity level and fear of movement/re-injury

Both ACL groups showed a lower self-reported knee function (Lysholm score and KOOS) compared to the controls (Table 4). All three groups showed similar general physical activity level (IPAQ) while both ACL groups had a lower knee-specific physical activity level according to the Tegner activity scale compared to controls (Table 4). Regarding fear of movement/re-injury, the ACL_R had a total score of 33 while ACL_PT scored 32 out of a maximum 68 on the TSK (Table 4). TSK was negatively correlated to KOOS-symptom (p=0.004, r=-0.297), Lysholm score (p=0.004, r=-0.344) and LSI of side hop (p=0.016, r=-0.298). The ACL-injured with no-or-low OA (K&L grade 0-1) had higher Lysholm and KOOS-symptom scores compared to those with moderate-to-high OA (K&L grade 2-4), while degree of OA had no influence on reported physical activity level or any of the other subscales of the KOOS.

Table 4. Self-reported knee function and fear-of-movement (mean and [SD]) and physical activity (median [range]) are presented. Comparison between ACL-injured participants and controls are reported.

<table>
<thead>
<tr>
<th></th>
<th>ACL_R n=33</th>
<th>ACL_PT n=37</th>
<th>Controls n=33</th>
<th>ACL_R - Controls</th>
<th>ACL_PT - Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lysholm</td>
<td>78 [18]</td>
<td>69 [17]</td>
<td>100</td>
<td>p&lt;0.001</td>
<td>p&lt;0.001</td>
</tr>
<tr>
<td>KOOS Pain</td>
<td>78 [18]</td>
<td>85 [16]</td>
<td>99 [1]</td>
<td>p&lt;0.001</td>
<td>p&lt;0.001</td>
</tr>
<tr>
<td>KOOS Symptoms</td>
<td>79 [20]</td>
<td>72 [19]</td>
<td>98 [2]</td>
<td>p&lt;0.001</td>
<td>p&lt;0.001</td>
</tr>
<tr>
<td>ADL</td>
<td>84 [16]</td>
<td>90 [15]</td>
<td>100</td>
<td>p&lt;0.001</td>
<td>p&lt;0.001</td>
</tr>
<tr>
<td>Sport/Rec</td>
<td>50 [28]</td>
<td>67 [29]</td>
<td>99 [2]</td>
<td>p&lt;0.001</td>
<td>p&lt;0.001</td>
</tr>
<tr>
<td>QoL</td>
<td>49 [22]</td>
<td>61 [25]</td>
<td>98 [3]</td>
<td>p&lt;0.001</td>
<td>p&lt;0.001</td>
</tr>
<tr>
<td>TSK</td>
<td>33 [7]</td>
<td>32 [7]</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Median(range)

| Tegner | 4 [3-7] | 4 [2-7] | 6 [3-7] | p=0.001 | p<0.001 |
| IPAD totala | 1593 | 1217 | 1893 | NS | NS |
| [480-7572] | [212-7398] | [499-8958] | NS | NS |

Independent t-test for knee function and Mann-Whitney U test for physical activity.

a=ACL_R n=32, ACL_PT n=37
b=ACL_R n=29, ACL_PT n=32, Controls n=31

Physical capacity

Comparison to controls (Table 5):

All participants could perform the one-leg hop and vertical jump. For the side hops, six ACL-injured (1 ACL_R and 5 ACL_PT) could not perform even one approved side hop on the injured leg and two of them also failed on the non-injured leg.
<table>
<thead>
<tr>
<th>Table 5. Physical capacity for both legs as well as Limb symmetry index (LSI) are presented in mean [SD]. Comparisons to controls are reported.</th>
<th>Group</th>
<th>Comparisons</th>
<th>ACLn</th>
<th>ACLn Controls</th>
<th>ACLn Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(n=33)</td>
<td>(n=37)</td>
<td>(n=33)</td>
</tr>
<tr>
<td><strong>One-leg hop, hop length (m)</strong></td>
<td>Injured leg</td>
<td>1.12 [0.27]</td>
<td>1.01 [0.28]</td>
<td>1.08 [0.22]</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>Non-injured leg</td>
<td>1.19 [0.26]</td>
<td>1.10 [0.29]</td>
<td>1.07 [0.24]</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Vertical jump, jump height (cm)</strong></td>
<td>Injured leg</td>
<td>20.2 [0.7]</td>
<td>17.8 [0.8]</td>
<td>20.6 [0.7]</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>Non-injured leg</td>
<td>21.6 [0.7]</td>
<td>20.9 [0.8]</td>
<td>21.5 [0.7]</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Side hop (number)</strong></td>
<td>Injured leg</td>
<td>13.6 [1.5]</td>
<td>9.4 [1.4]</td>
<td>17.9 [1.3]</td>
<td>p=0.029</td>
</tr>
<tr>
<td></td>
<td>Non-injured leg</td>
<td>16.0 [1.5]</td>
<td>13.3 [1.4]</td>
<td>19.2 [1.3]</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Concentric knee extension peak torque (Nm/kg)</strong></td>
<td>Injured leg</td>
<td>1.83 [0.37]</td>
<td>1.76 [0.42]</td>
<td>2.07 [0.35]</td>
<td>p=0.010</td>
</tr>
<tr>
<td></td>
<td>Non-injured leg</td>
<td>2.09 [0.37]</td>
<td>1.89 [0.42]</td>
<td>2.10 [0.38]</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>LSI (%)</td>
<td>88 [12]</td>
<td>91 [14]</td>
<td>100 [16]</td>
<td>p=0.004</td>
</tr>
<tr>
<td><strong>Eccentric knee extension peak torque (Nm/kg)</strong></td>
<td>Injured leg</td>
<td>2.57 [0.65]</td>
<td>2.40 [0.62]</td>
<td>2.90 [0.63]</td>
<td>p=0.041</td>
</tr>
<tr>
<td></td>
<td>Non-injured leg</td>
<td>2.97 [0.66]</td>
<td>2.72 [0.54]</td>
<td>3.01 [0.67]</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Concentric knee flexion peak torque (Nm/kg)</strong></td>
<td>Injured leg</td>
<td>1.41 [0.44]</td>
<td>1.22 [0.31]</td>
<td>1.39 [0.26]</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>Non-injured leg</td>
<td>1.12 [0.23]</td>
<td>1.11 [0.29]</td>
<td>1.18 [0.30]</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Eccentric knee flexion peak torque (Nm/kg)</strong></td>
<td>Injured leg</td>
<td>1.46 [0.34]</td>
<td>1.36 [0.33]</td>
<td>1.44 [0.31]</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>Non-injured leg</td>
<td>1.10 [0.21]</td>
<td>0.98 [0.17]</td>
<td>0.99 [0.17]</td>
<td>NS</td>
</tr>
<tr>
<td><strong>He:Qc</strong></td>
<td>Injured leg</td>
<td>0.63 [0.12]</td>
<td>0.63 [0.13]</td>
<td>0.56 [0.10]</td>
<td>p=0.022</td>
</tr>
<tr>
<td></td>
<td>Non-injured leg</td>
<td>0.54 [0.09]</td>
<td>0.59 [0.13]</td>
<td>0.59 [0.12]</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>LSI (%)</td>
<td>118 [53]</td>
<td>108 [18]</td>
<td>107 [22]</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Single-limb stance number of participants with floor-supports</strong></td>
<td>Injured leg</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>p=0.035</td>
</tr>
<tr>
<td></td>
<td>Non-injured leg</td>
<td>9</td>
<td>12</td>
<td>0</td>
<td>p=0.007</td>
</tr>
<tr>
<td><strong>Single-limb stance CoP path (m)</strong></td>
<td>Injured leg</td>
<td>8.0 [2.7]</td>
<td>8.0 [2.3]</td>
<td>7.8 [2.2]</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>Non-injured leg</td>
<td>8.8 [2.9]</td>
<td>8.7 [2.7]</td>
<td>7.4 [2.1]</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Single-limb stance CoP x SD (cm)</strong></td>
<td>Injured leg</td>
<td>0.78 [0.22]</td>
<td>0.90 [0.26]</td>
<td>0.82 [0.28]</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>Non-injured leg</td>
<td>0.80 [0.20]</td>
<td>0.92 [0.49]</td>
<td>0.76 [0.18]</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>LSI (%)</td>
<td>103 [29]</td>
<td>106 [27]</td>
<td>96 [22]</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Single-limb stance CoP y SD (cm)</strong></td>
<td>Injured leg</td>
<td>0.82 [0.20]</td>
<td>0.90 [0.30]</td>
<td>0.82 [0.18]</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>Non-injured leg</td>
<td>0.98 [0.43]</td>
<td>1.06 [0.41]</td>
<td>0.91 [0.37]</td>
<td>NS</td>
</tr>
</tbody>
</table>

a For controls, non-dominant leg is comparable to injured leg.
bACLn = 33, ACLn Controls = 33, Controls n=32  
cACLn = 32, ACLn Controls = 36, Controls n=33

dACLn = 28, ACLn Controls = 28, Controls n=18
**Results**

**Injured leg:** When comparing the injured leg to controls there were several differences (Table 5). The injured leg in ACL\(_R\) had similar jump capacity regarding one-leg hop and vertical jump compared to the legs of controls, while they had fewer side hops. The ACL\(_{PT}\) had lower vertical jumps and fewer side hops on the injured leg compared to controls. Regarding peak torque, the injured leg in ACL\(_R\) and ACL\(_{PT}\) had a lower concentric and eccentric knee extension peak torque compared to controls. In addition, ACL\(_{PT}\) had lower peak torque in eccentric knee flexion. The ACL-injured, both ACL\(_R\) and ACL\(_{PT}\), had a higher Hc:Qc ratio in the injured leg compared to controls. Regarding single-limb stance, the injured leg of the ACL-injured had significantly more floor-supports than controls while the CoP-path, CoP-x and CoP-y (for those without floor-supports) was similar to controls.

**Non-injured leg:** When comparing the non-injured leg (ACL\(_R\) and ACL\(_{PT}\)) to controls (Table 5) there were similar hop length (OLH), jump height (vertical jump), peak torques and H:Q ratios. In contrast, ACL\(_{PT}\) performed fewer side hops on the non-injured leg compared to controls and both ACL groups had significantly more floor-supports on the non-injured leg compared to controls. CoP measurements for those without floor-supports were, however, similar.

**Limb symmetry index (LSI):** Controls had significantly higher LSI in all jump tasks and in knee extension peak torque (concentric and eccentric) compared to both ACL\(_R\) and ACL\(_{PT}\). There were, however, no differences in LSI regarding knee flexion peak torque (concentric and eccentric) and H:Q ratio. Regarding jump capacity, the proportion of individual participants who displayed an LSI less than 90%, ranged from 27.3 to 63.6% for ACL\(_R\) and 43.2 to 76.0% for ACL\(_{PT}\) while the range was 27.3 to 57.6% for controls, with the largest proportion in the side hop. No differences were seen in LSI regarding CoP (Table 5).

**Comparison between injured and non-injured leg (Table 6).** There were shorter one-leg hops, lower vertical jumps and fewer side hops for the injured leg compared to the non-injured leg in both ACL\(_R\) and ACL\(_{PT}\). In ACL\(_{PT}\) there was a gender effect with shorter one-leg hops, lower vertical jumps and fewer side hops for women compared to men. Both ACL\(_R\) and ACL\(_{PT}\) showed a lower concentric and eccentric knee extension peak torque for the injured leg compared to the non-injured leg. ACL\(_{PT}\) had, in addition, a lower eccentric knee flexion peak torque for the injured leg compared to the non-injured leg. ACL\(_R\) showed no differences between the injured and non-injured leg regarding knee flexion peak torque (concentric and eccentric). In ACL\(_{PT}\), women displayed lower peak torques for knee flexion and extension during both concentric and eccentric contractions compared to men while in ACL\(_R\) the women displayed lower peak torque only in concentric knee extension and concentric knee flexion. No differences were seen between injured and non-injured legs regarding floor-support in single-limb stance. However, for ACL\(_R\) the injured leg had slightly lower CoP-y compared to the
Results

non-injured leg (p=0.043), while for ACLPT no differences were seen for CoP (CoP-path, CoP-x and CoP-y). Regardless of treatment there was no difference in jump capacity, peak torque and H:Q ratio between those who had no-or-low OA compared to those who had a moderate-to-high degree of OA (Table 6).

Table 6. Linear mix models were used for within-group comparisons. The F-values and p-values from the model are presented. “Participant” was included in the model as a random effect and all models had a significant random effect of “participant”.

<table>
<thead>
<tr>
<th></th>
<th>Leg</th>
<th>Gender</th>
<th>OA*</th>
<th>Interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>One-leg hop (m)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>F=9.4,  p=0.004</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>ACLPT</td>
<td>F=12.5, p=0.001</td>
<td>F=13.7, p=0.001</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Vertical jump (cm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>F=7.6, p=0.010</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>ACLPT</td>
<td>F=19.7, p&lt;0.0001</td>
<td>F=20.6, p&lt;0.001</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Side hop (n)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>F=15.5, p&lt;0.0001</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>ACLPT</td>
<td>F=26.8, p&lt;0.0001</td>
<td>F=10.8, p=0.002</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Con knee extension peak torque (Nm/kg)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>F=32.8, p&lt;0.0001</td>
<td>F=4.17, p=0.045</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>ACLPT</td>
<td>F=7.8, p=0.007</td>
<td>F=13.6, p&lt;0.001</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Ecc knee extension peak torque (Nm/kg)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>F=17.5, p&lt;0.0001</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>ACLPT</td>
<td>F=10.8, p=0.002</td>
<td>F=4.5, p=0.036</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Con knee flexion peak torque (Nm/kg)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>F=10.9, p=0.002</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>ACLPT</td>
<td>F=20.9, p=0.001</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Ecc knee flexion peak torque (Nm/kg)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>NS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLPT</td>
<td>F=7.8, p=0.008</td>
<td>F=7.3, p=0.011</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td><strong>He:Qc</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>F=12.7, p=0.001</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>ACLPT</td>
<td>F=5.7, p=0.022</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td><strong>He:Qc</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>NS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLPT</td>
<td>NS</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Bilaterally radiographic knee osteoarthritis (OA) was graded according to Kellgren & Lawrence (KL) and divided into participants with no-or-low (KL 0-1) or moderate-to-high (KL 2-4) degree of OA.

Correlations:

For the injured leg, a higher peak torque (Nm/kg) correlated with a higher Lysholm value (concentric knee extension p<0.001, r=0.44; eccentric knee extension p=0.008, r=0.32; concentric knee flexion p=0.006, r=0.34; eccentric knee flexion p<0.001, r=0.52). Likewise, a higher peak torque correlated with higher scores on the subscale KOOS-symptoms (concentric knee extension p=0.003, r=0.36; eccentric knee extension p=0.018, r=0.29; concentric knee flexion p=0.022, r=0.28; eccentric knee flexion p<0.001, r=0.52). No other correlations were found between peak torque and either of the other subscales of the KOOS or with the Tegner activity scale. Regarding CoP, low to moderate correlations (p<0.05; r=0.296 - 0.425) were found between older age and all CoP-variables (for CoP-y only for the non-injured leg in patients and non-dominant leg in controls). Higher BMI correlated
Results

with longer CoP-path (p<0.05, r=0.282) for the injured leg in patients and dominant leg in controls. Male gender correlated (p<0.05, r= 0.366 - 0.489) with longer CoP-path and larger CoP-x, the latter for the injured leg in patients and dominant leg controls. CoP was not correlated with Lysholm, KOOS and Tegner activity score.

**Movement pattern during one-leg hop**

*Comparison to controls (Table 7 and 8)*

ACL\(_R\) displayed larger external knee rotation in their injured leg at Initial contact and less internal knee rotation during Landing compared to controls. For their non-injured leg, the ACL\(_R\) showed a larger knee abduction ROM during Take-off and Landing. A larger maximal movement of CoM in relation to the ankle joint were seen on the non-injured side. ACL\(_P\) displayed a decreased knee flexion during Take-off and Landing, and larger knee abduction for both the injured and non-injured leg in comparison to controls. ACL\(_P\) also showed larger external knee rotation in their injured leg at Initial contact and less internal rotation during Landing. In addition, the ACL\(_P\) displayed less internal knee rotation during Take-off. CoM was more medially placed relative to the injured knee joint and with a less ROM of CoM during Take-off. Relative to the ankle joint, CoM was less laterally placed at Initial contact and during Landing, applied for the injured side.

*Comparison between injured and non-injured leg (Table 7 and 8)*

ACL\(_R\) displayed reduced maximal knee flexion and ROM before Take-off in the injured leg compared to the non-injured leg. After landing, reduced knee flexion ROM, maximal knee abduction and less internal knee rotation was found in the injured leg. CoM position was less laterally placed relative to the injured knee at Initial contact. In the Landing phase, less ROM of CoM in relation to knee and ankle joints was seen for the injured side. Males also showed less ROM of CoM in relation to the injured knee during Take-off. ACL\(_P\) displayed reduced maximal knee flexion and ROM during Take-off and Landing in the injured leg compared to the non-injured. The injured knee also showed a smaller internal rotation and ROM during Take-off and a larger external rotation at Landing. A gender difference was found where females showed less maximum knee flexion during Take-off and a smaller external rotation than males. The maximal movement of CoM in relation to the knee during Take-off was less for the male in the injured side, while female did not show any difference. CoM was less laterally positioned in relation to the ankle joint for the injured side. Males displayed a more laterally placed CoM in relation to the ankle joint than females. Those with no-or-low OA displayed larger knee abduction at Initial contact than those with moderate-to-high OA.

**Controls**

Jump capacity, floor-supports in single limb stance, peak torques, and movement patterns were similar in the dominant and non-dominant leg.
Table 7. Kinematic analysis of one-leg hop. The following variables are reported: 1) peak and Range Of Motion (ROM) of the knee angles in degrees, 2) maximal placement in lateral direction and range of the Center of Mass (CoM) in relation to the center of the knee and ankle joint, respectively, in cm (+medial and –lateral), and 3) these variables are also reported at initial contact. Mean and SD are presented.

<table>
<thead>
<tr>
<th>Variables</th>
<th>ACL Injured</th>
<th>ACL Non-injured</th>
<th>ACL Non-Dom</th>
<th>Controls Non-Dom</th>
<th>Controls Dom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee flexion angle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Take-off (max)</td>
<td>64.3 [8.8]</td>
<td>68.1 [7.6]</td>
<td>60.5 [9.5]</td>
<td>62.9 [8.3]</td>
<td>66.3 [5.9]</td>
</tr>
<tr>
<td>At Initial contact</td>
<td>19.7 [6.4]</td>
<td>19.5 [7.0]</td>
<td>17.7 [5.9]</td>
<td>17.0 [5.2]</td>
<td>19.5 [5.4]</td>
</tr>
<tr>
<td>Landing (max)</td>
<td>57.1 [9.8]</td>
<td>60.9 [10.8]</td>
<td>52.0 [8.6]</td>
<td>57.2 [8.4]</td>
<td>60.0 [11.0]</td>
</tr>
<tr>
<td>Landing (ROM)</td>
<td>38.8 [9.5]</td>
<td>42.3 [8.5]</td>
<td>38.3 [11.0]</td>
<td>43.4 [9.9]</td>
<td>41.8 [9.6]</td>
</tr>
<tr>
<td>Knee abduction angle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landing (max)</td>
<td>0.40 [5.37]</td>
<td>3.28 [4.94]</td>
<td>4.22 [6.08]</td>
<td>5.33 [3.95]</td>
<td>1.50 [5.08]</td>
</tr>
<tr>
<td>Knee internal rotation angle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CoM in relation to knee medio-lateral</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Take-off (max)</td>
<td>-0.58 [2.14]</td>
<td>-0.62 [2.11]</td>
<td>1.16 [1.77]</td>
<td>0.53 [2.43]</td>
<td>-0.52 [2.52]</td>
</tr>
<tr>
<td>At Initial contact</td>
<td>1.64 [2.08]</td>
<td>2.44 [1.84]</td>
<td>2.54 [1.29]</td>
<td>2.14 [1.86]</td>
<td>2.19 [1.35]</td>
</tr>
<tr>
<td>Landing (max)</td>
<td>0.19 [2.78]</td>
<td>0.74 [2.08]</td>
<td>1.13 [1.95]</td>
<td>0.80 [2.31]</td>
<td>0.66 [2.05]</td>
</tr>
<tr>
<td>CoM in relation to ankle medio-lateral</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Take-off (max)</td>
<td>-1.52 [0.83]</td>
<td>-1.70 [1.68]</td>
<td>-1.49 [1.58]</td>
<td>-1.55 [1.22]</td>
<td>1.71 [1.12]</td>
</tr>
<tr>
<td>Take-off (range)</td>
<td>3.41 [2.12]</td>
<td>3.36 [1.64]</td>
<td>2.88 [1.80]</td>
<td>2.45 [1.34]</td>
<td>3.04 [1.71]</td>
</tr>
</tbody>
</table>
## Results

Table 8. Linear mix models were used for within group comparisons. P-values are presented. "Participant" was included in the model as a random effect and all models had a significant random effect of "participant". For comparisons between ACL-injured and controls, ANOVA’s were used and p-values are reported.

<table>
<thead>
<tr>
<th>Knee flexion angle</th>
<th>ACL&lt;sub&gt;L&lt;/sub&gt; Controls</th>
<th>ACL&lt;sub&gt;R&lt;/sub&gt; Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take-off (max)</td>
<td>p=0.027 NS NS p=0.024 NS p=0.001 NS</td>
<td>NS NS p=0.0013 NS p=0.030 NS</td>
</tr>
<tr>
<td>Take-off (ROM)</td>
<td>p=0.050 NS NS p=0.001 NS</td>
<td>NS NS NS NS</td>
</tr>
<tr>
<td>At Initial contact</td>
<td>NS NS NS NS NS</td>
<td>NS NS NS NS</td>
</tr>
<tr>
<td>Landing (max)</td>
<td>NS NS NS NS p=0.026 NS</td>
<td>NS NS NS NS</td>
</tr>
<tr>
<td>Landing (ROM)</td>
<td>p=0.001 NS NS</td>
<td>NS NS NS NS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Knee abduction angle</th>
<th>ACL&lt;sub&gt;L&lt;/sub&gt; Controls</th>
<th>ACL&lt;sub&gt;R&lt;/sub&gt; Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take-off (max)</td>
<td>NS NS NS NS NS</td>
<td>NS NS NS NS</td>
</tr>
<tr>
<td>Take-off (ROM)</td>
<td>NS NS NS NS NS</td>
<td>NS NS NS NS</td>
</tr>
<tr>
<td>At Initial contact</td>
<td>NS NS NS NS NS</td>
<td>NS NS NS NS</td>
</tr>
<tr>
<td>Landing (max)</td>
<td>p=0.010 NS NS NS NS</td>
<td>p=0.008 NS NS</td>
</tr>
<tr>
<td>Landing (ROM)</td>
<td>NS NS NS NS NS</td>
<td>NS NS NS NS</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Knee internal rotation angle</th>
<th>ACL&lt;sub&gt;L&lt;/sub&gt; Controls</th>
<th>ACL&lt;sub&gt;R&lt;/sub&gt; Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take-off (max)</td>
<td>NS NS NS p=0.028 NS p=0.046 NS</td>
<td>NS NS p=0.049 NS</td>
</tr>
<tr>
<td>Take-off (ROM)</td>
<td>NS NS NS p=0.036 NS</td>
<td>NS NS NS NS</td>
</tr>
<tr>
<td>At Initial contact</td>
<td>NS NS NS NS NS p=0.002 NS</td>
<td>p&lt;0.001 NS p=0.0019 NS</td>
</tr>
<tr>
<td>Landing (max)</td>
<td>p=0.034 NS NS NS p=0.003 NS p=0.017 NS</td>
<td>p=0.026 NS p=0.001 NS</td>
</tr>
<tr>
<td>Landing (ROM)</td>
<td>NS NS NS NS NS</td>
<td>NS NS NS NS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CoM in relation to knee medio-lateral</th>
<th>ACL&lt;sub&gt;L&lt;/sub&gt; Controls</th>
<th>ACL&lt;sub&gt;R&lt;/sub&gt; Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take-off (max)</td>
<td>NS NS NS NS NS</td>
<td>NS NS p=0.012 NS</td>
</tr>
<tr>
<td>Take-off (range)</td>
<td>p=0.038 NS NS</td>
<td>NS NS p=0.037 NS</td>
</tr>
<tr>
<td>At Initial contact</td>
<td>NS NS NS NS NS</td>
<td>NS NS NS NS</td>
</tr>
<tr>
<td>Landing (max)</td>
<td>NS NS NS NS NS</td>
<td>NS NS NS NS</td>
</tr>
<tr>
<td>Landing (range)</td>
<td>p=0.034 NS NS NS</td>
<td>NS NS NS NS</td>
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</table>

<table>
<thead>
<tr>
<th>CoM in relation to ankle medio-lateral</th>
<th>ACL&lt;sub&gt;L&lt;/sub&gt; Controls</th>
<th>ACL&lt;sub&gt;R&lt;/sub&gt; Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take-off (max)</td>
<td>NS NS NS NS NS</td>
<td>NS NS NS NS NS</td>
</tr>
<tr>
<td>Take-off (range)</td>
<td>NS NS NS NS NS</td>
<td>NS NS NS NS</td>
</tr>
<tr>
<td>At Initial contact</td>
<td>NS NS NS NS NS</td>
<td>NS NS NS NS</td>
</tr>
<tr>
<td>Landing (max)</td>
<td>NS NS NS NS NS p=0.019 NS p=0.035 NS</td>
<td>NS NS p=0.013 NS</td>
</tr>
<tr>
<td>Landing (range)</td>
<td>p=0.003 NS NS NS NS</td>
<td>p=0.00 NS NS</td>
</tr>
</tbody>
</table>

* Bilaterally radiographic OA was graded according Kellgren & Lawrence (KL) and divided into participants with no-or-low (KL 0-1) or moderate-to-high (KL 2-4) degree of OA. I stand for injured leg, NI for non-injured leg, D for dominant leg and ND for Non-dominant leg.
Discussion

**Long-term consequences of an ACL injury**

The main findings of the present thesis suggest that regardless of treatment there are negative long-term consequences after an ACL injury when compared to age and gender matched controls. Our data demonstrate that persons more than 20 years after an ACL injury have an inferior self-reported knee function (Lysholm and KOOS) compared to controls. The results also show that both ACL groups, independent of treatment, have a lower knee-specific activity level (Tegner), while they have a similar level of general physical activity (IPAQ) compared to controls. Regardless of treatment, the injured leg displayed an inferior jump capacity compared to the non-injured leg. However, compared to controls the ACL-injured have a relatively good jump performance. Regarding muscle strength, the injured leg displayed reduced peak torque not only compared to the non-injured leg, but also in relation to the legs of healthy controls. The non-injured leg, however, showed similar peak torque compared to controls. Regardless of treatment, the balance in terms of number of floor-supports in single-limb stance was equally reduced for the injured leg and non-injured leg in comparison to controls. For those without floor-supports, similar CoP-path, CoP-x and CoP-y were seen for ACL$_R$, ACL$_PT$ and controls. Regarding movement pattern measured by kinematics (knee joint angles and CoM placement in relation to knee and ankle joints), both ACL$_R$ and ACL$_PT$ displayed asymmetries between the injured and non-injured leg. In comparison to controls, the ACL$_R$ group had similar kinematics with the exception of knee rotation. ACL$_PT$ showed several differences compared to controls both regarding knee angles and CoM placement in relation to knee and ankle joints. The ACL-injured with no-or-low radiological knee OA (Kellgren & Lawrence grade 0-1) rated better knee function (higher Lysholm and KOOS-symptom scores) compared to those with moderate-to-high knee OA (Kellgren & Lawrence grade 2-4), while degree of knee OA had no influence on the other subscales of the KOOS, reported physical activity level, jump capacity, peak torque or the kinematic variables.

**Self-reported knee function, physical activity level and fear of movement/re-injury**

The present thesis shows that a long-term consequence after ACL injury is a reduced self-reported knee function where the ACL-injured rated lower scores on Lysholm and KOOS compared to the matched controls as well as in comparison to other reference data (70, 72, 73, 143). Our results also indicate a decreased self-reported knee function compared to other long-term studies (see Table 1), for persons treated with ACL-reconstruction (56, 61, 63-66) as well as for persons treated with physiotherapy alone (55, 61, 62, 67, 71). There are only three studies with a follow-up time of about 20 years investigating self-reported knee function with Lysholm, showing scores from 53 to 90 (57,
Discussion

KOOS has, to our knowledge, not been used to measure knee function in studies over 20 years post injury.

As in line with other long-term studies the two KOOS-subscals; Sport/recreation and knee related quality of life, were the most affected. This applies both for ACL-injured treated with surgery (56, 61, 62, 68-70) as well as for those treated with physiotherapy alone (55, 61, 62, 70). The ACL-injured in the present study rated low scores (i.e. more dysfunction) on questions like: “How often are you aware of your knee problem?” and “Have you modified your lifestyle to avoid potentially damaging activities?” They also state difficulties with activities such as running and twisting-pivoting movements. Thus, approximately 20 years or more after an ACL injury, persons report symptoms and pain from the knee joint which results in large negative effects on knee quality of life as well as sport and recreational activities. For KOOS and Lysholm score there are no defined cut-off values for “good knee function”. However, regarding Lysholm score, Kostogiannis et al. have considered a score of 84-100 as good-to-excellent knee function (67) and Neuman et al. have regarded KOOS scores between 85-100 as normal knee function (62). When applying these cut-off values, our participants with an ACL injury have merely a poor to fair knee function. Combined, this indicates that knee function may deteriorate in persons after ACL injury over a longer time perspective.

Many ACL-injured persons are unable to successfully return to the same level of pre-injury sport participation (2, 31-33). This is of course a considerable negative consequence and disappointment for many persons. A decreased knee-specific activity level is also seen several years after injury. Five years after an ACL injury, Frobell et al. show that knee-activity level has decreases from a median Tegner level of 9 to a level of 4, regardless of treatment (34). Our data also show a decreased knee-specific activity level (9 to 4) over the 20 years, regardless of treatment. The persons with an ACL-injury also had a lower score on Tegner activity scale compared to our controls. Other long-term follow-up studies report Tegner scores between 4 to 6 (55-58, 61-65, 67, 71) and studies 20 years post injury show Tegner activity level 4 and 5 (57, 58). This is on parity or slightly higher compared to our results. Many rehabilitation programmes include recommendations for activity modification i.e. to avoid risk movements where pivoting loading on the knee occurs. Therefore, in the long-term perspective, it may be important to evaluate both the extent of knee-demanding activities that the ACL-injured persons can manage but also to estimate a more general activity level with focus on amount and intensity. In the present thesis, there was no significant group difference in general physical activity measured by IPAQ, even though the IPAQ median for the three groups differed. The IPAQ is mainly used in large epidemiology studies and our sample may have been too small to detect differences between groups. The fact that ACL-injured persons have a decreased knee-specific physical activity level while showing a similar general
level of physical activity as controls, may indicate that they are quite active but have chosen activities that pose less load on the knee joint.

It is important to be able to continue with an active lifestyle after injury since a decrease of physical activity level often leads to weight gain and many other negative health effects. A high BMI is also a risk factor for knee OA (144-146). Indeed, the ACL-injured in our study had a higher BMI compared to controls and also in relation to the general population of the same age in the same geographical region (147). In a qualitative study based on interviews of a subsample taken from the present study the informants also described problems with increasing weight after the injury, which they still struggle with many years afterwards (Fjellman-Wiklund et al in manuscript).

Fear of re-injury has been reported as a major cause for failure in returning to sport (32, 33, 35, 36) and fear of re-injury was highest at the time when the patients tried to return to sport (38). Persons who did not return to pre-injury activity levels still had a higher level of fear of movement/re-injury, that is higher TSK score, three to four years after injury (33). In our study, fear of movement/re-injury measured by TSK, showed a total score of 33 in ACLR and 32 in ACLeF out of a maximum of 68. In a population with low back pain, a score over 37±3 was considered to indicate a high level of fear of movement/kinesiophobia (148). Our values were below this cut-off. One hypothesis of ours was that a high fear of movement/re-injury (TSK) would be related to a lower physical activity level, knee function and inferior jump capacity. Correlations were, however, only seen between TSK and lower scores on Lysholm and KOOS subscale ‘symptom’ and the LSI for side hops. On the other hand, in the qualitative study referred to above, the informants describe limitations due to fear of pain and fear of re-injury. Due to fear of re-injury, they chose to avoid certain physical activities and instead chose “safe” activities (Fjellman-Wiklund et al in manuscript). A fear of re-injury is however not completely unjustified since the risk of sustaining a second ACL injury or a contralateral ACL injury is in fact even greater than the risk of sustaining a first time injury (16). A 10 year follow-up study showed that 12 % of the ACL-injured had a contralateral injury (149), which is in line with our study sample (see Fig. 2). The most important risk factor of sustaining a contralateral ACL injury was return to a high activity level (16).

Our data show that the ACL-injured with no-or-low radiological knee OA (Kellgren & Lawrence grade 0-1) rated higher scores on Lysholm and KOOS subscale ‘symptom’ compared to those with moderate-to-high knee OA (Kellgren & Lawrence grade 2-4), while degree of knee OA had no influence on the other subscales of the KOOS, or reported physical activity level (Tegner activity scale and IPAQ). The KOOS subscales ‘symptom’ and ‘pain’ have earlier shown a weak correlation with radiological knee OA (150), while other long-term follow-up studies have reported no association between radiological knee OA and knee function (e.g. IKDC, Lysholm) (60, 62, 63) or
physical activity (63). This indicates that the grade of radiological OA cannot solely predict self-reported knee function.

**Physical capacity**

This thesis adds new knowledge regarding the physical capacity in the long-term perspective after an ACL injury. To our knowledge, there are no studies with a follow-up time of more than 20 years that investigate physical capacity. There are six follow-up studies, 15-16 years after injury, which assess physical capacity in the form of jumps or strength (see Table 1). When comparing our results to these follow-up studies, the present study indicates that the side difference may increase over an even longer perspective than 15 years. Interestingly, our data show that persons with an ACL-injury with no-or-low radiological knee OA (Kellgren & Lawrence grade 0-1) had equal physical capacity compared to those with moderate-to-high OA (Kellgren & Lawrence grade 2-4), but since many of the ACL-injured display OA, we cannot entirely isolate the direct effects of ACL injury from the contribution of OA.

None of the long-term follow-up have compared the physical capacity to a control group. It is important to compare physical capacity with reference data since studies have shown that there may be bilateral deficits following a unilateral ACL injury (74, 76-78). If there is a bilateral deficit it may lead to a falsely high LSI, since LSI is calculated as a ratio between the values of the legs. Furthermore, it is crucial to match the control group both regarding age and gender since jump capacity, strength and balance changes will deteriorate with increasing age and differ between males and females (151-153). The present thesis shows, regardless of treatment, bilateral deficits in balance with equally as many floor-supports of the injured and non-injured leg, compared to controls who had no floor-supports during single-limb stance for 30 s. Some of the kinematics were also bilaterally affected compared to controls. Regarding jump capacity and strength however, the non-injured leg displayed equal capacity to controls.

**Jump capacity**

In the present thesis, two maximum jumps (OLH and vertical jump) and one jump of a more endurance character (side hop) were performed. To test three different types of jumps has been suggested to be more decisive for evaluation of functional performance (109, 110). OLH is the most commonly applied test of physical capacity in clinics and for research. This applies also for the long-term follow-up studies (see Table 1). In the present thesis, the smallest differences in jump capacity between the injured leg and non-injured leg, as well as in comparison to controls, were seen in the OLH test. Our data show that hop length was equally good for ACL-injured (ACL\(L_L\) and ACL\(R_R\)) and controls. Even if there was a significantly shorter hop for the injured leg compared to the non-injured leg the difference was less than 10 % (ACL\(L_L\) LSI of 94 % and ACL\(R_R\) LSI of 92 %), which indicates a good result. The controls in our study had a mean LSI of 100 % while other reference data has shown a mean LSI of 94 % (152), which is in parity with the results for our ACL-
injured. Even if the mean LSI shows a good jump capacity, many of the ACL-injured had a LSI less than 90 % (27 % of ACLx and 43 % of ACLxT). Other long-term studies utilising OLH (15-16 years after injury) show better results, with only 8-35 % of those treated with surgery (56, 63, 65, 66) and 15 % of those treated with physiotherapy only (55) displaying LSI values less than 90 %. This suggests that the side difference may increase over an even longer time perspective, but more research is required to verify this.

The result for the vertical jump is in parity with the result of OLH, while an even larger reduced jump capacity was seen for the side hop. Stensbirk et al. 2013 also reported a lower LSI for a jump task with sideways movements; with a mean LSI of 87 % for cross-over hop and 92 % for OLH (56). When exploring the side hop, six of the ACL-injured could not perform even one approved side hop, while all the controls could perform side hops. As many as 76 % of the ACL-injured had a LSI of less than 90 %. The side hop may be considered more challenging for the knee joint and therefore more discriminative than the OLH and vertical jump. Many of the ACL-injured also expressed discomfort before the side hop test. The side hop was also the only jump task that significantly correlated with fear of movement/re-injury (TSK). Even for controls the side hop was challenging, as shown by a lower mean LSI and that 19 controls had a LSI <90 %. In conclusion, the ACL-injured can manage reasonably well in some jumps, but do less well in the more knee-demanding side hop. This is in line with the result that the ACL-injured have equal general physical activity level (IPAQ) while they also have a lower knee-specific activity level (Tegner) compared to controls.

Knee muscle peak torque

Our results showed that participants with ACL injury had reduced strength in the injured leg compared to their non-injured leg, but also in relation to the legs of healthy controls. Knee muscle weakness is one of the main dysfunctions after an ACL injury (30, 46). A review study shows, however, that the strength deficit may lessen with time (30). To our knowledge, only one long-term study has assessed knee muscle strength and showed that ACL-injured treated with physiotherapy have good strength with a mean LSI of 96.5 % for concentric knee extension and 101 % for concentric knee flexion (55). Three studies with shorter follow-up time (10-13 years) have reported a LSI between 88-90 % in concentric knee extension and a LSI of 92-99 % in concentric knee flexion, regardless of treatment (154-156). The present thesis also show a reduced knee extension peak torque, ACLx showed a LSI of 88 % both for concentric and eccentric contractions, while ACLxT showed a LSI of 93 % for concentric and 88 % for eccentric contractions. Regarding knee flexion peak torque, ACLx had no side differences, while ACLxT had a reduced eccentric knee flexion peak torque of 11 %. This suggests that an ACL injury may lead to a persistent reduction of peak torque in the injured leg and may even become more evident with time, which is contradictory to earlier suggestions that the strength difference may be reduced over time (30). The deficits may also be even larger since angle-specific muscle torque at less than
40° knee flexion has shown even larger strength deficits in ACL-injured (157). This needs to be further investigated.

Eccentric contraction has not previously been evaluated in the long-term perspective. Our data show a reduced eccentric knee extension peak torque regardless of treatment. Eccentric muscle contractions are important in many activities, not least in jump landing. During recent years, rehabilitation has started to focus on eccentric quadriceps strength and rehabilitation programs containing eccentric training has shown greater improvements in strength and hop-performance than a rehabilitation program without eccentric training (53). Testing of eccentric knee flexion strength is even rarer. In the present study ACL<sub>PT</sub> had a reduced eccentric knee flexion peak torque. Eccentric hamstrings strength has been shown to be important in, e.g. late swing in running (158). Eccentric hamstrings strength is also likely to be important at initial contact in a jump landing, e.g. during OLH to decelerate the forward swing of the shank and avoid landing with excessive extension. Indeed, the kinematic analyses show that the injured leg in ACL<sub>PT</sub> have less knee flexion in the landing phase both when comparing to non-injured leg and controls. Even if studies have shown a high reliability for isokinetic testing of eccentric contraction (135), it has been hypothesized that many factors may influence performance so that the muscle may not be fully activated. Suggested factors include pain, central inhibitory neuro-physiological mechanisms, and discomfort (159, 160). The discomfort, especially for ACL<sub>PT</sub>, may be explained by an increased knee joint laxity and perhaps difficulty to control an increased translation in the knee joint due to the ACL deficit. Indeed, isokinetic eccentric knee extensions in ACL-deficient knees have shown 38 % higher anterior tibial translation compared to the non-injured knee, while no differences have been found in translation for concentric contractions (161).

In functional tests, such as jump tasks, the hamstring co-contraction is important since hamstrings may be effective in maintaining knee stability through synergistic action to the ACL (162). The muscular balance across the knee joint is vital and a high H:Q ratio is desirable since a low H:Q ratio is shown to be a risk factor for sustaining an ACL injury (23-25) and may also discriminate knee OA (163). Our results show that the ACL-injured had a higher Hc:Qc ratio in the injured leg compared to the non-injured leg and to controls. This was, however, explained by the reduced quadriceps strength in the injured leg rather than sufficient hamstrings strength. This concludes that a H:Q ratio is not a useful measure if the quadriceps strength is reduced.

Consistent with other research (164, 165), our data show a moderate correlation between peak torque, both in knee flexion and extension, and self-reported knee function measured by Lysholm score. For KOOS, only the subscale ‘symptoms’ were associated with peak torque.
Single-limb stance

No previous study has investigated balance in the long-term, despite a negative impact on balance and proprioception previously shown in the short-term (46, 74-76). Our data show that ACL-injured, regardless of treatment, have an inferior balance in both the injured and non-injured leg in comparison to controls. All controls managed to stand on one leg during 30 s while 39% in ACLR and 50% in ACLPT failed to stand on one leg without floor supports with the other foot. This is in line with a recent published review article which shows an impaired postural control, in a shorter perspective, in both the injured and non-injured leg compared to controls (74).

For the participants who managed to stand on one leg during 30 s there were no differences in CoP-path, CoP-x and CoP-y between ACLR, ACLPT and controls. This is in contrast to other studies that have shown larger postural sway and an inferior postural balance for ACL-injured (74). Of course, this may be due to the fact that we removed all participants who failed to stand on one leg from the CoP analyses, i.e. removed those with reduced balance. However, when comparing injured and non-injured leg, no differences in CoP were seen for ACLPT, while for ACLR a slightly lower CoP-y was seen for the injured leg compared to the non-injured leg.

Older age is described in the literature to negatively influence balance in single-limb stance (152, 166) and therefore balance is an important outcome in the long-term perspective. The present study also showed that older age had a negative effect on balance with a larger migration of CoP. Our data also show that male gender correlated with longer CoP-path and larger CoP-x, indicating inferior balance compared to females. A better balance for females has also been reported elsewhere (152, 167). The knee-related outcome (Tegner, Lyholm, KOOS and knee laxity) did, however, not correlate with CoP. Regarding knee laxity, other studies have also found no influence on single-limb stance (168-171). This is probably explained by the fact that the single-limb stance test does not challenge the translational or torsional forces. Our results indicate that balance training is an important part in rehabilitation, both in the short and long-term perspectives, and may be of uttermost value to prevent falls as this groups enters older age.

Movement pattern

Our data show that the ACL-injured more than 20 years post injury have an altered movement pattern during one-leg hop. With the exception of knee rotation, the ACLR seem to have quite similar movement patterns compared to controls. ACLPT, however, have a more altered movement pattern compared to controls with differences in both knee joint angles and CoM placement in relation to ankle and knee joints. To our knowledge, only one study has evaluated the kinematics (gait and cross-over hops) more than 10 years after an ACL injury. This 16 year follow-up study did not show any kinematic differences compared to controls (172), but might have been
underpowered since it was based only on six reconstructed and six conservatively treated patients.

Regardless of treatment, our data show altered knee rotation kinematics in the injured leg compared to the non-injured leg and to controls, especially in the landing phase. Other studies have also pointed to less internal rotation in the reconstructed knee. A study analysing OLH showed less internal rotation in the surgically reconstructed knee at initial contact (96), which has also been demonstrated in other tasks such as drop landing and gait (86, 97). One role of the ACL is to avoid excessive tibial internal-external rotation (7). Our data indicate that reconstruction surgery may restore the knee biomechanics to some extent. An ACL reconstruction seems to restore the translational component (173, 174) while the reconstruction does not restore the rotation kinematics, which has also been discussed earlier (97, 174). The ACL consists of two bundles of fibres: the anteromedial and the posterolateral bundle. Both bundles provide anterior and rotational stability to the knee, but have different tensions throughout the range of motion. The anteromedial bundle is tightened in flexion whereas the posterolateral bundle is more tightened in extension of the knee (5-7). More recent surgical techniques may better restore also the rotational instability. Drilling the femoral tunnel through an anteromedial portal (173, 175) and the use of double-bundle reconstructions (44) have been shown to better restore the rotation component. More knowledge and research is needed regarding the rotation laxity after an ACL injury, especially during functional tasks.

Altered kinematic were also observed in knee flexion and knee abduction. As described earlier, movement patterns with large knee abduction and small knee flexion are associated with a higher risk for an ACL injury (19, 20). Studies show that the ACL injury often occurs when landing with the knee slightly flexed and the tibia rotates inwards with an additional “valgus collapse” (8, 9, 11, 12). Rehabilitation and prevention programmes therefore focus on “knee over the foot” strategies and on proper landing and cutting techniques. This includes landing softly, with larger knee and hip flexion and, if possible landing on two feet (8, 22, 54). Our data show less knee flexion in the injured knee upon landing for ACL PT compared to non-injured leg and to controls. This is in line with earlier studies showing reduced knee flexion in the ACL-injured knee at initial contact when landing on one foot (96) as well as on two feet (176). Regarding knee adduction and abduction, our data show that the ACLx, in general, seem to have higher knee adduction compared to controls, while ACL PT have more knee abduction compared to controls. Deneweth et al (2010) also demonstrated larger knee adduction in the ACL-reconstructed knee throughout the one-leg hop compared to controls, which is similar to our data when considering the whole OLH. Also regarding the results for ACL PT, there are studies that support the findings with larger knee abduction in ACL-deficient knees (176). The ACL-injured seem, however, to have a similar pattern on both injured and non-injured leg, which indicated bilateral kinematic adaptions. Other studies have also revealed bilateral
kinematic adaptations (177, 178) which points to the importance of a comparison to a matched control group with healthy knees.

In general, the injured leg for ACLPT shows a less laterally positioned CoM in relation to the knee and ankle joint compared to controls. This may be interpreted as a positive compensatory strategy for the increased knee abduction position but also since there is a higher risk for an ACL injury when the CoM is placed more laterally (8, 21). Even if a movement pattern is different to that of controls, it might be a functionally good solution. In rehabilitation and prevention training a movement strategy is advocated with “knee over the foot” and good trunk control (8, 22, 54) to avoid a large knee abduction and a laterally placed CoM.

Many factors may of course influence the kinematics, such as hop length, strength, knee stability, physical activity level, OA, meniscus injuries, gender and BMI. In the kinematic analysis we used OA and gender as factors and kinematics did not differ between those with no-or-low radiological knee OA and those with moderate-to-high OA. However, the majority had moderate-to-high OA in their injured knee and no-or-low OA in the non-injured leg. We cannot entirely isolate the direct effects of ACL injury with the contribution of OA. The relationship between the kinematics and OA needs to be further investigated, especially the role of the rotation laxity. Increased knee rotation and peak knee adduction moments have been discussed as two potential biomechanical alterations that may contribute to the onset and progression of knee OA after an ACL injury (179).

**Measuring knee function**

Many dimensions need to be considered when estimating knee function and it is a true challenge to define a “good knee function”. Since there is no “gold standard” in measuring outcome after ACL rehabilitation several scores and tests are usually employed. Some of the scores and functional tests are constructed especially with the purpose of evaluating the extent of the ACL injury, effect of treatment in the short-term and with regard to the decision to return to sport. In the long run, other dimensions such as the persons’ satisfaction with the treatment outcome and how they can participate in activities at work, physical activities and in social activities may be even more important. In the present thesis, most of the outcome variables are classified in the ICF dimensions of body function and activity. It would have been desirable to investigate even more items in participation.

Age and gender are two factors in ICF’s dimensions of personal factors and have been shown to influence some of the outcome variables. Despite this, no scores or tests are age or gender specific so far. Tegner activity level and KOOS, for instance, differ both between genders and have an effect of age (73, 180, 181), while for Lysholm score no effect of age and gender has been seen (73). Physical capacity, such as balance, strength and jump capacity are also influenced by age and gender (152, 153, 182). The outcomes may therefore
need to be adjusted for age and gender. This also supports the importance of comparing to an age and gender matched control group.

Both knee-specific and more general physical activity levels were estimated in the present thesis. However, IPAQ may not have been sensitive enough and is difficult to use on a smaller study sample. Other studies also show that it is a challenge to reliably capture the general activity level in any population (183). In this long-term perspective, an interesting question to consider would be if the participants are as active as they would like to be and if not, the reason why.

In the present thesis, fear of movement/re-injury was measured and classified as emotional function in the dimension body function/structure in ICF (see Fig. 1). A review article by teWierike et al describes many different psychosocial factors that may influence the management of an ACL injury. Factors include; coping, fear of movement/re-injury, goal adjustment, locus of control, self-efficacy, optimism, adherence etc. (184). How persons cope with their ACL injury in a long-term perspective still needs to be further investigated.

Regarding physical capacity, a LSI of less than 90 % has been considered unsatisfactory in terms of both strength and hop performance (108, 112). However, there are too few studies that have researched cut-off values for different functional performance. For instance, the mean LSI for our controls differed from 93 to 100 %, with the lowest LSI for the side hop. Different cut-off values may also be appropriate if returning to sport is considered or to evaluate results in the long-term perspective.

In general, there is difficulty in quantifying functional knee stability during functional tasks and there is a need for further develop of these kind of non-invasive measurements of knee stability. In a recent study by Grip & Häger 2013 (141) a knee finite helical axis (FHA) variable was explored as a measurement of functional knee stability. Shortly, FHA describes the amounts of flexion/extension, abduction/adduction and internal/external rotation that are involved in a rotation. The proposed FHA variable takes the variation of the FHA during a specific motion. This variable has so far been tested on knee-healthy individuals showing that side hop was more challenging to the functional stability of the knee (defined as a larger variation in the FHA position during the side hop) compared to a bilateral squat. This new way to assess functional stability will be further evaluated in ACL-injured.

**Methodological considerations**

This thesis was based on a cross-sectional study of two cohorts carried out more than 20 years after an ACL injury. A long-term study is of course a challenge since many potential factors may influence the knee function over the years. OA may influence the results particularly since 90 % of the ACL-
injured displayed some form of OA in their injured knee. This thesis cannot separate direct effects of ACL injury versus the contribution of OA. The present thesis provides interesting long-term results after two different types of treatment, although not constructed as a randomised control trial back in the 80’s. Therefore we considered direct group comparisons not valid.

The external validity should also be considered. One limitation of the present thesis may be a sample bias. The study sample in the present thesis is a part of the patients treated initial. There were drop-outs from injury until the 20 years follow up at the orthopaedic department (will be presented elsewhere), which of course is a limitation. Another sample bias could be that only those with high knee function accepted to participate in the functional performance testing. Eleven ACL-injured individuals that participated in the orthopaedic/radiological tests declined to participate in the functional performance tests. There were, however, no significant differences in background variables between those individuals (see Appendix). On the other hand, ACL-injured persons with low knee function may have been more interesting to participate from the beginning in the orthopaedic/radiological part. Both the surgical techniques and physiotherapy treatment have progressed over the last 20 years, but many ACL-injured have been treated according to these methods in the mid-80’s and live with that outcome. However, all this together may of course affect the ability to generalize the results to a general population of ACL-injured individuals.

The recruitment of knee-healthy controls was achieved through convenience sampling. Other studies of controls show a median level of Tegner activity score 5-6 in the age range of 30-60 years (72, 73) which is in parity compared to our controls. Our control group may have a better knee function than expected of a true reference group probably, due to our exclusion criteria. Our controls all had the highest score on Lysholm while other reference data with similar aged controls show median scores of 100 (range 90-100) (72) and 94 (43-100) (73). Our controls seem also to have higher scores than other reference data on KOOS (70, 181). This might influence the efficacy of generalizability with this control group.

In general, the internal validity may be considered as high. As described earlier, the different knee-specific scores (Lysholm score, KOOS, Tegner activity scale) used in the present thesis all have high reliability and validity in an ACL-injured population. The TSK and IPAQ has not been tested for reliability and validity for an ACL population, although TSK has been previously applied to a population of ACL-injured patients (33, 38, 128). The different jumps (OLH, vertical jump and side hop) have a high reliability and validity, and the use of three different types of jumps has been considered as more decisive for evaluation of functional performance after an ACL injury (109, 110). It is also a strength of the study that hop distance and jump height were measured by means of a movement analysis system with a very high accuracy compared to the use of a measuring tape, which is the most common
method. The number of side hops and floor-supports in single-limb stance was verified by video, which is a further strength. Even if similar high ICCs for concentric (ICC 0.93-0.95) and eccentric contractions (ICC 0.93-0.95) have been reported (135), the reliability of eccentric contractions can be discussed. The reliability may be lower for eccentric compared to concentric testing as factors such as pain, knee laxity, central inhibitory neurophysiological mechanisms, and discomfort may influence the muscles to the extent that they are not fully activated (159, 160). Regarding the kinematics, factors such as using skin markers, skin movements, marker placement, small motions and artefacts may influence the reliability of 3D movement analysis (185, 186). This may influence the reliability of especially variables such as rotation and ab- or adduction in the knee joint. The results in the present study are however in line with other studies. One strength was that the same physiotherapist (ET) attached all markers and tested all participants. Regarding the kinematic variables, there were some missing data due to hidden markers. This applies especially for CoM in relation to knee and ankle joints since all body segments are needed for calculations of CoM.

**Clinical implications and further research**

Regardless of treatment, the present thesis indicates negative long-term consequences more than 20 years after an ACL injury. There are only a few long-term studies with a follow-up time of more than 20 years and to our knowledge none of these studies have evaluated physical capacity. Our data indicates that both self-reported knee function and physical capacity may deteriorate over time when compared to follow-up studies 15 years post injury. More research on long-term consequences is required to verify this.

As described earlier, many persons with an ACL-injury do not successfully return to their pre-injury sport. As a physiotherapist it is important to keep that in mind. Our results indicate that ACL-injured persons have a decreased knee-specific activity level also in the long-term perspective. It is desirable to be able to continue with an active lifestyle and to avoid a weight gain. Therefore, it is important to find physical activities during initial rehabilitation with a high physical intensity but with a low load on the knee joint. Both knee-specific and general physical activity level are important measurements after an ACL injury. However, studies examining the long-term effects of a more general activity level and in comparison to matched controls are lacking. Fear of movement/re-injury needs to be considered in rehabilitation since it seems to be an important factor for return to sport activities. More research is needed on the role of fear of movement/re-injury on knee function, physical activity level and functional performance in a longer perspective.

Knee muscle deficits, in both concentric and eccentric contractions, were seen regardless of treatment. Aiming for a good knee muscle strength in the long-term perspective, rehabilitation should focus on restoring normal strength of
the injured leg in concentric as well as eccentric strength, especially in knee extension. There is, however, a need for more systematic research evaluating knee muscle strength in the long-term perspective while also addressing eccentric contractions. Further research is also needed on angle-specific muscle torque since there may be even larger strength deficits at less than 40⁰ of knee flexion.

Balance has not previously been investigated in the long-term perspective. This thesis shows an impaired balance in both injured and non-injured leg in comparison to controls similar to that which has been found in studies with a short-term perspective. This concludes that balance training is important in rehabilitation both in the short and long-term perspectives. These bilateral deficits also highlights the importance of comparing with reference data from controls.

To gain further knowledge regarding movement patterns and potential compensatory movements after an ACL injury more research regarding kinematics, in low as well as high load activities, is needed. In rehabilitation focus should be both on capacity and quality of movement. Knowledge about movement patterns is most likely crucial when designing prevention programmes as well as rehabilitation programmes.
Conclusions

• ACL-injured individuals have a significantly lower self-reported knee function compared to age and gender matched controls, but also lower scores than other studies on individuals with an ACL injury with a shorter follow-up time. This indicates that knee function may decrease over a longer time perspective exceeding 20 years.

• Regardless of treatment ACL-injured individuals have a lower knee-specific activity level while showing a similar general activity level to controls more than 20 years post-injury. This indicates that ACL-injured persons are active but have chosen activities that imply less loading on the knee joint.

• Fear of movement/re-injury may be associated with self-reported knee function and jump capacity in the long-term perspective. The role of fear of movement/re-injury still needs to be further explored in this population.

• Regardless of treatment, the injured leg had an inferior jump capacity compared to the non-injured leg. In comparison to controls, the results indicate that individuals with an ACL-injury can manage reasonably well in some jumps but have an inferior performance in jumps that are more knee-demanding.

• An ACL injury may lead to a persistent reduction of knee extension peak torque regardless of treatment. The rehabilitation should therefore focus on restoring normal knee muscle strength of the injured leg in concentric as well as eccentric strength. For ACLPT a strength reduction was evident also in eccentric knee flexion which needs to be further explored. The peak torques were also correlated with self-reported knee function.

• In the long-term perspective, the ACL-injured had an inferior balance regarding single-limb stance. Interestingly, the inability to stand without contralateral supports was seen both for the injured leg and non-injured leg and in both ACLR and ACLPT.

• ACL-injured persons with moderate-to-high radiological knee OA rated lower self-rated knee function on Lysholm and KOOS subscale ‘symptom’ compared to those with no-or-low OA, while no differences were seen regarding physical activity level, jump capacity, strength or kinematics. Further studies are needed regarding the role of OA.

• Altered movement patterns compared to controls were observed more than 20 years after an ACL injury. With the exception of knee rotation, the ACLR group had similar movement patterns to controls. This indicates that a reconstruction may restore the knee biomechanics to some extent. The ACLPT group seems to use some compensatory movement strategies during the one-leg hop.
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References


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References

References


126. IPAQ scoring protocol. www.ipaq.ki.se.
References


References


Appendix

Description of individuals that declined to participate in the functional performance tests. Data on participants that declined to participate were collected at the orthopaedic clinic. Since there were only two participants in the ACL\textsuperscript{PT} who declined to participate, we have chosen to treat all drop-outs together in one group.

<table>
<thead>
<tr>
<th></th>
<th>Drop outs (n=11)</th>
<th>Test group (n=70)</th>
<th>Statistics between drop outs and test group</th>
</tr>
</thead>
<tbody>
<tr>
<td>N participants</td>
<td>11</td>
<td>70</td>
<td>-</td>
</tr>
<tr>
<td>ACL\textsuperscript{L} / ACL\textsuperscript{PT}</td>
<td>9 / 2</td>
<td>33 / 37</td>
<td>-</td>
</tr>
<tr>
<td>Male / female</td>
<td>7 / 4</td>
<td>44 / 26</td>
<td>-</td>
</tr>
<tr>
<td>Means [SD]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age at test</td>
<td>46.2 [2.2]</td>
<td>46.9 [5.4]</td>
<td>NS</td>
</tr>
<tr>
<td>Years since injury</td>
<td>23.9 [0.5]</td>
<td>23.5 [2.1]</td>
<td>NS</td>
</tr>
<tr>
<td>Years between injury - surgery</td>
<td>3.2 [0.5]</td>
<td>3.6 [2.3]</td>
<td>NS</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>169.7 [3.0]</td>
<td>174.4 [9.1]</td>
<td>NS</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>87.3 [7.4]</td>
<td>83.0 [15.6]</td>
<td>NS</td>
</tr>
<tr>
<td>BMI (kg / m\textsuperscript{2})</td>
<td>29.8 [1.7]</td>
<td>27.2 [3.3]</td>
<td>NS</td>
</tr>
<tr>
<td>KOOS Symptoms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pain</td>
<td>75.7 [6.2]</td>
<td>75.1 [19.6]</td>
<td>NS</td>
</tr>
<tr>
<td>ADL</td>
<td>90.8 [2.1]</td>
<td>81.5 [17.2]</td>
<td>NS</td>
</tr>
<tr>
<td>Sport/rec</td>
<td>96.6 [1.8]</td>
<td>87.7 [15.8]</td>
<td>NS</td>
</tr>
<tr>
<td>QOL</td>
<td>76.0 [5.6]</td>
<td>58.1 [29.7]</td>
<td>NS</td>
</tr>
<tr>
<td>Lysholm at present</td>
<td>61.9 [7.1]</td>
<td>55.7 [24.4]</td>
<td>NS</td>
</tr>
<tr>
<td>One-leg hop (m)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hop length injured leg</td>
<td>1.12 [0.09]</td>
<td>1.06 [0.28]</td>
<td>NS</td>
</tr>
<tr>
<td>non-injured leg</td>
<td>1.25 [0.08]</td>
<td>1.14 [0.29]</td>
<td>NS</td>
</tr>
<tr>
<td>LSI one-leg hop (%)</td>
<td>89 [2]</td>
<td>93 [1]</td>
<td>NS</td>
</tr>
<tr>
<td>Median [range]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\*Mann-WhitneyU test
Dissertations written by physiotherapists, Umeå University 1989–2014

Birgitta Bergman. Being a physiotherapist - Professional role, utilization of time and vocational strategies. Umeå University Medical Dissertations, New Series no 251, 1989 (Department of Physical Medicine and Rehabilitation)

Inger Wadell. Influences from peripheral sense organs on primary and secondary spindle afferents via gamma-motoneurones - A feedback mechanism for motor control and regulation of muscle stiffness. Umeå University Medical Dissertations, New Series no 307, 1991 (Department of Physiology)


Birgit Rööblad. Visual and proprioceptive control of arm movement - Studies of development and dysfunction. Diss. (sammanfattning) 1994 (Department of Paediatrics)

Charlotte Häger-Ross. To grip and not to slip - Sensorimotor mechanisms during reactive control of grasp stability. Umeå University Medical Dissertations, New Series no 429, 1995 (Department of Physiology)

Lars Nyberg. Falls in the frail elderly – Incidence, characterics and prediction with special reference to patients with stroke and hip fractures. Umeå Medical Dissertations, New Series no 483, 1996 (Department of Geriatric Medicine)

Margareta Barnekow-Bergkvist. Physical capacity, physical activity and health - A population based fitness study of adolescents with an 18-year follow-up. Umeå University Medical Dissertations, New Series no 494, 1997 (Departments of Physiology and Technology, National Institute for Working Life and Epidemiology and Public Health)

Britta Lindström. Knee muscle function in healthy persons and patients with upper motor neurone syndrome. Umeå University Medical Dissertations, New Series no 505, 1997 (Departments of Physical Medicine and Rehabilitation and Clinical Neuroscience)

Monica Mattsson. Body Awareness - applications in physiotherapy. Umeå University Medical Dissertations, New Series no 543, 1998 (Departments of Psychiatry and Family Medicine)

Hildur Kalman. The structure of knowing. Existential trust as an epistemological category. Umeå studies in the humanities. 145, 1999 (Department of Philosophy and Linguistics)

Hamayun Zafar. Integrated jaw and neck function in man: studies of mandibular and head-neck movements during jaw opening-closing tasks. Umeå University Medical Dissertations, New series no 74, 2000 (Departments of Odontology, Clinical Oral Physiology and Centre for Musculoskeletal Research, National Institute for Working Life, Umeå)

Lillemor Lundin-Olsson. Prediction and prevention of falls among elderly people in residential care. Umeå University Medical Dissertations, New Series no 671, 2000 (Department of Community Medicine and Rehabilitation, Physiotherapy and Geriatric Medicine)

Christina Ahlgren. Aspects of rehabilitation – with focus on women with trapezius myalgia. Umeå University Medical Dissertations, New Series no 715, 2001 (Department of Public Health and Clinical Medicine, Occupational Medicine)
Ann Öhman. Profession on the move - changing conditions and gendered development in physiotherapy. Umeå University Medical Dissertations, New series No 730, 2001 (Departments of Community Medicine and Rehabilitation, Physiotherapy and Public Health and Clinical Medicine, Epidemiology)

Kerstin Söderman. The female soccer player – Injury pattern, risk factors and intervention. Umeå University Medical Dissertations, New series no 735, 2001 (Departments of Surgical and Perioperative Sciences, Sports Medicine, and Community Medicine and Rehabilitation, Physiotherapy)

Lena Grönlund-Lundström. Rehabilitation in light of different theories of health. Outcome for patients with low-back complaints – a theoretical discussion. Umeå University Medical Dissertations, New series no 760, 2001 (Departments of Public Health and Clinical Medicine, Epidemiology, and Community Medicine and Rehabilitation, Social Medicine)

Kerstin Waling. Pain in women with work-related trapezius myalgia. Intervention effects and variability. Umeå University Medical Dissertations, New series no 762, 2001 (Departments of Public Health and Clinical Medicine, Occupational Medicine, and Community Medicine and Rehabilitation, Physiotherapy)

Eva-Britt Malmgren-Olsson. Health problems and treatment effects in patients with non-specific musculoskeletal disorders. A comparison between Body Awareness Therapy, Feldenkrais and Individual Physiotherapy. Umeå University Medical Dissertations, New series no 774, 2002 (Department of Community Medicine and Rehabilitation, Physiotherapy and Department of Psychology)

Jane Jensen. Fall and injury prevention in older people living in residential care facilities. Umeå University Medical Dissertations, New series no 812, 2003 (Department of Community Medicine and Rehabilitation, Physiotherapy and Geriatric Medicine)

Ann-Cristine Fjellman-Wiklund. Musicianship and teaching. Aspects of musculoskeletal disorders, physical and psychosocial work factors in musicians with focus on music teachers. Umeå University Medical Dissertations, New series no 825, 2003 (Department of Community Medicine and Rehabilitation, Physiotherapy)

Börje Rehn. Musculoskeletal disorders and whole-body vibration exposure among professional drivers of all-terrain vehicles. Umeå University Medical Dissertations, New series no 852, 2004 (Department of Public Health and Clinical Medicine, Occupational Medicine)

Martin Björklund. Effects of repetitive work on proprioception and of stretching on sensory mechanisms. Implications for work-related neuromuscular disorders. Umeå University Medical Dissertations, New series no 877, 2004 (Department of Surgical and Perioperative Sciences, Sports Medicine Unit, Umeå University, The Center for Musculoskeletal Research, University of Gävle, Umeå, and Alfta Forskningsstiftelse, Alfta)

Karin Wadell. Physical training in patients with chronic obstructive pulmonary disease – COPD. Umeå University Medical Dissertations, New series no 917, 2004 (Departments of Community Medicine and Rehabilitation, Physiotherapy; Public Health and Clinical Medicine, Respiratory Medicine and Allergy, Surgical and Perioperative Sciences, Sports Medicine)

Peter Michaelson, Sensorimotor characteristics in chronic neck pain. Possible pathophysiological mechanisms and implications for rehabilitation. Umeå University Medical Dissertations, New series no 924, 2004 (Departments of Surgical and Perioperative Sciences, Sports Medicine Unit, University of Umeå, Southern Lappland Research Department, Vilhelmina, Centre for Musculoskeletal Research, University of Gävle, Umeå)

Ulrika Aasa. Ambulance work. Relationships between occupational demands, individual characteristics and health related outcomes. Umeå University Medical Dissertations, New series no 943, 2005 (Department of Surgical and Perioperative Sciences, Sports Medicine and Surgery, University of Umeå and Centre for Musculoskeletal Research, University of Gävle)

Ann-Katrin Stensdotter. Motor Control of the knee. Kinematic and EMG studies of healthy individuals and people with patellofemoral pain. Umeå University Medical Dissertations, New series no 987, 2005 (Department of Community Medicine and Rehabilitation, Physiotherapy)
Dissertations


Erik Rosendahl. Fall prediction and a high-intensity functional exercise programme to improve physical functions and to prevent falls among older people living in residential care facilities. Umeå University Medical Dissertations, New Series no 1024, 2006 (Department of Community Medicine and Rehabilitation, Geriatric Medicine and Physiotherapy)

Michael Stenvall. Hip fractures among old people. Their prevalence, consequences and complications and the evaluation of a multi-factorial intervention program designed to prevent falls and injuries and enhance performance of activities of daily living. Umeå University Medical Dissertations, New Series no 1040, 2006 (Department of Community Medicine and Rehabilitation, Geriatric Medicine and Physiotherapy)

Petra von Heideken Wågert. Health, physical ability, falls and morale in very old people: the Umeå 85+ Study. Umeå University Medical Dissertations, New Series no 1038, 2006 (Department of Community Medicine and Rehabilitation, Geriatric Medicine and Physiotherapy)

Karl Gisslén. The patellar tendon in junior elite volleyball players and an Olympic elite weightlifter. Umeå University Medical Dissertations, New Series no 1073, 2006 (Department of Surgical and Perioperative Sciences, Sports Medicine Unit)

Gerd Flodgren. Effect of low–load repetitive work and mental load on sensitising substances and metabolism in the trapezius muscle. Umeå University Medical Dissertations, New series no 1130, 2007 (Department of Surgical and Perioperative Sciences, Sports Medicine Unit, Centre of Musculoskeletal Research, University of Gävle, Umeå, and the Department of Community Medicine and Rehabilitation, Rehabilitation Medicine)

Staffan Eriksson. Falls in people with dementia. Umeå University Medical Dissertations, New series no 1135, 2007 (Department of Community Medicine and Rehabilitation, Physiotherapy and Geriatric Medicine)

Jonas Sandlund. Position-matching and goal-directed reaching acuity of the upper limb in chronic neck pain: Associations to self-rated characteristics. Umeå University Medical Dissertations, New series no 1182, 2008 (Department of Surgical and Perioperative Sciences, Sports Medicine Unit, Umeå University, Centre of Musculoskeletal Research, University of Gävle, Umeå)


Charlotte Åström. Effects of vibration on muscles in the neck and upper limbs. With focus on occupational terrain vehicle drivers. Umeå University Medical Dissertations, New series no 1195, 2008 (Department of Community Medicine and Rehabilitation, Physiotherapy)

Ellinor Nordin. Assessment of balance control in relation to fall risk among older people. Umeå University Medical Dissertations, New series no 1198, 2008 (Department of Community Medicine and Rehabilitation, Physiotherapy)

Bertil Jonsson. Interaction between humans and car seat. Studies of occupant seat adjustment, posture, position and real world neck injuries in rear-end impacts. Umeå University Medical Dissertations, New Series no 1163, 2008 (Department of Surgical and Perioperative Sciences, Sports Medicine Unit)

Jenny Röding. Stroke in the younger. Self-reported impact on work situation, cognitive function, physical function and life satisfaction. A national survey. Umeå University Medical Dissertations, New series no 1241, 2009 (Department of Community Medicine and Rehabilitation, Physiotherapy)

Therese Stenlund. Rehabilitation for patients with burn out. Umeå University Medical Dissertations, New series no 1237, 2009 (Department of Public Health and Clinical Medicine, Occupational and Environmental Medicine)
Elisabeth Svensson. Hand function in children and persons with neurological disorders. Aspects of movement control and evaluation of measurements. Umeå University Medical Dissertations, New series no 1261, 2009 (Department of Community Medicine and Rehabilitation, Physiotherapy)

Helena Nordvall. Factors in secondary prevention subsequent to distal radius fracture. Focus on physical function, co-morbidity, bone mineral density and health-related quality of life. Umeå University Medical Dissertations, New series no 1252, 2009 (Department of Community Medicine and Rehabilitation Physiotherapy and Department of Surgical and Perioperative Sciences, Orthopaedics)


Ulrik Röijezon. Sensorimotor function in chronic neck pain. Objective assessments and a novel method for neck coordination exercise. Umeå University Medical Dissertations, New series no 1273, 2009 (Department of Community Medicine and Rehabilitation, Physiotherapy, Centre of Musculoskeletal Research, University of Gävle, Umeå)

Birgit Eaberg. Work experiences among healthcare professionals in the beginning of their professional careers. A gender perspective. Umeå University Medical Dissertations, New series no 1276, 2009 (Department of Community Medicine and Rehabilitation, Physiotherapy and Department of Public Health and Clinical Medicine, Epidemiology and Public Health Sciences)

Per Jonsson. Eccentric training in the treatment of tendinopathy. Umeå University Medical Dissertations, New series no 1279, 2009 (Department of Surgical and Perioperative Sciences, Sports Medicine Unit)

Taru Tervo. Physical activity, bone gain and sustainment of peak bone mass. Umeå University Medical Dissertations, New series no 1282, 2009 (Department of Surgical and Perioperative Sciences, Sports Medicine, Department of Community Medicine and Rehabilitation, Geriatric Medicine, Department of Community Medicine and Rehabilitation, Rehabilitation Medicine)

Kajsa Gildenstam. Gender and physiology in ice hockey: a multidimensional study. Umeå University Medical Dissertations, New series no 1309, 2010 (Department of Surgical and Perioperative Sciences, Sports Medicine Unit)

Margareta Eriksson. A 3-year lifestyle intervention in primary health care. Effects on physical activity, cardiovascular risk factors, quality of life and costeffectiveness. Umeå University Medical Dissertations, New series no 1333, 2010 (Department of Community Medicine and Rehabilitation, Physiotherapy and Department of Public Health and Clinical Medicine, Epidemiology and Public Health Sciences)

Eva Holmgren. Getting up when falling down. Reducing fall risk factors after stroke through an exercise program. Umeå University Medical Dissertations, New series no 1357, 2010 (Department of Community Medicine and Rehabilitation, Physiotherapy and Department of Public Health and Clinical Medicine, Medicine)

Tania Janaudis Ferreira. Strategies for exercise assessment and training in patients with chronic obstructive pulmonary disease. Umeå University Medical Dissertations, New series no 1360, 2010 (Department of Community Medicine and Rehabilitation, Physiotherapy)

Sólveig Ása Árnadóttir. Physical Activity, Participation and Self-Rated Health Among Older Community-Dwelling Icelanders. A Population-Based Study. Umeå University Medical Dissertations, New series no 1361, 2010 (Department of Community Medicine and Rehabilitation, Physiotherapy)

Maria Wiklund. Close to the edge. Discursive, embodied and gendered stress in modern youth. Umeå University Medical Dissertations, New series no 1377, 2010 (Department of Public Health and Clinical Medicine, Epidemiology and Global Health and Department of Community Medicine and Rehabilitation, Physiotherapy)
Catharina Bäcklund. Promoting physical activity among overweight and obese children: Effects of a family-based lifestyle intervention on physical activity and metabolic markers. Umeå University 2010 (Department of Food and Nutrition)

Helene Johansson. En mer hälsofrämjande häls- och sjukvård: hinder och möjligheter utifrån professionernas perspektiv. Umeå University Medical Dissertations, New series no 1388, 2010 (Department of Public Health and Clinical Medicine, Epidemiology and Global Health)

Häkan Littbrand. Physical exercise for older people: focusing on people living in residential care facilities and people with dementia. Umeå University Medical Dissertations, New series no 1396, 2011 (Department of Community Medicine and Rehabilitation, Geriatric Medicine and Physiotherapy)

Marlene Sandlund, Motion interactive games for children with motor disorders. Umeå University Medical Dissertations, New series no 1419, 2011 (Department of Community Medicine and Rehabilitation, Physiotherapy)

Ann Sörlin, Health and the Elusive Gender Equality. Can the impact of gender equality on health be measured? Umeå University Medical Dissertations, New series no 1420, 2011 (Department of Public Health and Clinical Medicine, Epidemiology and Global Health)

Björn Sundström, On diet in ankylosing spondylitis. Umeå University Medical Dissertations, New series no 1444, 2011 (Department of Public Health and Clinical Medicine, Reumatology)

Gunilla Stenberg, Genusperspektiv på rehabilitering för patienter med rygg- och nackhesvär i primärvård. Umeå University Medical Dissertations, New series no 1482, 2012 (Department of Community Medicine and Rehabilitation, Physiotherapy and Umeå centre for Gender Studies)

Mattias Hedlund, Biomechanical and Neural Aspects of Eccentric and Concentric Muscle Performance in Stroke Subjects. Implications for resistance training. Umeå University Medical Dissertations, New series no 1510, 2012 (Department of Community Medicine and Rehabilitation, Physiotherapy)

Joakim Bagge, TNF-alfa och neurotrophins in achilles tendinosis. Umeå University Medical Dissertations, New series no 1538, 2013 (Department of Integrative Medical Biology, Anatomy and Department of Surgical and Perioperative Sciences, Sports Medicine)

Gunilla Larsson, Motor development, mobility and orthostatic reactions in Rett syndrome. Loss of function, difficulties and possibilities. Umeå University Medical Dissertations, New series no 1568, 2013 (Department of Community Medicine and Rehabilitation, Physiotherapy)

Ludvig J Backman, Neuropeptide and catecholamine effects on tenocytes in tendinosis development. Studies on two model systems with focus on proliferation and apoptosis. Umeå University Medical Dissertations, New series no 1572, 2013 (Department of Integrative Medical Biology, Anatomy and Department of Surgical and Perioperative Sciences, Sports Medicine)

Sven Blomqvist, Postural balance, physical activity and capacity among young people with intellectual disability. Umeå University Medical Dissertations, New series no 1579, 2013 (Department of Community Medicine and Rehabilitation, Physiotherapy)