Is seeing just believing?

Measurement properties of visual assessment of Postural Orientation Errors (POEs) in people with anterior cruciate ligament injury

JENNY ÄLMQVIST NAE | FACULTY OF MEDICINE | LUND UNIVERSITY

Is seeing just believing?

Measurement properties of visual assessment of Postural Orientation Errors (POEs) in people with anterior cruciate ligament injury

Jenny Älmqvist Nae

LUND
UNIVERSITY

DOCTORAL DISSERTATION

by due permission of the Faculty of Medicine, Lund University, Sweden.
To be defended at HSC, Margaretavägen 1B, Lund on 11 June 2020, at 9.00 am.

Faculty opponent
Professor Tron Krosshaug

Organization	Document name
LUND UNIVERSITY, Sweden Department of Health Sciences Reasearch group Sport Sciences	**DOCTORAL DISSERTATION**
Author(s): Jenny Älmqvist Nae	**Date of issue:** June 11, 2020

Is seeing just believing? Measurement properties of visual assessment of Postural Orientation Errors (POEs) in people with anterior cruciate ligament injury

Abstract: Rupture of the anterior cruciate ligament (ACL) is a common knee injury among young physically active populations. The injury results in impaired physical functions, such as joint instability, limitations in daily activities and sport-specific activities, and worse movement quality, e.g., altered postural orientation. Postural orientation is defined as the ability to maintain alignment between body segments, and undesirable postural orientation is suggested to be a risk factor for subsequent injury. The “gold standard” for measuring postural orientation is with three-dimensional motion analysis. However, there is a need for a systematic feasible approach to evaluate postural orientation in the clinical setting, such as with visual assessment. Therefore, the primary aim of this thesis was to develop and evaluate clinically feasible measures of postural orientation in participants with or without lower extremity injury. Secondary aims were to evaluate sex differences in postural orientation and the association between postural orientation and other measures of physical function and self-reported outcomes, in men and women undergoing rehabilitation after ACL reconstruction.

One systematic review with meta-analysis was conducted to summarize measurement properties of visual assessment of postural orientation in healthy populations, and populations with lower extremity injury (paper I). Evaluation of measurement properties (i.e., face validity, interpretability, internal consistency, inter-rater reliability, and measurement error) of a test battery for visual assessment of postural orientation errors (POEs) in patients with ACL injury were reported in two cross-sectional studies (papers II–III). Sex differences in POE scores (i.e., total POE score, POE subscales activity of daily living (ADL) and sport, and segment-specific POEs across tasks) were investigated in one cross-sectional study (paper IV). In the same paper, the association between POE scores and hop performance and Patient-Reported Outcome Measures (PROMs) were evaluated, in men and women with ACL reconstruction, separately.

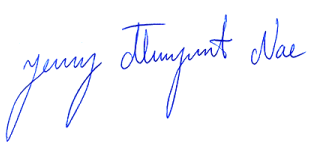
This thesis shows that visual assessment of the segment-specific POE knee medial-to-foot position (KMFP) is associated with two-dimensional and three-dimensional kinematic variables, and shows moderate to almost perfect reliability for the KMFP in healthy populations. For other segment-specific POEs or for patients with lower extremity injury there were not enough studies to permit any synthesis. The evaluation of measurement properties (face validity, interpretability, and internal consistency) of visual assessment of POEs during a variety of functional tasks in patients with ACL injury, resulted in the final test battery of 5 functional tasks (single-leg mini squat, stair descending, forward lunge, singe-leg hop for distance, and side-hop) and 6 segment-specific POEs (foot pronation, KMFP, femur medial to shank, femoral valgus, deviation of pelvis in any plane, and deviation of trunk in any plane). Women demonstrated worse POE scores compared with men and worse POE scores were associated with worse hop performance in women (especially the POE subscale ADL), but not in men.

The results from this thesis indicate that visual assessment of the segment-specific POE KMFP is valid and reliable in healthy populations. However, there is limited evidence of measurement properties for visual assessment of other segment-specific POEs, and in patients with lower extremity injuries. The test battery for visual assessment of POEs showed no floor or ceiling effects, high internal consistency, and good inter-rater reliability in patients with ACL injury. This indicates that visual assessment of POEs can be used in patients with ACL injury, both in research and in clinical practice. Furthermore, the results suggest that postural orientation should be evaluated separately for men and women, and that the POE subscale ADL could be used to help clinicians to decide when it is time to progress to jumping exercises during rehabilitation of ACL injuries.

Key words: knee injury, lower extremity, anterior crutiate ligament, orientation/spatial, postural orientation, performance-based measures, reproducibility of results, hop performance, patient reported outcome measures

Classification system and/or index terms (if any)

Supplementary bibliographical information		**Language** English
ISSN 1652-8220 Lund University, Faculty of Medicine Doctoral Dissertation Series 2020:78		**ISBN** 978-91-7619-940-4
Recipient’s notes	**Number of pages** 80	Price
	Security classification	

Signature  Date 2020-05-05

Is seeing just believing?

Measurement properties of visual assessment of Postural Orientation Errors (POEs) in people with anterior cruciate ligament injury

Jenny Älmqvist Nae

LUND
UNIVERSITY

Cover photo illustrated by Frida Nilsson

Faculty of Medicine
Department of Health Sciences
Research group Sport Sciences

ISBN 978-91-7619-940-4
ISSN 1652-8220

Printed in Sweden by Media-Tryck, Lund University
Lund 2020

To my family

Table of Contents

Abstract

Rupture of the anterior cruciate ligament (ACL) is a common knee injury among young physically active populations. The injury results in impaired physical functions, such as joint instability, limitations in daily activities and sport-specific activities, and worse movement quality, e.g., altered postural orientation. Postural orientation is defined as the ability to maintain alignment between body segments, and undesirable postural orientation is suggested to be a risk factor for subsequent injury. The "gold standard" for measuring postural orientation is with three-dimensional motion analysis. However, there is a need for a systematic feasible approach to evaluate postural orientation in the clinical setting, such as with visual assessment. Therefore, the primary aim of this thesis was to develop and evaluate clinically feasible measures of postural orientation in participants with or without lower extremity injury. Secondary aims were to evaluate sex differences in postural orientation and the association between postural orientation and other measures of physical function and self-reported outcomes, in men and women undergoing rehabilitation after ACL reconstruction.

One systematic review with meta-analysis was conducted to summarize measurement properties of visual assessment of postural orientation in healthy populations, and populations with lower extremity injury (paper I). Evaluation of measurement properties (i.e., face validity, interpretability, internal consistency, inter-rater reliability, and measurement error) of a test battery for visual assessment of postural orientation errors (POEs) in patients with ACL injury were reported in two cross-sectional studies (papers II–III). Sex differences in POE scores (i.e., total POE score, POE subscales activity of daily living (ADL) and sport, and segment-specific POEs across tasks) were investigated in one cross-sectional study (paper IV). In the same paper, the association between POE scores and hop performance and Patient-Reported Outcome Measures (PROMs) were evaluated, in men and women with ACL reconstruction, separately.

This thesis shows that visual assessment of the segment-specific POE knee medial-to-foot position (KMFP) is associated with two-dimensional and three-dimensional kinematic variables, and shows moderate to almost perfect reliability for the KMFP in healthy populations. For other segment-specific POEs or for patients with lower extremity injury there were not enough studies to permit any synthesis. The evaluation of measurement properties (face validity, interpretability, and internal consistency) of visual assessment of POEs during a variety of functional tasks in patients with ACL injury, resulted in the final test battery of 5 functional tasks (single-leg mini squat, stair descending, forward lunge, singe-leg hop for distance, and side-hop) and 6 segment-specific POEs (foot pronation, KMFP, femur medial to shank, femoral valgus, deviation of pelvis in any plane, and deviation of trunk in any plane). Women demonstrated worse POE scores compared with men and worse

POE scores were associated with worse hop performance in women (especially the POE subscale ADL), but not in men.

The results from this thesis indicate that visual assessment of the segment-specific POE KMFP is valid and reliable in healthy populations. However, there is limited evidence of measurement properties for visual assessment of other segment-specific POEs, and in patients with lower extremity injuries. The test battery for visual assessment of POEs showed no floor or ceiling effects, high internal consistency, and good inter-rater reliability in patients with ACL injury. This indicates that visual assessment of POEs can be used in patients with ACL injury, both in research and in clinical practice. Furthermore, the results suggest that postural orientation should be evaluated separately for men and women, and that the POE subscale ADL could be used to help clinicians to decide when it is time to progress to jumping exercises during rehabilitation of ACL injuries.

.

Populärvetenskaplig sammanfattning

En främre korsbandsskada i knät är vanligt förekommande bland fysiskt aktiva personer inom sporter som innehåller vridningar, inbromsningar och snabba riktningsförändringar, såsom handboll och fotboll. Skadan kan exempelvis leda till en instabil knäled, försämrad funktion i vardagliga och idrottspecifika aktiviteter, försvagade lårmuskler, försämrad rörelsekvalité och nedsatt självskattad funktion och livskvalité. Förmågan att hoppa på ett ben, lårstyrka och självskattad knäfunktion är vanliga funktionsmått som utvärderas under rehabilitering av patienter med främre korsbandsskada. Försämrad rörelsekvalité är en möjlig riskfaktor för att drabbas av en ny knäskada. Rörelsekvalité är därmed ytterligare en faktor som anses vara viktig att utvärdera hos patienter med en främre korsbandsskada. Postural orientering, dvs. förmågan att positionera kroppsdelar i förhållande till varandra och omgivningen, är en del av rörelsekvalité. I denna avhandling benämner vi avvikande postural orientering som ”Postural Orientation Errors” (POEs). Tredimensionell rörelseanalys (med höghastighetskameror) anses vara ”gold standard” för att mäta postural orientering, men då utrustningen är dyr och kräver ett laboratorium är denna mätmetod inte praktiskt möjlig att använda kliniskt. Därmed behövs det en klinisk användbar metod för att mäta postural orientering, exempelvis med visuell bedömning. Det primära syftet med denna avhandling var därför att utvärdera kliniska mått på postural orientering hos personer med eller utan skada i nedre extremiteten. Sekundära syften var att undersöka om postural orientering skiljer sig mellan män och kvinnor, samt att undersöka eventuella samband mellan postural orientering och andra funktionsmått hos män respektive kvinnor som genomgår rehabilitering efter en främre korsbandsrekonstruktion.

En systematisk litteraturgranskning genomfördes för att sammanfatta mätegenskaper för olika metoder av visuell bedömning av POEs (exempelvis att metoderna mäter det de avser att mäta och att de är tillförlitliga och upprepningsbara) (studie I). Studier på personer med eller utan skada i nedre extremiteten var inkluderade i litteraturgranskningen. I två tvärsnittsstudier (studie II–III) utvecklades ett testbatteri för visuell bedömning av POEs, innehållande övningar med varierande svårighetsgrad för patienter med främre korsbandsskada. Testbatteriets mätegenskaper utvärderades för att säkerställa att testbatteriet mäter det vi avser att det ska mäta och att bedömningarna är tillförlitliga och upprepningsbara. Skillnad i POEs mellan män och kvinnor med främre korsbandsrekonstruktion undersöktes i en tvärsnittsstudie (studie IV). I samma studie undersöktes även sambandet mellan POEs och hoppförmåga och mellan POEs och självskattade variabler (så som knäfunktion och livskvalité).

Denna avhandling visar att visuell bedömning av knäts position i förhållande till foten är relaterad med vissa tvådimensionella och tredimensionella mått hos friska individer, samt att knäts position i förhållande till foten är tillförlitlig och

upprepningsbar mellan olika bedömare och inom samma bedömare. Det fanns inte tillräckligt med studier på andra POEs eller på patienter med skada i nedre extremiteten för att sammanställa något resultat. Testbatteriet för visuell bedömning av POEs innehöll från början 9 funktionella test och 7 POEs. Ytterligare ett test och 2 POEs inkluderades i studie III. Flera funktionella test och POEs exkluderades successivt efter utvärderingar av olika mätegenskaper, vilket resulterade i det slutliga testbatteriet med 5 funktionella test (enbensknäböj, trappgång nerför, utfallssteg framåt, enbenslängdhopp och sidhopp) samt 6 POEs (fot, knä, lår, höft och bål). Avhandlingen visar även att kvinnor har sämre postural orientering jämfört med män, samt att sämre postural orientering är relaterad med kortare hopplängd och färre sidhopp hos kvinnor men inte hos män.

Resultaten från denna avhandling tyder på att visuell bedömning av knäts position i förhållande till foten kan användas hos friska populationer. Det behövs däremot fler studier på visuell bedömning av andra POEs, samt på patienter med skada i nedre extremiteten. Det slutgiltiga testbatteriet för visuell bedömning av POEs visade goda mätegenskaper hos patienter med främre korsbandsskada. Detta tyder på att visuell bedömning av POEs kan användas hos patienter med främre korsbandsskada, både vid forskning och i kliniken. Avhandlingens resultat tyder även på att kvinnor och män bör utvärderas separat med avseende på postural orientering, samt att visuell bedömning av POEs skulle kunna användas av kliniker som stöd vid beslut om progression i rehabilitering av främre korsbandsskada, exempelvis vid initiering av hoppövningar.

List of papers

I. Nae J, Creaby MW, Cronström A, Ageberg E. Measurement properties of visual rating of postural orientation errors of the lower extremity - A systematic review and meta-analysis. Physical Therapy in Sports. 2017, 27:52-64.

II. Nae J, Creaby MW, Nilsson G, Crossley K, Ageberg E. Measurement properties of a test battery to assess postural orientation during functional tasks in patients undergoing ACL injury rehabilitation. The Journal of orthopaedic and sports physical therapy. 2017, 47(11):863-873.

III. Nae J, Creaby MW, Ageberg E. Extended Version of a Test Battery for Visual Assessment of Postural Orientation Errors: Face validity, Internal Consistency, and Reliability. Accepted for publication in Physical Therapy, May 3, 2020. DOI: http://doi.org/10.1093/ptj/pzaa092

IV. Nae J, Creaby MW, Cronström A, Ageberg E. Sex differences in Postural Orientation Errors and association with hop performance and patient reported outcome measures in patients with ACL injury: an exploratory study. In manuscript.

Thesis at glance

Aim/s	Main results	Conclusions
Paper I To systematically review measurement properties of visual observation and rating of postural orientation in people with or without musculoskeletal disorders of the lower extremity	28 studies were included, in which 4 measurement properties were evaluated (content validity, criterion validity, reliability and measurement error). Meta-analysis showed that healthy participants assessed as having a knee medial-to-foot position (KMFP) had an increased peak 2D and 3D knee abduction, and 3D hip internal rotation angle. KMFP showed moderate to almost perfect inter-, and intra-rater reliability in healthy populations.	The KMFP seems to be reliable and valid for use in healthy populations, however it remains to be determined in injured populations. Further studies are needed on other segment-specific POEs, as well as on injured popoulations.
Paper II To assemble a test battery for visual assessment of postural orientation errors (POEs) during functional tasks and to evaluate face validity, interpratability, internal consistency, inter-rater reliability, and measurement error in patients with ACL injury	9 functional tasks and 7 POEs were initially included in the test battery. Face validity discussions resulted in exclusion of 3 tasks, floor effects were found in 4 POEs during different tasks, and internal consistency analysis resulted in exclusion of 2 tasks and one POE. The final test battery was refined to include 4 tasks and 4 POEs, with substantial to almost perfect agreement between two raters.	Good internal consistency, good inter-rater reliability, acceptable measurement error, and no floor or ceiling effects were observed for the final test battery. These results suggest that the test battery is valid and reliable for visual assessment of POEs in patients with ACL injury.
Paper III To further develop the test battery for visual assessment of POEs and evaluate face validity, internal consistency, and inter-rater reliability of this extended version of the test battery in patients with ACL reconstruction (ACLR)	Focus group discussions resulted in that one task (side-hop) and two POEs were added to the test battery from paper II. Internal consistency analysis mainly resulted in exclusion of the trunk deviation in any plane from three tasks. The inter-rater reliability of the side-hop showed substantial to almost perfect agreement. The final test battery included 5 tasks, and 6 POEs.	The result from this paper showed good internal consistency and good inter-rater reliability for the final test battery after including the side-hop, femur medial to shank, and femoral valgus. This suggests that the test battery can be used to evaluate postural orientation in patients with ACLR, both in research and in clinical practice.
Paper IV To evaluate sex differences in visual assessment of POEs and the association between postural orientation and hop performance and PROMs in men and women undergoing rehabilitation after ACLR	Women had significantly worse POE scores compared with men. Shorter hop distance and fewer side-hops were associated with worse POE scores (especially the POE subscale ADL), in women. In men, worse POE scores were associated with longer hop distance. Few moderate associations were found between POE scores and PROMs.	The results indicate that postural orientation should be evaluated for men and women separately, and that the POE subscale ADL could be used by clinicians to decide when to progress to jumping exercise, especially in women.

Definitions

Construct	A well-defined and precisely demarcated subject of measurement [1]
Movement quality	The ability to regulate or direct the mechanisms that are essential to movement, including aspects related to the individual, the task, and the environment [2]
Postural control	A complex motor skill derived from the interaction of multiple sensorimotor processes, mainly postural orientation and postural stability [3]
Postural orientation	The ability to maintain alignment between body segments and the environment during a static or dynamic activity [3]
Postural stability	The coordination of sensorimotor strategies to stabilise the body's centre of mass during self-initiated and externally triggered disturbances [3]
Physical function	The ability to move around and perform daily and recreational activities [4, 5]
Patient-reported outcomes (PROs)	A measures of outcomes reported directly from the patient without any interpretation by anyone else [6]
Patient-reported outcome measures (PROMs)	Tools for measuring PROs, often patient-reported questionnaires [6]
Measurement properties	Features of a measurement instrument that reflect the quality of the measurement instrument [7]

Abbreviations

2D: Two-dimensional
3D: Three-dimensional
ACL: Anterior cruciate ligament
ACLR: Anterior cruciate ligament reconstruction
ACL-QoL: The Anterior Cruciate Ligament-Quality of Life
ADL: Activity of daily living
COHD: Crossover hop for distance
COSMIN: COnsensus-based Standard for the selection of health Measurement Instruments
DJ: Drop-jump
DS: Deep squat
FL: Forward lunge
ICC: Intraclass Correlation Coefficient
KOOS: Knee Injury and Osteoarthritis Outcome Score
KMFP: Knee Medial-to-Foot Position
K-SES: Knee Self-Efficacy Scale
LESS: The Landing Error Scoring System
MS: Mini squat
OA: Osteoarthritis
POEs: Postural Orientation Errors
PRISMA: the Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PROs: Patient-Reported Outcomes
PROMs: Patient-Reported Outcomes Measures
PROSPERO: the International Prospective Register of Systematic Reviews
SA: Stair ascending
SD: Stair descending
SDM: Standard difference in mean
SEM: Standard error of measurement
SF-36: the 36 Item Short-Form Health Survey
SH: Side-hop
SLHD: Single-leg hop for distance
SLS: Single-leg min squat
Sport/rec: Sport and recreation

Introduction

Anterior cruciate ligament injury

Anatomy

The anterior cruciate ligament (ACL) is an intra-articular ligament that provides stability to the knee joint [8, 9]. The main function of the ACL is to limit the motions of anterior tibial translation and internal tibial rotation [8, 9]. The ligament consists of two bundles, the anteromedial bundle and the posterolateral bundle, which provide stability to the knee during different motions. When the knee is flexed the anteromedial bundle provides stability, and the posterolateral is loose, while during knee extension the posterolateral bundle is tight and the anteromedial bundle is loose [10]. Thus, the ACL is an important structure that provides stability throughout the range of motion.

Injury mechanism

ACL injury is common among young and physically active populations that perform sports that include motions of twisting, cutting, and changes of direction, such as soccer, handball, and basketball [11]. The injury mechanism of a torn ACL has been analyzed from video recordings during handball and basketball matches [12, 13]. A consistent kinematic pattern has been observed at the time of injury, and at the initial contact phase the knee is close to extension, and just after initial contact increased knee flexion, knee abduction and internal rotation of the knee occurs [12, 13]. Next, external rotation of the knee has been observed, which is suggested to be the result of the torn ACL [12]. The etiology of ACL injury is complex, and several factors are suggested to increase the risk of injury, including both extrinsic factors (i.e., from outside the body) and intrinsic factors (i.e., within a person) [14, 15]. Examples of extrinsic risk factors that are suggested to increase the risk of an ACL injury are playing on wet or artificial grass, the type of shoes worn, and cold weather conditions [14, 16-18]. Some suggested intrinsic risk factors are female sex, kinematic asymmetry, increased knee joint laxity, lower hamstrings to quadriceps strength ratio, family history of ACL injuries, and previous knee injury [14, 19-21]. Thus, such complexity makes the prevention of ACL injuries challenging.

Epidemiology

The reported annual incidence of MRI-verified ACL injuries in the general population aged 10 to 64 years is 0.81 per 1,000 persons [11], and the incidence among athletes is reported to be 1.5 per 10,000 athlete exposures (played hours or player-days) [22]. Women have an incidence of 1.9 ACL injuries per 10,000 athlete exposures, while men have an incidence of 0.9, which corresponds to a 1.7 times increased incidence rate in women compared to men [22]. The risk of re-injury is a concern for those returning to sport, and the incidence rate of a second ACL injury (i.e., re-injury or an injury to the contralateral knee) is reported to be 18.2 per 10,000 athlete exposures [23]. In the event of a second ACL injury, it usually occurs within the first 2 years after return to sport [24, 25], which has raised concerns that athletes are returning to cutting and pivoting sports too early [26].

Consequences of ACL injury

An injury to the ACL results in both acute short-term consequences, such as, pain, swelling, and reduced range of motion, and long-term functional impairments, such as joint instability [27], changed kinematic patterns [28, 29], reduced and/or asymmetrical muscle strength [30], and worse hop performance [31]. These impairments can have consequences such as a re-injury [19, 21, 32, 33] and/or early onset of knee osteoarthritis (OA) [34-36]. A systematic review reported a prevalence of 0–100% for radiographic knee OA more than 10 years after ACL injury and a prevalence of 15–35 % for symptomatic knee OA [37]. Therefore, the evaluation of treatment outcomes, e.g., potential risk factors for re-injury and knee OA, may be important for a successful ACL injury rehabilitation and for preventing future re-injury or disease.

Treatment of an ACL injury

Treatment of an ACL injury includes either rehabilitation alone or rehabilitation combined with reconstructive surgery of the ligament [38, 39]. Factors such as young age and high activity level are mentioned as possible indicators for surgery [40]. It has been reported that surgery does not seem to improve objective physical function (i.e., strength, hop performance) or self-reported outcomes compared with rehabilitation alone [40-43]. Only one high-quality RCT (the KANON study) has been performed comparing surgical treatment with rehabilitation alone [41]. The KANON data do not support one treatment option over the other, but the results suggest that patients with ACL injury should start with non-surgical treatment before surgery is considered [40, 43].

Contemporary approaches to rehabilitation have focused on the time since injury/surgery during the different phases of rehabilitation, e.g., phase 2 was

described as week 2 to 9, phase 3 as week 9 to 16, and so on [44]. Recently, rehabilitation guidelines have changed from this time-based approach, to an individualized and criterion-based approach, i.e., a patient should progress to the next phase in rehabilitation when certain goals are achieved, e.g., a predefined range of motion or strength symmetry [38, 39]. There are usually four phases, with different goals to achieve, described in clinical guidelines for ACL injury rehabilitation [38, 39]. The preoperative phase is for those who plan to undergo an ACL reconstruction (ACLR) [38], and this phase should start as soon as possible to improve postsurgical outcomes [45]. In the acute phase, the rehabilitation focuses on reduced knee joint effusion and restored range of motion. In the intermediate phase, the goal is to increase muscle strength and to be able to perform sport-specific activities, such as single-leg jumping. To prepare the patient for a safe return to sport, the late phase of rehabilitation should focus on sport-specific demands and on the patient's own specific goals and expectations [38, 39]. Therefore, with an individualized approach the rehabilitation process is customized to each patient depending on the demands of their sport, what level they want to return to, and their own personal goals.

Evaluation of treatment outcomes

Evaluation of treatment outcomes is important in health care to monitor progress or setbacks, to make decisions regarding progress from one phase in rehabilitation to the next, and for decisions regarding return to sport [38, 39, 46]. The main goal with ACL injury treatment is to optimize long-term quality of life (e.g., patient-reported outcomes (PROs)) and to restore physical function (e.g., muscle strength, hop performance, and movement quality) [38, 39]. General questions for the physical therapist to reflect on before they allow the athlete to go back to sports are whether there has been sufficient time since the injury/surgery for the graft to heal, and whether the athlete is psychologically and physically ready to return to sport.

Patient-reported outcome measures (PROMs)

PROs are the responses from the patient without interpretation by anyone else [6], and the value of PROs has gained increased focus in health care in recent decades [47]. Patient-reported outcome measures (PROMs) are tools to measure PROs [6]. PROMs can be either generic (general quality of life, e.g., the 36 Item Short-Form Health Survey (SF-36)), disease-specific (focusing on a specific disease/injury, e.g., The Anterior Cruciate Ligament-Quality of Life (ACL-QoL)), or domain-specific (focus on a specific domain of a disease/injury, e.g., Knee Injury and Osteoarthritis Outcome Score subscale Sport and recreation (KOOS Sport/rec)) [6]. A systematic review reported that impaired knee-specific QoL still persists in patients ≥5 years after ACL injury [42]. Psychological factors, such as fear of re-injury and low confidence in their knee, are associated with not returning to the same level of sport

after ACLR [48, 49]. Therefore, it is important to evaluate whether the patient is psychologically ready to return to sport during rehabilitation of an ACL injury.

Physical function

Physical function is defined as the ability to move around and perform daily and recreational activities [4, 5], including multidimensional aspects such as mobility, muscle performance, and movement quality [5]. Muscle strength is an important measure of objective physical function, and it is often measured as peak torque. Patients with ACL injury have reduced muscle strength, especially in the knees and hips, compared with healthy populations [30], and this reduction in muscle strength has been reported to persists for as many as 20 years after injury compared with healthy controls [50]. Single leg hop tasks are commonly used to measure physical function after ACL injury in both clinical settings and in research [31, 51]. For measures of hop performance and muscle strength, the limb symmetry index (LSI) is often used to compare side-to-side differences [43]. The LSI is a score for the injured leg, expressed as the percentage of the performance of the non-injured leg (LSI = (injured leg/non-injured leg) x 100) [52]. However, the use of LSI has been questioned by some authors [53-55]. An ACL injury leads to a reduced level of physical activity, which may result in reduced muscle strength in the non-injured leg as well [53, 54]. Thus, the LSI might overestimate the patient's knee function, which may result in returning to sport too early with an increased risk of re-injury as a possible outcome [53, 55]. Also, measures of muscle strength or hop performance do not reveal information regarding movement quality during the performance of functional tasks, an aspect that may be important regarding the risk of re-injury [19, 21, 39].

Movement quality can be defined as the ability to regulate or direct the mechanisms that are essential to perform a specific movement, including aspects related to the individual, the task, and the environment [2]. Movement quality has gained increased interest in recent years, and this has led to the development of several movement screening tools, especially in healthy active populations [56]. However, a potential limitation with several of these screening tools is the use of a sum score, which often is a combination of different mechanisms (multidimensional constructs) that are essential to perform an optimal movement, such as range of motion, balance, and alignment between segments [56-58] (Table 1). The recommendation from the COSMIN guidelines is to include one score for each construct because a sum score with multidimensional constructs results in lost information regarding each separate construct [1]. Also, if using a sum score good internal consistency needs to be obtained to ensure a unidimensional construct [1]. The internal consistency was evaluated for the Functional Movement Screen (FMS) [59] with the aim to assess movement quality (e.g., range of motion, alignment, pain, and balance) [59-61]. The result showed poor Cronbach's alpha for the sum score ($\alpha = 0.39$) [59], indicating that it is inappropriate to use the sum score, possibly because of multidimensional

constructs [1]. Therefore, test instruments for evaluation of movement quality should predefine the construct or constructs under study to make sure that the score of the test instrument measures the construct it intends to measure, e.g., range of motion, balance, or postural orientation.

Table 1. Examples of movement quality screening tools that use various constructs in their sum score

Author (year)	Screening tool	Constructs assessed and summed into a total score
Cook et al. 2006 [60, 61]	Functional movement screen (FMS)	Postural orientation, range of motion, pain, balance
Frohm et al. (2012) [62]	Nine-test screening battery (F-9)	Postural orientation, range of motion, pain, balance
Harrison et al. (1994) [63]	Single leg standing test	Postural orientation, balance
McCunn et al. (2017)[64]	The Soccer Injury Movement Screen (SIMS)	Postural orientation, muscle stiffness, balance, landing technique
McKeown et al. (2014) [65]	Athletic Ability Assessment (AAA)	Posturla orientation, balance, depth of a squat, landing technique
Padua et al. (2009) [58]	The Landing Error Scoring System (LESS)	Postural orientation, stance width, knee stiffness in landing
Trulsson et al. (2010) [57]	The test for substitution patterns (TSP)	Postural orientation, balance, stiffness, body weight distribution, stride length

Postural orientation

Postural control is a complex motor skill derived from the interaction of multiple sensorimotor processes, mainly from postural stability (e.g., balance) and postural orientation (e.g., the knee in relation to the foot) [3]. The definition of postural orientation is the ability to maintain alignment between body segments and the environment during a static or dynamic activity [3]. Patients who return to sports with altered postural orientation (e.g., increased three-dimensional (3D) knee abduction) may have an increased risk of sustaining a second ACL injury [19, 21]. Two cross-sectional studies report that patients with ACL injury had altered postural orientation, in terms of reduced 3D hip abduction and knee flexion angle, during jump-landing tasks compared with healthy controls and compared with the non-injured leg despite having normal quadriceps strength and hop symmetry (i.e., LSI ≥90%) [66, 67]. Thus, evaluation of postural orientation is suggested to complement aspects not captured by measures of strength or hop performance [38, 39, 53, 55]. There are several ways in which postural orientation can be evaluated, for example with two-dimensional (2D) and 3D motion analysis systems and by visual assessment [55, 68, 69].

3D motion analysis

The 3D motion analysis system is referred to as the "gold standard" for measuring postural orientation [58, 68]. A common method is to use an eight or nine-camera motion analysis system to capture motions in all planes, i.e., frontal, sagittal, and transverse planes [69-72]. Reflective markers are attached to pre-specified anatomical landmarks on the body, and then the angles are calculated based on the positions of these reflective markers, which are supposed to represent the movement of the bones. However, the equipment is expensive, laboratory-based, and time-consuming and requires an expert for analyzing and interpreting the results, therefore, it is not a clinically feasible method to assess postural orientation.

2D motion analysis

A simpler way than the 3D motion analysis is to evaluate postural orientation with 2D measurements, using a single video camera. The 2D measurement is a projection of the plane aligned with the camera, thus it is not the true movement of an anatomical plane [69]. One example of a commonly used 2D measure is the frontal plane projection angle, which is the angle created by the intersection of the line between the ankle and patella and the line between the anterior superior iliac spine and patella [73]. Cross-sectional studies report that the frontal plane projection angle is associated with 3D knee abduction [74] and 3D hip adduction angles [73] and with visual assessment of changes in lower extremity movement patterns [75].

Visual assessment

Visual assessment of postural orientation is a clinically feasible method to evaluate postural orientation during the performance of functional tasks, and it can be performed either live in a clinical setting or from video recordings [68, 76]. The methods used to visually assess postural orientation vary in the literature according to the choice of scoring scale (e.g., binary or ordinal) [68, 76], the assessment of a single joint/segment or multiple joints/segments [68, 76-78], and the choice of a single task or the use of a variety of tasks [68, 76, 79]. Thus, there is no established systematic approach of how to visually assess postural orientation, see Table 2 for examples of different methods used for visual assessment of postural orientation (for details, see paper I).

Table 2. An overview of methodological differences in visual assessment of postrual orientation

Author (year)	Video or live assessments	Use of scoring scale	Specific joint/segments assessed	General assessment of whole body/parts of body	Task/s used
Ageberg et al. (2010) [68]	Live	Binary (Yes/no)	Knee medial to foot position	No	Single-leg mini squat
Chmielewski et al. (2007) [78]	Both live an from video	4-point oridinal scale	Trunk, pelvis and hip	Trunk, pelvis, knee	Single-leg mini squat, lateral step-down
Stensrud et al. (2011) [79]	Live	3-point ordinal scale	na	Pelvis, knee	Single-leg mini squat, single-leg vertical drop-jump, two-legged vertical drop-jump
Whatman et al. (2012) [76]	From video	Binary (Yes/No) 3-point, and 4-point ordinal scale	Trunk, pelvis, knee and foot	Trunk, pelvis, knee, foot	Small knee bend,single-leg mini squat, forward lunge, hop lunge
Örtqvist et al. (2011) [77]	Live	Cathegorical (medial, lateral or neutral)	Knee medial to foot position	No	Single-leg mini squat

na=not applicable

Sex difference in postural orientation

Several studies have shown that women have worse 3D knee abduction during a drop-jump task compared with men [19, 80, 81]. However, in visual assessment of movement quality there are to our knowledge only two studies reporting on sex differences. The results show that healthy women, and women with ACL injury, have worse movement quality compared with men, measured with the Landing Error Scoring System (LESS) [58, 82]. However, the LESS combines different constructs in its sum score (e.g., postural orientation, stance width, and stiff landing), and it is only assessed during a single task [58, 82]. Thus, there is still limited evidence as to whether there are sex differences in visual assessment of postural orientation. Such information could add value to clinical practice, e.g., whether men and women with ACL injury should be treated differently regarding postural orientation.

Measurement properties of a test instrument

To be able to draw conclusions based on scores from test instruments they need to be valid and reliable [83]. Consequently, before a test instrument can be used in research and in clinical practice the measurement properties (e.g., reliability, validity, and responsiveness) of the test instrument need to be evaluated [83]. The COnsensus-based Standards for the selection of health Measurement Instruments

(COSMIN) panel conducted an international Delphi study to reach consensus regarding the taxonomy, terminology, and definitions of different measurement properties [25]. The COSMIN panel has also developed a checklist for assessing the methodological quality of studies that report the measurement properties of health measurement instruments [83]. The aim with this checklist is to improve the quality of research on test instruments [83]. The COSMIN guidelines mention three main quality domains, i.e., reliability, validity, and responsiveness. These domains include one or more measurement properties to be evaluated (e.g., the reliability domain includes reliability, internal consistency, and measurement error) (Figure 1) [25].

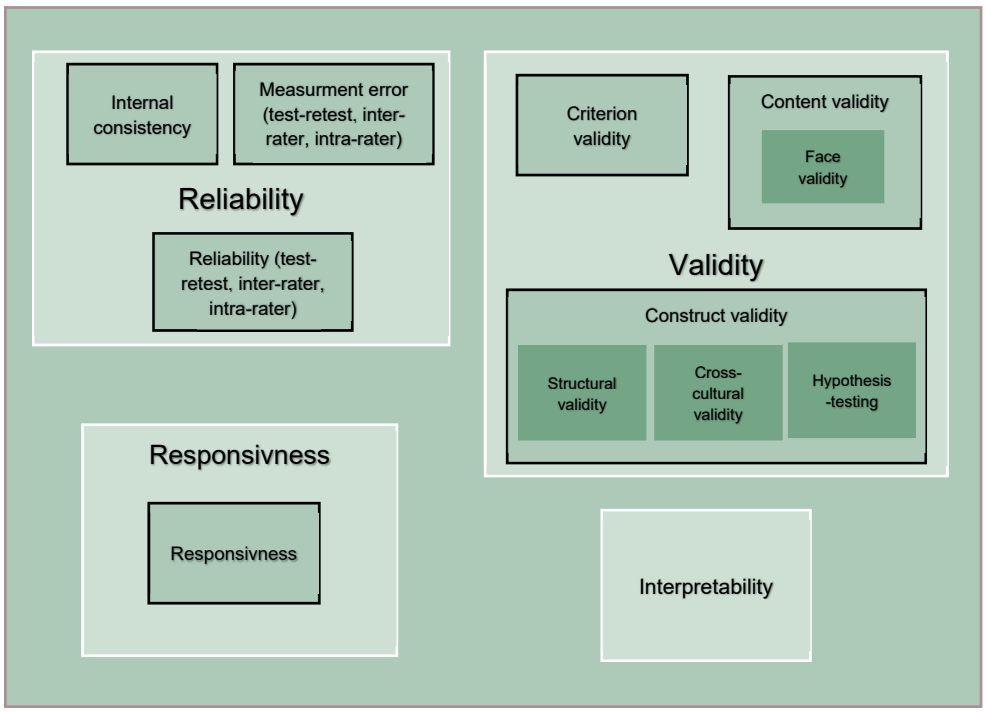


Figure 1. The taxonomy of relationships between measurement properties defined by the COSMIN panel. Adapted from Mokkink et al 2010 [25].

Reliability

Reliability is defined as "the degree to which the measurement is free from measurement error" [25], i.e., how well the measurement can distinguish between patients despite the presence of measurement error [1]. High reliability is of great importance to be able to trust that the test instrument can produce consistent results

over repeated measurements. Measurement properties under this domain include internal consistency, reliability, and measurement error [25].

Internal consistency

Internal consistency measures the interrelatedness among items in a score [25], i.e., whether items measure the same construct. This is often evaluated with Cronbach's alpha (α), with values between 0.7 and 0.95 considered good [83]. The item-total correlation value is also an indicator of whether items correlate with a total score [84]. An item-total correlation value above 0.3 indicates that the item is a good contributor to the construct of the total score of a test instrument, whereas values below 0.3 indicate that the item does not contribute to the construct of the score [84].

Reliability

Reliability is a measure of whether the outcome of a test instrument is the same on different test conditions. Reliability includes evaluation of test-retest (between different test occasions), inter-rater (between different raters), and intra-rater (within a rater) reliability [25]. Intraclass correlation coefficient (ICC) and kappa statistics are commonly used [1, 83, 85], and values >0.6 are considered to indicate substantial agreement [86]. ICC statistics are appropriate for continuous or ordinal data, and kappa statistics are appropriate for ordinal or categorical data [1, 87].

Measurement error

Measurement error is the systematic and random error in a score that is not due to a true change in the construct to be measured [25], and such errors can be evaluated with standard error of measurement (SEM) and limits of agreement [88].

Validity

Validity is the degree to which a measurement instrument measures the construct it proposes to measure [25]. Measurement properties under this domain include content validity, construct validity (e.g., structural validity, hypothesis testing) and criterion validity [25].

Content validity

Content validity is the degree to which the content of a measurement instrument reflects the construct to be measured [25]. It is based on judgment of the relevance of the items within a test instrument, i.e., their relevance for the construct under study and for the population under study [89]. The first aspect in the validation process is to discuss if the items within a test instrument seem to be an adequate reflection of the construct to be measured (face validity) [25]. No quantitative measures are used to assess face validity [1]. One approach is to gather a group of experts (patients and/or health care providers) and ask for their first impression of

whether an item included in a test instrument represents the construct under study [1].

Construct validity

Construct validity is defined as the degree to which the score of a measurement instrument is consistent with hypotheses, e.g., with regard to internal relationships, relationships with other instruments, or differences between relevant groups [25]. Construct validity should be used when there is no "gold standard" measurement to compare the result with. In construct validity, it is assumed that the test instrument measures the construct to be measured, and it can be evaluated regarding three aspects, i.e., structural validity, hypothesis testing, and cross-cultural validity [25].

Criterion validity

Criterion validity is the degree to which a measurement instrument reflects a "gold standard" measurement [25]. Criterion validity can be divided into concurrent validity (i.e., the association between the score of the gold standard and the score of test instrument under study) and predictive validity (i.e., the ability of the test instrument to predict the result of the gold standard measurement) [1]. The association between the two scores can be evaluated using Spearman's, or Pearson's correlation coefficients [1].

Responsiveness

Responsiveness is the ability of a measurement instrument to detect change over time in the construct to be measured, i.e., the validity of a change score [25]. Test instruments used in clinical practice need to be able to evaluate patients over time in order to know whether they are improving or getting worse. Thus, responsiveness is an essential measurement property to evaluate in a test instrument [25].

Interpretability

Interpretability is an important characteristic of a test instrument included in the COSMIN taxonomy, however, according to the COSMIN panel it is not considered a measurement property [25]. The reason for not being interpreted as a measurement property is because interpretability does not refer to the quality of the measurement instrument, but to the degree to which it is clear what the scores from a measurement instrument means [1]. One part of interpretability is whether the score of a test instrument has floor and ceiling effects, i.e., the percentage of patients who achieve the minimum and maximum score of a test instrument [1]. Floor and ceiling effects can affect the responsiveness of a test instrument, e.g., with floor effects present at baseline no further improvements can be detected by the test instrument at follow-up, thus resulting in poor responsiveness [1]. Therefore, it is important to evaluate interpretability in order to make sure that a test instrument has the potential to detect change over time.

Rationale of the thesis

Visual assessment of postural orientation has gained a lot interest in recent years, and there is an increasing number of studies on the measurement properties of visual assessment of postural orientation [68, 76, 78, 79, 90-92]. However, until now, a systematic summary of the knowledge of measurement properties of visual assessment of postural orientation has not been conducted.

Altered postural orientation (i.e., 3D hip and knee kinematics) is suggested to be a risk factor for sustaining a second ACL injury [19, 21]. Three-dimensional motion analysis is the "gold standard" for measuring postural orientation, but visual assessment of postural orientation is better suited as a clinical method. Thus, there is a need for a systematic approach for visual assessment of postural orientation during functional tasks in patients with ACL injury.

Results from previous studies suggest that women with ACL injury have worse postural orientation (e.g., increased 3D abduction) during a jumping task compared with men [19, 80]. However, until now sex differences have not been studied for visual assessment of postural orientation as a separate construct during the execution of daily and sport-specific activities.

Body functions (e.g., range of motion, muscle strength, and postural orientation) are prerequisites for performing complex tasks such as jumping and for self-reported function. However, there is limited research on the associations between postural orientation and hop performance and PROMs or whether these associations differ between men and women with ACL injury.

Overall aim and goal of the thesis

The overall aim of the thesis was to develop and evaluate clinically feasible measures of postural orientation in participants with or without injury to the lower extremity. The goal was to assemble a clinically feasible test battery that is valid and reliable to use during different phases of the rehabilitation process for both men and women with ACL injury.

Specific aims

1. Systematically review the measurement properties of visual observation and rating of postural orientation in participants with or without musculoskeletal disorders of the lower extremity (paper I).
2. Assemble a test battery for assessing postural orientation during functional tasks with increasing demands on the lower extremity (papers II-III).
3. Investigate the face validity, interpretability, internal consistency, inter-rater reliability, and measurement error of the test battery for visual assessment of postural orientation in patients with ACL injury (papers II-III).
4. Determine sex difference in postural orientation and the association between visual observation of postural orientation and hop performance and Patient-Reported Outcome Measures in men and women undergoing rehabilitation after ACL-reconstruction (paper IV).

Methods for papers I–IV

Overview of the papers

Table 1. Overview of the papers included in the thesis

	Paper I	Paper II	Paper III	Paper IV
Study design	Systematic review and meta-analysis	Cross-sectional study	Cross-sectional study	Cross-sectional study
Material/ Participants	Previous studies with evalaution of measurement properties of visual assessment of postural orientation	Patients (n=51) with ACL injury, with or without ACLR, age between 18-39	Patients (n=53) with ACLR, age between 18-40	Men (n=29) and women (n=24) with ACLR, age between 18-40
Methods	Systematic review according to PRISMA guidelines. Metodological quality of measurement properties of visual assessment of postural orientation assessed according to the COSMIN checklist.	Development and evaluation of measurement properties of a test battery for visual assessment of postural orientation	Further development and evaluation of measurment properties of an extended version of the test battery	Sex differences in postural orientation, and associations with other measures of physical function and self-reported outcomes
Data analysis	Meta-analysis performed when possible, otherwise repored descriptevely.	Face valdity discussions, test for interpretability (floor and ceilig effects), internal consistency (Cronbach's alpha) and inter-rater reliability ($ICC_{2,1}$, quadratic weighted kappa)	Face valdity discussions, test for internal consistency (Cronbach's alpha) and inter-rater reliability ($ICC_{2,1}$, quadratic weighted kappa)	Mann-Whitney test for analysis of sex differences in postural orientation , Spearman's rank correlation coefficient for analysis of associations between postural orientation, hop performance and PROMs

ACL=anterior crutiate ligament, ACLR=anterior crutiate ligament injury, PRISMA= Preferred Reporting Items for Systematic Reviews and Meta-Analyses, COSMIN= COnsensus-based Standards for the selection of health Measurement Instruments, ICC= intraclass correlation coefficients, PROMs= patient-reported outcome measures

Materials and Participants

The first paper was a systematic review and meta-analysis with the purpose to summarize what has been reported regarding the measurement properties of visual assessment of postural orientation. Paper I included 28 articles, 5 of which included populations with musculoskeletal injury (n = 92) and 23 of which included healthy subjects (n = 1298) (Figure 1). In paper II, the cohort consisted of 51 patients with ACL injury (23 women, 28 men), with or without reconstructive surgery, recruited from physical therapy clinics in Skåne, Sweden, during the years 2012–2013. Exclusion criteria were age <18 and >40 years, use of crutches, and injuries or diseases overriding the symptoms of the knee injury (Figure 2). Papers III and IV included the same cohort of 53 patients (24 women, 29 men) with ACLR, mainly recruited from the Department of Orthopedics, Skåne University Hospital, Sweden. Invitations to participate in the study were sent out to all patients who had undergone an ACLR during the time period 1 June 2015 until 15 March 2016 (n = 165). In addition, the study was advertised at physical therapy clinics in Skåne, Sweden (Figure 3). Exclusion criteria for papers III and IV were age <18 and >40 years, less than 16 weeks post-ACLR or having finalized their rehabilitation, use of crutches, medial collateral ligament injury grade 3, and injuries or diseases overriding the symptoms of the knee injury. See Table 3 for patient characteristics for papers II–IV.

The original papers in this thesis were approved by the Advisory Committee for Research Ethics in Health Education at the Faculty of Medicine of Lund University (VEN 48-12) and by the Region Ethical Review Board in Lund, Sweden (2014/163 for paper II and 2015/581 for papers III-IV).

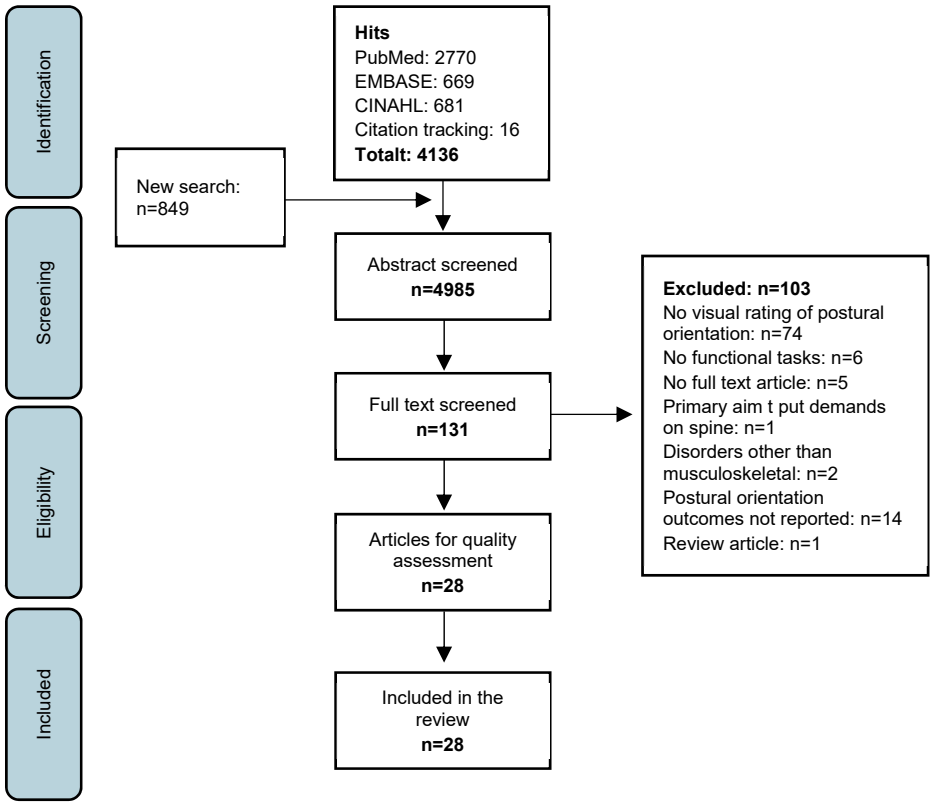


Figure 1. Flow chart of the inclusion and exclusion process in paper I

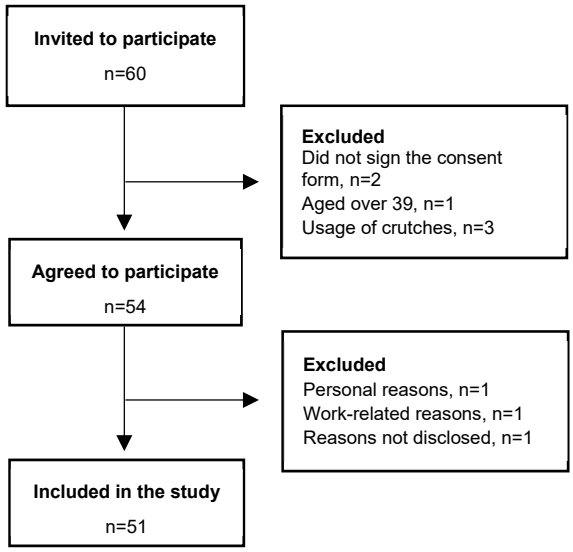


Figure 2. Flow chart of inclusion process in paper II

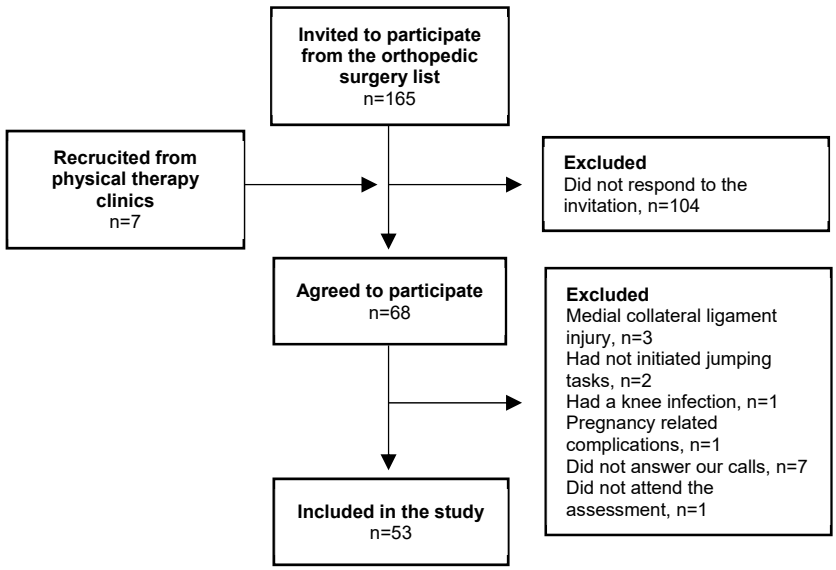


Figure 3. Flow chart of inclusion process in paper III-IV

Table 3. Patient characteristics papers II-IV

Characteristics	Paper II	Papers III-IV		
	Total n=51 (28 men, 23 women)	Men n=29	Women n=24	Total n=53
Age (years)*	24.5 (5.5)	27.1 (6.2)	26.3 (6.9)	26.7 (6.5)
Height (cm)*	177 (7.5)	179 (6.7)	167 (5.8)	174 (8.7)
Weight (kg)*	75 (12)	80.6 (12.7)	67.7 (9.2)	75 (13)
BMI (kg/m^2)*	24 (2.8)	25 (3.2)	24.3 (3.3)	24.7 (3.2)
Tine since injury, for non-reconstructed n=13 (weeks)*	39 (40)	na	na	na
Reconstruction, n (%)	38 (75)	29 (100)	24 (100)	53 (100)
ACL revision surgery, n (%)	3 (6)	2 (6.9)	5 (20.9)	7 (13.2)
Time since ACLR (weeks)*	42 (47)	28.4 (6.3)	27 (6.7)	28 (6.5)
Associated injuries, n (%)	34 (67)	22 (75.9)	17 (70.8)	39 (74)
Bilateral ACL, n (%)	2 (4)	2 (6.9)	3 (12.5)	5 (9)
Meniscal injury, n (%)	25 (49)	19 (65.5)	14 (58.3)	33 (62)
Collateral ligament injury, n (%)	14 (28)	7 (24.1)	6 (25)	13 (25)
Cartilage, n (%)	16 (31)	7 (27.6)	3 (12.5)	11 (21)
Other, n (%)	1 (2)	1 (3.4)	2 (8.3)	3 (6)
Tegner activity level pre-injury †	9 (8-9)	8 (6-9)	8 (6-9) n=23	8 (6-9)
Tegner activity level at test occasion †	4 (3-7)	3 (2-4.5)	3 (3-4) n=23	3 (2.25-4)
KOOS subscales*				
Pain	74 (18.5)	61 (14.6)	59 (8.1)	60 (12.1)
Symptoms	84 (15.9)	81 (12.2)	86 (11.2)	83 (11.9)
Function in daily living	92 (10.8)	94 (8.5)	95 (7.3)	95 (7.9)
Function in sport/recreation*	59 (27.1)	58 (21.9)	59 (24.8)	59 (23)
Knee related QoL	53 (22.5)	48 (19.8)	50 (14.7)	49 (17.6)

†=median (quartiles), *=mean (SD), BMI=body mass index, ACL=anterior cruciate ligament, KOOS=Knee Injury and Osteoarthritis Outcome score, QoL=qualit of life, na=not applicable

Systematic review (paper I)

The systematic review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The protocol was registered in the International Prospective Register of Systematic Reviews (PROSPERO) (2013: CRD42013005414).

Literature searches

Systematic searches were conducted in the Medline (PubMed), CINAHL and EMBASE databases in August 2013, and an updated search was performed in August 2016. The search terms included the following three main filters: 1) words describing the constructs under study (e.g., postural orientation, movement quality), 2) words describing the targeted population (e.g., knee, lower extremity), and 3) words describing the measurement properties (e.g., validity, reliability). For a detailed description of the search strategy see paper I.

Eligibility criteria and methodological quality

Full text original studies reporting at least one measurement property for a method of visual assessment of postural orientation during the performance of a functional task were included in the review. Studies on healthy participants or patients with lower extremity injuries, studies on men and/or women, and with persons of all ages were included. Screening of the titles, abstracts, and full text papers against the eligibility criteria was performed independently by two of the authors. The methodological quality of the studies that met the inclusion criteria was then assessed by the same authors using a checklist for quality assessment of observational studies [93]. To be included in the review, a quality index score of ≥50% was required. Methodological quality was evaluated for each specific measurement property in the included studies using the COSMIN checklist [94].

Development of a test battery for visual assessment of postural orientation errors (POEs) (papers II–III)

Focus group discussions were held in papers II–III to discuss the face validity of the test battery for visual assessment of postural orientation. In this thesis, undesirable postural orientation is referred to as postural orientation errors (POEs). In paper II, three physical therapists, with 3–15 years of clinical experience, discussed and determined which tasks and segment-specific POEs to be included in the initial test battery. The decisions were based on current scientific knowledge, e.g., the results from paper I, and clinical experience. In the next step, two additional experts were included in the focus group, including one exercise scientist with a doctoral degree specializing in biomechanics and one physical therapist with a doctoral degree. The relevance of the tasks and POEs was discussed in this focus group, resulting in the inclusion and exclusion of tasks and POEs in paper II. In paper III, three experts (two physical therapists and one exercise scientist) from the focus group in paper II discussed the need for additional tasks and POEs to contribute new content to the

construct of postural orientation, resulting in one additional task and two additional POEs.

Functional tasks used for visual assessment of POEs (papers II–IV)

In this thesis, functional tasks with increasing difficulty were included to simulate the progression from daily activity tasks to sport-specific tasks, representing the start and end-phase of rehabilitation. Ten tasks were included in the thesis (papers II–IV) and five tasks remained in the final test battery (papers III–IV) (Figure 4 A–E). The participants performed all tasks on their injured leg at one test occasion and they wore shorts, sports bras (women), and their own shoes. Three practice trials were allowed to familiarize them with the task and to avoid learning effect. The execution of each task was video recorded from a frontal view (paper II: 1920 × 1080 pixels, 30 Hz, Everio GZ-HM650BE, JVC, Yokohama, Japan; paper III: 1920 × 1080 pixels, 30 Hz, Qualisys motion capture system, Gothenburg, Sweden) for later assessment of segment-specific POEs. All tasks included in this thesis were based on previously reported studies, and the executions are described below.

Mini squat (paper II) [57]

Instructions for the mini squat (MS) were to stand barefoot with feet hip-width apart, squat until knees were flexed to approximately 70°–90°, and then rise again. The task was repeated 5 times. POEs were assessed during the entire movement.

Single-leg mini squat (papers II–IV) [68]

Instructions for the single-leg mini squat (SLS) were to flex the knee, until they could not see their toes (approximately 60°), and then return to extension (paper II). The task was repeated 5 times. POEs were assessed during the entire movement. In paper III, an adjustable bench was placed behind the patient to ensure that the depth of the squat was 60°.

Stair ascending (paper II) [95]

Instructions for the stair ascending (SA) were to take a step onto the step board (30 cm high) and return to the starting position in front of the step board. The leading leg was evaluated. The task was repeated 5 times, and POEs were assessed during the loading phase.

Stair descending (papers II–IV) [96]

Instructions for the stair descending (SD) were to step down from a 30 cm high step board and then return to the starting position. The loading leg was evaluated. The task was repeated 5 times. POEs were assessed during the loading phase of the step-down movement.

Forward lunge (papers II–IV) [97]

Instructions for the forward lunge (FL) were to take a long stride forward, flex the knees to approximately 90°, and push back to starting position by extending the front leg. The task was repeated 3 times. POEs of the front leg were assessed from the first contact with the floor until maximum knee flexion.

Deep squat (paper II) [60]

Instructions for the deep squat (DS) were to place the hands behind the neck and slowly flex the knees into as deep a squatting position as possible, and then return to the starting position. It was allowed for the heels to lift from the floor. The task was repeated 3 times, and POEs were assessed during the entire movement.

Drop-jump (paper II) [19]

Instructions for the drop-jump (DJ) were to drop from the step board with both feet leaving the box simultaneously, then perform a maximal vertical jump upon landing. Arm swing was allowed. The task was performed 3 times, and POEs were assessed during the second landing, from the first contact with the floor, to extended knees.

Single-leg hop for distance (papers II–IV) [98]

Instructions for the single leg hop for distance (SLHD) were to jump forward as far as possible, taking off and landing on the same foot and maintaining balance upon landing for 2 to 3 seconds. Arm swing was allowed during the jump. The task was repeated 3 times, and POEs were assessed from first contact with the floor to approximately 3 seconds after landing.

Crossover hop for distance (paper II) [99]

Instructions for the crossover hop for distance (COHD) were to jump forward as far as possible diagonally crossing a line 3 consecutive times, taking off and landing on the same leg and maintaining balance for 2 to 3 seconds at the last landing. Arm swing was allowed during the jump. The task was repeated 3 times, and POEs were assessed at the last landing, from first contact with the floor to approximately 3 seconds after landing.

Side-hop (papers III–IV) [100]

Instructions for the side-hop (SH) were to hop on the injured leg from side-to-side (i.e. in the frontal plane) over two parallel lines, 30 cm apart, 7 times at a self-selected pace, commencing with a hop lateral to the test leg. POEs were assessed when the patella reached its lowest point (maximum knee flexion) during 3 medial and 3 lateral landings, whereof the last landing was not assessed.

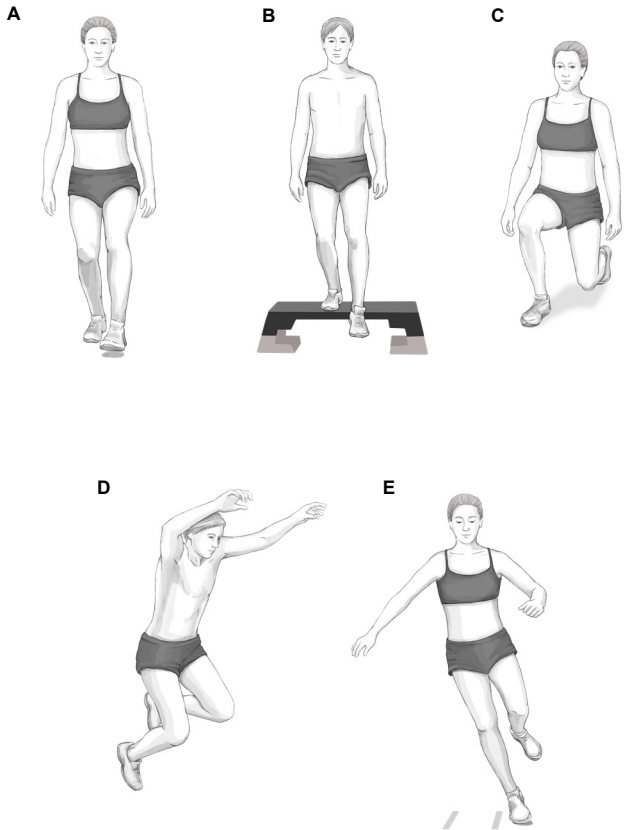


Figure 4 A–E. Functional tasks included in the final test battery: A) sinle-leg mini squat, B) stair descending, C) forward lunge, D) single-leg hop for distance, and E) side-hop. ©Frida Nilsson

Segment-specific POEs

Nine segment-specific POEs were chosen to be included in the test battery for visual assessment of postural orientation (papers II–IV). The POEs were chosen based on findings from the systematic review (paper I) and based on clinical experience. Seven segment-specific POEs were included initially in paper II, and three POEs were excluded for various reasons (paper II), i.e., arm segment POE, kinematic asymmetry, and joint flexion on landing. Two additional segment-specific POEs were added in paper III, i.e., femoral valgus and femur medial to shank. Detailed descriptions of each segment-specific POE included in the final test battery (papers III–IV) are provided in Table 4.

Table 4. Detailed description of the visual assessment and scoring of segment-specific POEs in papers II-IV.

Segment-specific POEs	Scoring of "0" Good (no POE)	Scoring of "1" Fair (minor POE)	Scoring of "2" Poor (major POE)
Deviation of trunk in any plane	The absence of a trunk position into forward lean, lateral lean and/or rotation indicates no POE	A slight position of the trunk into forward lean, lateral lean and/or rotation indicates minor POE	A clear position of the trunk into forward lean, lateral lean and/or rotation indicates major POE
Deviation of pelvis in any plane	The absence of pelvis into lateral deviation, pelvic tilt and/or rotation of pelvis respectively indicates no POE	A slight position of the pelvis into lateral deviation, pelvic tilt and/or rotation of pelvis respectively indicates minor POE	A clear position of the pelvis into lateral deviation, pelvic tilt and/or rotation of pelvis respectively indicates major POE
Femoral valgus	The absence of femoral valgus indicates no POE	A slight position of femoral valgus indicates minor POE	A clear position of femoral valgus indicates major POE
Femur medial to shank	Mid-point of medial and lateral femoral condyles is lateral to tibial tuberosity	Mid-point of medial and lateral femoral condyles is in-line with tibial tuberosity	Mid-point of medial and lateral femoral condyles is medial to tibial tuberosity
Knee Medial-to-Foot Position	Mid-point of patella is in line with or lateral to the second toe	Mid-point of patella is placed medial to the second toe	Mid-point of patella is clearly placed medial to the big toe
Foot pronation	The absence of pronation of the medial arch of the foot, navicular bone and the medial malleolus indicates no POE	A slight position of pronation of the medial arch of the foot, navicular bone and the medial malleolus indicates a minor POE	A clear position of pronation of the medial arch of the foot, navicular bone and the medial malleolus indicates a major POE

POEs=postural orientation errors

Scoring of POEs

The visual assessment and scoring of POEs was performed from video recordings of the performance of each functional task. Two experienced physical therapists independently performed the visual assessment of segment-specific POEs of the lower extremity and trunk. The video recordings were viewed independently by each rater, and they were allowed to watch the video as many times as they needed, and in slow-motion if required.

The scoring of POEs was developed in papers II–III. The segment-specific POEs were scored on an ordinal scale from 0 to 2 where 0 = good (no signs of POEs), 1 = fair (minimal signs of POEs), and 2 = poor (clear signs of POEs) (Table 4, Figure 5 A–C). If a patient performed a task with very poor postural orientation so that the task did not have any similarities to the expected execution, a maximum within-task POE score was given (i.e., the number of POEs in that task times 3). A segment-specific POE was scored as fair or poor when it occurred 3 times out of 5 (for tasks performed with 5 repetitions) or at least 2 times out of 3 (in tasks performed with 3 repetitions). In cases where one of each category was scored, a score of fair was given. For each task a within-task POE score was calculated as the sum of all segment-specific POEs, and the total POE score was a score for the whole test battery, i.e. the sum of all POEs within and across tasks.

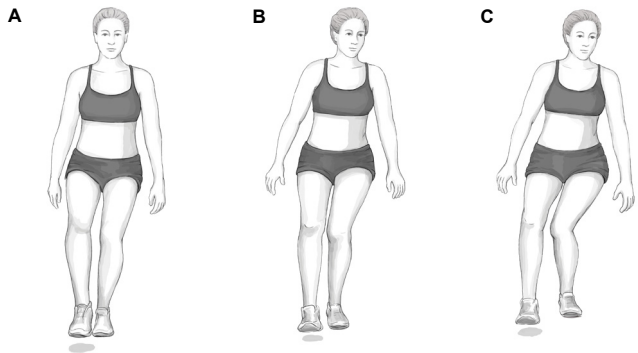


Figure 5 A–C. Visual assessment and scoring of segment-specific POEs of the trunk, hip, thigh, knee and ankle: A) scoring of good (no signs of POEs), B) scoring of fair (minimal signs of POEs), and C) scoring of poor (clear signs of POEs). ©Frida Nilsson

In paper III, two subscales were added, the POE subscale activities of daily living (ADL) (including SLS, SD, and FL) and the POE subscale Sport (including SLHD and SH). Each within-task POE score, the total POE score, and the POE subscales were transformed to percentage scales (from 0 to 100), with 0 representing good postural orientation and 100 representing poor postural orientation. The calculation formulas were:

$$Within\ task\ POE\ score = \frac{Sum\ of\ POE\ scores\ within\ a\ task}{Maximum\ possible\ within\ task\ POE\ score}\ x\ 100$$

$$Total\ POE\ score = \frac{Sum\ of\ all\ POE\ scores}{Maximum\ possible\ Total\ POE\ score} x\ 100$$

$$POE\ subscale\ score = \frac{Sum\ of\ POE\ scores\ within\ a\ subscale}{Maximum\ possible\ subscale\ score} x\ 100$$

Hop performance (paper IV)

Single-leg hop for distance (SLHD)

The SLHD was performed according to the description above. The distance was measured in centimeters from toe at take-off to the heel at landing, and the longest jump from three trials for the injured leg was used in the analysis. The SLHD has shown excellent test-retest reliability (ICC = 0.92) and responsiveness through rehabilitation of patients with ACLR [51].

Side-hop (SH)

The SH was performed by hopping on the injured leg from side-to-side over two parallel lines 30 cm apart. The number of jumps during 30 seconds for the injured leg was used in the analysis. The SH has shown excellent test-retest reliability in patients with ACLR (ICC = 0.87) [101].

Patient-Reported Outcome Measures (PROMs) (paper IV)

Five PROMs were used in paper IV to assess self-reported knee function and knee-specific quality of life (QoL). The PROMs were chosen because they were considered relevant for POE scores.

The Knee injury Osteoarthritis Outcome Score (KOOS)

The KOOS is a knee-specific PROM appropriate to use in patients with knee injuries with an increased risk of developing OA [102]. The subscales QoL and Sport/rec were used in the analysis. KOOS has showed good reliability ($ICC_{2,1} > 0.75$ for all subscales), is valid against the SF-36, and is responsive to change [103, 104].

The Anterior Cruciate Ligament-Quality of Life (ACL-QoL)

ACL-QoL is a quality of life questionnaire specifically developed for ACL injuries and consists of five subscales [105]. Two subscales were chosen as relevant for postural orientation, i.e., the subscales "recreational activities and sport participation or competition" and "lifestyle". The Swedish version of the ACL-QoL has shown good internal consistency ($\alpha = 0.97$), test-retest reliability (ICC = 0.71–0.97), and is valid against the KOOS ($r = 0.87$) and the SF-36 ($r = 0.65–0.72$) [106].

Knee Self-Efficacy Scale (K-SES)

K-SES is also an injury-specific questionnaire for patients with ACL injury and is aimed at measuring perceived self-efficacy [107]. K-SES can be divided into two subscales, K-SES subscale Present and K-SES subscale Future. The K-SES subscale Present was used in this thesis. K-SES has shown good test-retest reliability (ICC = 0.75) and is valid against SF-36 ($r_s = 0.8$) and KOOS ($r_s = 0.4–0.7$) [107].

Global knee function

The global knee function was used as an estimation of the patients' global knee function on a visual analogue scale (VAS) from 1 to 100 mm, interpreted as from "normal knee function, no difference to uninjured side" to "totally disabled" [108]. The VAS scale is used for different purposes, e.g., pain and function, and measures

of knee function with the VAS are reported to be reliable and valid in patients with knee injury [109, 110].

Statistical analysis

Paper I

Meta-analyses were performed when possible using the Comprehensive Meta-Analysis software (version 2.2.064, Biostat, Englewood, USA). The effect size with 95% CI was calculated as the standard difference in mean (SDM) in 3D or 2D kinematics between those with or without POEs. In each meta-analysis, only data from one task were allowed, and if one study reported data from more than one task, the task that was represented in the most studies was included. Because heterogeneity between studies was expected, e.g., different tasks and methods were used, a random-effects model was used. The between-studies heterogeneity in effect size was calculated with the Q-test and expressed as I^2 statistics. Descriptive statistics were used for results not included in meta-analyses. The interpretation of the reliability results for a POE was performed if ≥3 studies reported data. An inverse-variance weighted average [111] was calculated for studies that reported multiple results, for example, several intra-rater results or data for men and women separately. Funnel plots with trim and fill imputations were used to evaluate publication bias [112].

Papers II–III

SPSS (versions 20 to 25, IBM Corporation, New York, USA) was used for calculations in papers II–IV. Floor and ceiling effects (paper II) for segment-specific POEs within a task were investigated using frequency tables and skewness. A POE was excluded when ≥70% of patients scored 0 (floor effect) or 2 (ceiling effect). Internal consistency (Cronbach´s alpha (α)) was analyzed to explore if any task or POEs should be excluded from the test battery (papers II–III). An α between 0.7 to 0.95 was considered adequate for a task to be retained in the test battery [88]. A segment-specific POE was excluded from a task if the α value increased with exclusion of that specific POE and if the corrected item-total correlation between a POE and the within-task POE score was below 0.3 [84]. In papers II–III, inter-rater reliability was calculated using the quadratic weighted kappa for segment-specific POEs [85, 113], and the $ICC_{2,1}$ for within-task POE scores [87]. Percent agreement was calculated for segment-specific POEs in cases when the weighted kappa was not possible to calculate. Measurement error was evaluated for the total POE score (paper II) by calculating the standard error of measurement (SEM) and the smallest

detectable change (SDC). The SDC at both the group level (SDC_{group} = $SDC_{individual}/\sqrt{n}$), and at an individual level ($SDC_{individual}$ = 1.96 × √2 × SEM) was calculated [88].

Paper IV

The Mann-Whitney U-test was used to evaluate sex differences in POE scores. P-values ≤0.05 were considered statistically significant. To evaluate associations between postural orientation and hop performance (as measured in centimeters and the number of hops on the injured leg) and between postural orientation and PROMs, the Spearman's rank correlation coefficient (r_s) was used. Sex differences in POE scores and hop performance were identified (paper IV), and thus the associations were analyzed separately for men and women. Associations >0.3 were considered moderate [114].

Results

Systematic review (paper I)

The systematic review included 28 studies in which four measurement properties were evaluated, specifically content validity, criterion validity, reliability, and measurement error.

Criterion validity was evaluated in 14 studies, of which 9 validated the visual assessment of the segment-specific POE KMFP against 2D and 3D kinematics. The segment-specific POE KMFP could be evaluated with meta-analyses in healthy populations. The result showed that those who were visually assessed as having KMFP had an increased peak knee abduction angle in 2D (SDM: –0.84, 95% CI: –1.31 to –0.36) and in 3D (SDM: –3.40, 95% CI: –6.09 to 0.70) (Figure 6) and an increased 3D hip internal rotation angle (SDM: –2.26, 95% CI: –3.67 to –0.86), compared with those assessed as having a knee over foot position. The criterion validity of other segment-specific POEs was either analyzed in single studies or used different populations or statistical methods, and thus no synthesis was possible.

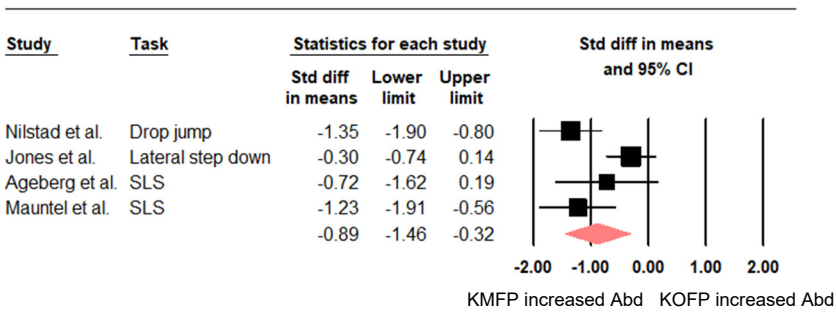


Figure 6. Difference in 3D knee abduction between individuals with a knee medialt-to-foot position (KMFP) or a knee over foot position (KOFP).

Reliability was reported in 23 studies. The segment-specific POE KMFP showed moderate to almost perfect inter-rater and intra-rater reliability in healthy populations. The reliability of other segment-specific POEs (i.e., knee flexion/extension, trunk POE, and ankle POE) and within-task POE scores showed

mixed results from poor to almost perfect agreement (see paper I for detailed results). Content validity and measurement error were only reported in single studies, and thus no synthesis of the results could be performed.

Measurement properties of the test battery for visual assessment of POEs (papers II–III)

The processes of the development of the test battery for visual assessment of POEs (papers II–III), including the results from each step of the evaluation of measurement properties, are described in Figure 7.

Face validity

At the beginning of the process, as well as after each analysis, face validity was discussed in focus groups in papers II–III to agree upon whether the included tasks and POEs reflected the construct under study. In paper II, the DS and COHD were excluded as a first step in the face validity analysis. The DS was excluded because execution of this task was considered to require other constructs than just postural orientation, for example range of motion and balance. The COHD was excluded because two tasks with single-leg hop for distance characteristics were considered redundant. The SLHD was chosen over the COHD because it requires less space and is commonly used in the clinic. After the internal consistency analysis, the focus group discussed the remaining tasks and concluded to keep the SLS despite having an α-value below 0.7 (0.692) because it is a task frequently used in research and by clinicians. The focus group also decided to exclude the SA due to similarities to the SLS and the SD.

In paper III, limitations in the final test battery from paper II were discussed in the focus group (for details, see Figure 2 in paper III). A common ACL injury mechanism is a cutting maneuver, and therefore it was considered reasonable to include such a task in the test battery. The SH was chosen to be added since it is an easy task to administer, and it can be analyzed from video-recordings in the frontal plane. The segment-specific POE KMFP was also discussed, and concern was raised regarding whether KMFP was the result of knee kinematics or ankle kinematics, because the reference points are placed on the proximal and distal segments which are linking two joints (i.e., knee and ankle). Suggested solutions from the focus group were to add two new segment-specific POEs of the lower extremity, i.e., femur medial to shank and femoral valgus.

Interpretability (floor and ceiling effects) (paper II)

In paper II, floor effects were found for segment-specific POEs in some tasks, which excluded them from further analysis (Figure 7). Arm segment POEs showed floor effects in the MS, SA, SD, and FL; deviation of trunk in any plane in the SA, FL, and DJ; KMFP in the MS; joint flexion on landing in the DJ and SLHD; and kinematic asymmetry in the MS. No ceiling effects were observed.

Internal consistency

The MS and the DJ were excluded in paper II based on low α-values (<0.184). The segment-specific POE arm was excluded from the SLS due to low item-total correlation value (0.017). The remaining tasks in paper II had α-values ranging from 0.692 to 0.904. Analysis of Cronbach's α was repeated in paper III for the final test battery from paper II, and it resulted in poor internal consistency, with α-values ranging from 0.07 to 0.597. After the inclusion of the task SH and the segment-specific POEs femur medial to shank and femoral valgus (paper III), the internal consistency analysis was repeated. Segment-specific POEs were excluded from some tasks due to low item-total correlation values (<0.3) (Figure 7). In the final test battery, all tasks showed good internal consistency, with α-values ranging from 0.712 to 0.823.

Inter-rater reliability

The segment-specific POEs within all tasks showed weighted kappa values ranging from 0.31 to 0.875 in papers II–III, (Table 5). Within-task POE scores in paper II resulted in weighted kappa values representing substantial to almost perfect agreement, including values of 0.664 for the SLS, 0.824 for the SD, 0.802 for the FL, and 0.863 for the SLHD. In paper III, reliability was only evaluated for the additional parts of the test battery, and the within-task POE score for the SH lateral landing showed an ICC value of 0.798 and the SH medial landing showed an ICC value of 0.903, representing substantial to almost perfect agreement.

Measurement error (paper II)

For the total POE score, the SDC_{group} was 0.7 points and the $SDC_{individual}$ was 5.01 points.

Table 5. The final test battery of tasks and POEs assessed within each task, and weighted kappa (95% CI) for each segement-specific POE within each task

	Ankle POE	Knee POEs		Thigh POE	Hip POEs	Trunk POEs
Functional tasks	**Foot pronation**	**KMPF**	**Femur medial to shank**	**Femoral valgus**	**Deviation of pelvis in any plane**	**Deviation of trunk in any plane**
SLS	0.517 (0.37-0.96)	0.592 (0.32-0.86)	0.631 (0.29-0.81)	0.753 (0.48-1.0)	0.429 (0.13-0.73)	0.524 (0.15-0.9)
SD	na	na	0.492 (0.09-0.89)	0.638 (0.18-1.0)	na	na
FL	na	0.606 (0.12-1.0)	0.314 (0.07-0.52)	0.724 (0.41-0.87)	0.768 (0.3-1.0)	na
SLHD	na	0.808 (0.49-1.0)	0.547 (0.20-0.89)	0.668 (0.44-0.89)	0.686 (0.34-1.0)	na
SH lateral landing	na	0.417 (0.02-0.82)	0.31 (0.06-0.56)	0.815 (0.42-1.0)	na	na
SH medial landing	na	96.5%*	0.655 (0.44-0.87)	0.78 (0.61-0.95)	0.505 (0.17-0.84)	0.628 (0.22-1.0)
Subscale ADL	Sum score of the SLS, SD and FL					
Subscale Sport	Sum score of the SLHD and SH					
Total POE score	Sum score of all tasks					

* Percent agreement was calculated because weighted kappa was not possible to calculate due to too many zeros. na=not applicable, POEs=postural orientation errors, KMFP=knee medial-to-foot position, SLS=single-leg mini squat, SD=stair descending, FL=forward lunge, SLHD=single-leg hop for distance, SH=side-hop, ADL=activities of daily living

Final test battery (papers III–IV)

The final test battery included 5 functional tasks and 6 segment-specific POEs (Figure 7). Detailed descriptions of the included segment-specific POEs in each task are presented in Table 5. The median (IQR) for each within-task POE score, POE subscale, and the total POE score, as well as the calculation formulas for the percentage scale, are presented in Table 6.

Table 6. The median and inter quartile range (IQR) for each within-task POE score, POE subscales and total POE score, for the total group, and for men and women separately, and the calculation for the within-task POE score, subscales and total POE score

Functional tasks	Total group, n=53	Men, n=29	Women, n=24	Calculation formulae
SLS	17 (11-28)	17 (11-30.5)	17 (12.5-22)	$\frac{\text{sum score}}{18} x\ 100$
SD	25 (0-33)	17 (0-33)	33 (21-33)	$\frac{\text{sum score}}{6} x\ 100$
FL	25 (8-33)	17 (8-25)	25 (19-42)	$\frac{\text{sum score}}{12} x\ 100$
SLHD	33 (25-44)	25 (12.5-37.5)	33 (25-42)	$\frac{\text{sum score}}{12} x\ 100$
SH	27 (17-33)	21 (10.5-33)	29 (21-38)	$\frac{\text{sum score}}{24} x\ 100$
POE Subscale ADL	19 (11-28)	15.5 (11-24.25)a	25 (14.75-32.5)	$\frac{\text{sum score}}{36} x\ 100$
POE Subscale Sport	31 (19-35)	25 (12.5-34.5)	31 (28-36)a	$\frac{\text{sum score}}{36} x\ 100$
Total POE score	25 (17-31)	20.5 (14-29)a	26 (21-33)a	$\frac{\text{sum score}}{72} x\ 100$

POE=postural orientation error, SLS=single-leg mini squat, SD=stair descending, FL=forward lunge, SLHD=single-leg hop for distance, SH=side-hop, ADL=activities of daily living

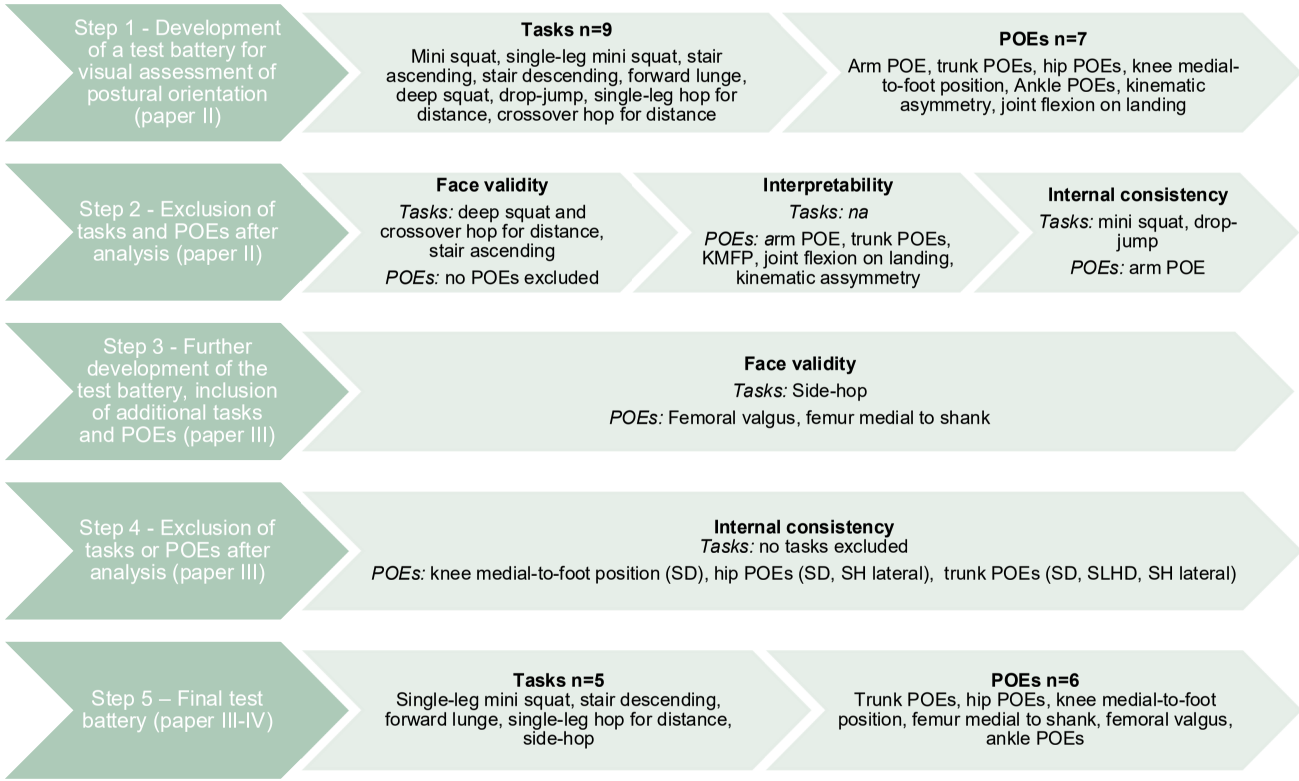


Figure 7. The process of inclusion and exclusion of tasks and POEs in the test battery for visual assessment of POEs (papers II-III). Abbreviation**s**: na=not applicable, POEs=postural orientation errors, KMFP=knee medial-to-foot position, SD=stair descending, SLHD=single-leg hop for distance, SH=side-hop

Sex differences (paper IV)

Women had worse POE scores compared with men (p<0.053), except for the KMFP across tasks (p = 0.106) and the deviation of pelvis in any plane across tasks (p = 0.294) (Figures 8–9).

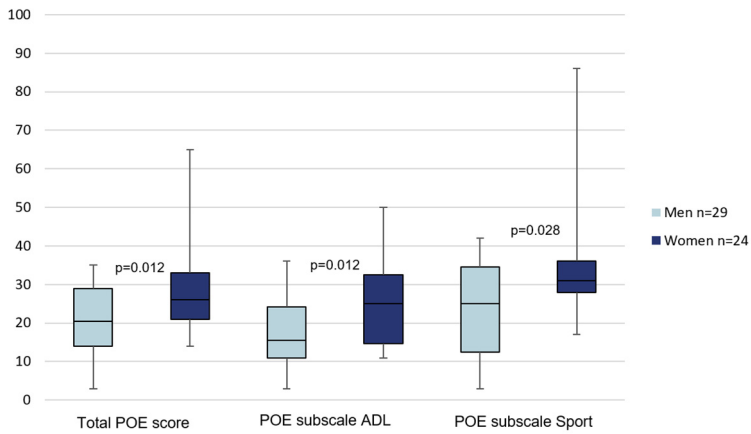


Figure 8. Box plots show min-max, median and quartiles for the Total POE score, POE subscale ADL and POE subscale Sport, for men and women separately. Higher values indicate worse POEs. Mann-Whitney test was used to evaluate differences between men and women in POE scores.

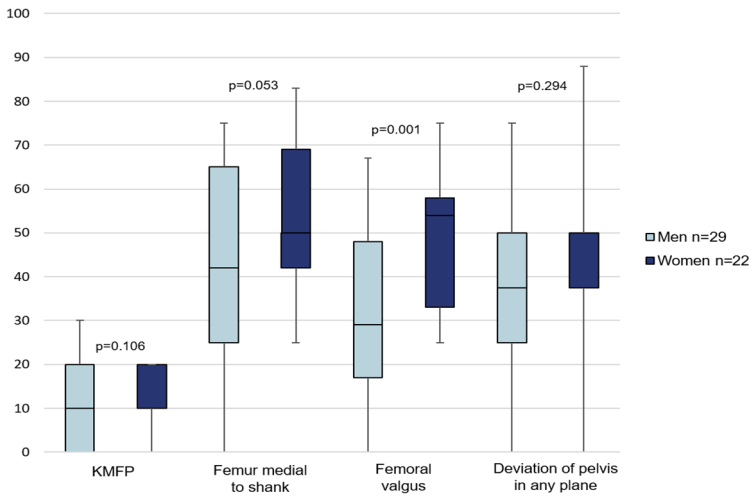


Figure 9. Box plots show min-max, median and quartiles for segment-specific POE scores across tasks, for men and women separately. Higher values indicate worse POEs. Mann-Whitney test was used to evaluate differences between men and women.

Associations between POE scores and hop performance and PROMs (paper IV)

There were associations, with correlation coefficients above 0.3, between POE scores and hop performance (two associations (12.5%) in men, and five associations (31%) in women) and between POE scores and PROMs (one association (3%) in men, and three associations (9%) in women). All associations are presented in detail in paper IV (Tables 4-5).

Hop performance

In women, a shorter hop distance during the SLHD and fewer side-hops during the SH were associated with worse POE scores (r_s = –0.333 to –0.518). In men, a longer hop distance during the SLHD was associated with worse POE scores (r_s = 0.3).

PROMs

In women, moderate associations were found between segment-specific POEs across tasks (i.e., femur medial to shank and deviation of pelvis in any plane) and the KOOS Sport/rec and the K-SES subscale Present (r_s = 0.33, –0.331, –0.387). In men, worse femur medial to shank across tasks was associated with worse KOOS Sport/rec (r_s = –0.313).

Discussion

The main aim of this thesis was to summarize and evaluate the measurement properties of clinically feasible measures of postural orientation in participants with or without injury to the lower extremity. A systematic review with meta-analysis and two original papers were conducted for that purpose (papers I–III). The systematic review showed that the segment-specific POE KMFP was reliable and valid in healthy populations, but there was not enough evidence on visual assessment of POEs in patients with lower extremity injury. Consequently, the development and evaluation of measurement properties of a test battery for visual assessment of POEs in patients with ACL injury was performed in papers II–III. The results showed no floor or ceiling effects, high internal consistency, and good reliability for the final test battery for visual assessment of POEs, suggesting that the test battery can be used to measure postural orientation in patients with ACL injury.

Second aims with the thesis were to evaluate sex differences in POE scores and the association between POE scores and hop performance and PROMs in men and women undergoing rehabilitation after ACLR (paper IV). Women had worse POE scores compared with men, and the worse POE scores in women were associated with hop performance, whereas men with worse POE scores performed better on the SLHD. These results suggest that different approaches to rehabilitation may need to be considered between the sexes in order to improve postural orientation.

Content validity (face validity)

Evaluation of content validity is suggested as an important first step in the validation process of whether the items or tasks in a test instrument are a reflection of the construct to be measured in the chosen study population [25, 88]. Despite this, only one study, in the systematic review (paper I) reported on content validity [115]. The author reported the ranking of five functional tasks by four clinicians, from the most to the least useful task for visual assessment of knee flexion angle [115]. As a first step in the development of the test battery for visual assessment of POEs in patients with ACL injury, experts in Physical Therapy and Sport Science discussed which tasks and POEs should be included in the test battery (papers II–III). The reasoning behind the decisions of the focus group was reported as face validity. In paper II,

three tasks were excluded based on face validity discussions, one because it lacked the ability to reflect the construct of postural orientation, and two because they were discussed to be redundant and to have similar constructs as other tasks in the test battery.

The final test battery from paper II was further discussed by a focus group in paper III. Because a common injury mechanism for the ACL injury is a cutting maneuver [20, 116], such a task was added to the test battery. The SH was added to the test battery because it can be assessed in the frontal plane from video-recordings and has shown good ability to discriminate between injured and non-injured leg in the number of hops during 30 seconds [101]. Another aspect discussed in the focus group in paper III was the visual scoring of the KMFP. The locations of the reference points were discussed as limitations in the validity of the assessment because the reference points are separated by two joints (i.e., the knee and ankle), and it was argued that KMFP may be the result of knee and/or ankle kinematics. This could mean that in the test battery from paper II no POEs evaluated the knee specifically. If that were the case, it could be argued that the POEs in the test battery were not reflective of the study population, i.e., patients with ACL injury. Therefore, in paper III additional POEs were included, i.e., the femur medial to shank and the femoral valgus POE. It was presumed that they represent lower extremity kinematics better than the KMFP POE because their reference points are located above and below the joint/segment they target. However, to determine which POEs best represent knee kinematics, criterion validity needs to be evaluated in future studies.

Criterion validity

Validation of a measurement score is dependent on the situation it is applied to (e.g., healthy or injured populations), thus criterion validity must be evaluated for different target groups [1]. In paper I, the meta-analyses suggested that visual assessment of KMPF is valid against 2D and 3D kinematics in healthy populations. Criterion validity of the KMFP could not be determined in populations with knee injury in paper I because few studies were conducted on injured populations. Despite this, the KMFP POE has been used in several studies on populations with ACL injury [57, 117, 118]. The lack of evaluation of criterion validity means that it cannot be known whether the score of the test instrument measures the construct it is supposed to measure [25]. In the remaining papers in this thesis, the criterion validity was not investigated, however, this is the next step in the validation process of the test battery for visual assessment of POEs in patients with ACL injury, i.e., to investigate the association between segment-specific POEs and 3D kinematics.

Interpretability

Floor and ceiling effects of a test instrument score are important to evaluate because they can affect the responsiveness of a test instrument, e.g. with floor effects present no further improvements can be detected over time [1]. Studies on PROMs often evaluate the floor and ceiling effects of the questions included in the questionnaire [110, 119, 120], however, no studies in the systematic review (paper I) performed an interpretability analysis of the included POEs in a test battery. To our knowledge, paper II is the first study to evaluate floor and ceiling effects for visual assessment of postural orientation. The floor and ceiling effects of each segment-specific POE during each task were assessed using a cut-off point of greater than 70% of patients scoring the highest or lowest possible score, which was the cut-off used for a PROM with a similar scoring scale as ours [110]. Found floor effects were found for some segment-specific POEs in certain tasks, resulting in exclusion of those specific POEs from the tasks in question. No interpretability analysis was performed in paper III for the added task and POEs. The reason for this was because in paper III only patients in the late phase of rehabilitation was included, and more floor effects might be present in that phase. Thus, it was not found to be relevant to exclude POEs based on floor effects in paper III. The range of data for POE scores can vary between populations with knee injury and other populations, and this can influence the floor and ceiling effects of POE scores. Future studies on other populations, e.g., healthy populations or patients with other lower extremity injuries, need to repeat the evaluation of floor and ceiling effects for POE scores.

Internal consistency

The COSMIN panel defines internal consistency as the interrelatedness among the items in a measurement instrument [25], and in a reflective model all items in measurement instrument are expected to change when the construct changes, and thus high item-total correlations should be expected [84, 89]. A test battery for visual assessment of POEs is, in our opinion, a reflective model, thus, postural orientation should be evaluated as a separate construct. Internal consistency was not evaluated in any study included in the systematic review (paper I). However, one reason for excluding studies in the systematic review was that several test instruments used multidimensional constructs, such as postural orientation, pain, flexibility, and balance, summed into a single test score [57, 58, 121, 122]. Internal consistency has been evaluated in one of these test instruments, resulting in poor Cronbach's alpha ($\alpha = 0.39$) [59], which strengthens the argument that the use of a sum score for test instruments with multidimensional constructs is not recommended. A potential danger with including different constructs in the same sum score could be that each specific construct could be masked and interpretation

of findings is difficult. To avoid this, sub-scores could be used for separate constructs.

The internal consistency of the final test battery from paper II was evaluated in both papers II and III. Paper II reported good internal consistency, whereas paper III reported poor internal consistency. Cronbach's alpha is dependent on variation in the population, thus higher internal consistency is found in heterogeneous populations compared with homogenous populations [1]. Therefore, the differences between the cohorts in paper II (heterogeneous populations with or without ACLR with wide ranges in time since injury/surgery) and paper III (a homogenous population with ACLR, between 10–16 months post-surgery) could explain some of the differences in the Cronbach's alpha. In paper III, the second internal consistency analysis (after adding the SH, femur medial to shank, and femoral valgus) resulted in deletion of the deviation of trunk in any plane from some tasks due to low item-total correlation values (<0.3), i.e., an indication that the item does not contribute to the construct under study [84]. One explanation for the low item-total correlation values may be the inclusion of the additional POEs to the test battery in paper III, which may have contributed to a shift in the construct of visual assessment of postural orientation towards the lower extremity.

Whether the KMFP POE represents knee kinematics or not was discussed in the focus group (face validity), but after the internal consistency analysis the KMFP remained as a POE in the test battery, suggesting that the KMFP POE is associated with the construct of postural orientation. However, future studies may reveal whether visual assessment of KMFP is valid against 3D kinematic data and whether the KMFP, femoral valgus, and femur medial to shank POEs complement each other or if they may provide similar information, thus that one POE is redundant.

Reliability

Reliability was the most commonly evaluated measurement property in the systematic review (paper I). The COSMIN panel has developed guidelines for how to analyze reliability in order to enable comparison of results between studies [25, 83]. However, different statistical methods were used to calculate reliability in the included studies in paper I and therefore the possibility to perform a meta-analysis was limited. Sixteen of the 28 included studies were published before, the same year, or the year after the COSMIN guidelines were published, which might be one reason for the inconsistent use of statistical methods. One would hope that the availability of the COSMIN guidelines will result in the use of similar statistical methods in future studies so that comparisons between studies can be performed.

The segment-specific POE KMFP showed moderate to almost perfect agreement in healthy populations (paper I), which was similar to the agreement of the KMFP

assessment in paper II in patients with ACL injury. The clear description of the assessment criteria for the KMFP (i.e. patella medial to the 1st or 2nd toe) has been suggested as one factor that may contribute to high reliability [78]. In contrast, the assessment criteria for other POEs, e.g., movement away from neutral for the deviation of trunk in any plane [76, 123], is open for interpretation for each rater, thus lowering the chance of high reliability. The reliability of the deviation of trunk in any plane in papers II–III was slightly better compared to the result in paper I. Because of methodological differences between the included studies in the systematic review, the following aspects that might improve reliability for visual assessment of POEs were discussed in paper I: 1) to include as detailed descriptions as possible, 2) to assess POEs that are relevant for the chosen plane, e.g., knee flexion cannot be properly assessed in the frontal plane, 3) to evaluate measurement properties for different populations in order to incorporate aspects of variability in patients, as well as in raters, and 4) to perform the visual assessment from video recordings with the possibility to pause, watch multiple times, and watch in slow-motion. When developing our test battery (papers II–III), these aspects were considered, which could be one explanation for the higher reliability for the deviation of trunk in any plane compared with the result in the systematic review.

Sex differences in POEs

Women are suggested to have an increased risk of sustaining an ACL injury compared with men [20]. One suggested explanation for this sex differences is that women have worse postural orientation (measured as 3D knee abduction) during the performance of functional tasks, compared with men [19, 80, 81]. To our knowledge, there is only one test battery before ours, the LESS, that has been used for investigating sex differences in visual assessment of aspects of movement quality [58], with worse LESS scores reported in women with ACL injury compared with men [58, 82]. Similar results were obtained in paper IV, that women with ACL injury had worse postural orientation compared with men. In the LESS, the movement patterns of the trunk, hip, knee, and ankle are visually assessed during the drop-jump, however, the LESS score includes multidimensional constructs, i.e., apart from postural orientation it also includes stance width and stiff landing. In comparison, our test battery for visual assessment of POEs includes only one construct, i.e., postural orientation. Thus, due to the differences in constructs being studied, comparing findings between the LESS score and the POE scores is limited. Due to the reported sex differences in postural orientation, future studies should consider separate evaluations of postural orientation for men and women.

Men and women differ in various ways that may influence postural orientation, for example knee joint laxity [14], hormones, anthropometrics (e.g., pelvic width) [90], muscle strength, and muscle activation [80], and this supports the argument that men

and women should to be evaluated separately. Underlying factors for sex differences in postural orientation are not well explored, but there are a few possible modifiable and non-modifiable underlying factors. Pelvic width is a non-modifiable anthropometric factor that differs between men and women, with women having a wider pelvis normalized to height [124]. There is, however, conflicting evidence as to whether pelvic width is associated with postural orientation. One study reported that a wider pelvis to femoral length ratio was associated with a greater knee valgus angle [125], but another study reported no association between pelvis width to femoral length ratio and 3D hip adduction in women [126]. Pelvic width might be one reason why women had worse femoral valgus compared with men in paper IV. Femoral valgus is the angle created by the intersecting of a longitudinal line and a line from the patella towards the anterior superior iliac spine, and this angle might be more extensive with a wider pelvis, e.g., positioning the reference point on the pelvis more laterally. However, pelvic width was not measured in paper IV, and thus this is a subject for further study. There are also a few modifiable factors that may explain sex differences in postural orientation, such as muscle strength and muscle activation [80]. One study reported associations between increased 3D knee abduction and lower knee muscle strength and lower trunk muscle activation patterns in women with ACL injury, but not in men [80]. Information regarding underlying modifiable factors that could improve POEs may be important to further improve rehabilitation programs aimed at restoring postural orientation in patients with ACL injury. Future studies need to focus on underlying modifiable factors for POEs, such as muscle strength and activation patterns in men and women separately.

Association between POEs and hop performance and PROMs

The association between visually assessed movement quality and hop performance in patients with ACL injury was investigated in one study [127]. They found an association between worse movement quality and worse hop performance [127], however, the ability to compare findings between this study and paper IV is limited because they did not analyze men and women separately. Our study is the first to report the association between postural orientation and hop performance, in men and women separately.

Worse POE scores in women were associated with shorter hop length and fewer side-hops, and the strongest association was with the POE subscale ADL. A possible explanation could be that good postural orientation in ADL tasks may be required to perform well during complex activities, such as jumping tasks. This is in line with the clinical guidelines for ACL injury rehabilitation, i.e., when patients can perform exercises from the acute phase with proper movement quality they can progress to

the intermediate phase (initiating jumping exercises) of their rehabilitation [38, 39]. The POE subscale ADL may be used to help guide clinicians when it is time to progress to jumping exercises, especially in women.

For men, the associations between POE scores and hop performance showed the opposite association, i.e., that worse POE scores (e.g., the within-task POE score for SLHD) were associated with longer hop distance. With increasing hop distance, the demands on the landing also increase, which might explain the worse POE scores with increased jumping distance. Similar findings were described in one cross-sectional study, and the authors reported worse postural orientation during a drop-jump (measured with 3D hip adduction) in men with ACL injury compared with healthy controls, despite having normal hop LSI (i.e., >90%) [66]. This indicates that measures of hop performance might not be a sufficient measure to capture postural orientation in men. Norouzi et al. suggest that kinematic analysis, in combination with muscle strength and hop performance analysis, could add information regarding the decision regarding return to sport [66]. Visual assessment of POEs may be a valuable tool for such kinematic analyses, but this needs to be evaluated in future studies.

Association between POEs and PROMs

Worse self-reported knee function and quality of life has been reported in patients with ACL injury up to 5 years after injury compared with healthy controls [42, 128]. The relationship between PROMs and aspects of movement quality in patients with lower extremity injuries or disorders has been investigated in some cross-sectional studies, but with inconsistent findings [127, 129-131]. No association between aspects of movement quality and PROMs was reported in some studies [129, 130], while others reported that worse movement quality is associated with worse PROMs [127, 131]. However, even though studies have reported sex differences in PROMs, with women reporting worse PROMs compared with men [132, 133], paper IV is the first study to evaluate the association between PROMs and postural orientation for men and women with ACLR separately. There were almost no associations between POE scores and PROMs in paper IV (there were 4 out of 68 moderate associations, and it is possible that these were due to chance, i.e., type I error), indicating that the patient's perceived knee function and quality of life is not reflected by their postural orientation. However, longitudinal studies have shown that future PROMs (e.g., 5 years after injury) were associated with asymmetry in 3D kinematics of the trunk and knee during a landing task [134], and with worse movement quality measured with visual assessment [131]. Thus, whether POE scores can predict future PROMs needs to be further studied.

Methodological considerations

The papers included in this thesis have some methodological considerations. A limitation with paper I was that the meta-analyses included only small numbers of studies, between 2 and 5. Despite this, we found large effects sizes between visual assessment of KMFP and 2D and 3D kinematics, indicating good criterion validity. Another limitation in the meta-analyses was that we included different tasks, thus we cannot rule out that the criterion validity of the KMFP may differ between tasks. However, a study by Marshall et al. reported that knee kinematics during an SLS were associated with knee kinematics during a single leg landing task [135], thus similar movement patterns might be expected to be found in different task.

The heterogeneity of the cohort in paper II may be a limitation. I included patients who were currently under rehabilitation after an ACL injury (independent of the phase of rehabilitation), thus both patients with ACLR and patients treated with rehabilitation alone were included. Due to the broad inclusion criteria, the time span since injury or ACLR became wide (ranging from 7 to 151 weeks since injury, and from 4 to 243 weeks since ACLR). This resulted in missing data for 10 patients who were too early in their rehabilitation to perform jumping tasks, and this might have affected the power in our results for the jumping tasks. However, the heterogeneity of the cohort was chosen because I wanted to include a representable population from physical therapy clinics, and because I wanted to ensure that the test battery for visual assessment of POEs was applicable to use independent of the rehabilitation phase. For the cohort in papers III–IV, the inclusion criteria were changed to include a more homogenous group of patients with ACLR at the late phase of rehabilitation (i.e., >16 weeks post-ACLR) and thus had initiated jumping exercises. These criteria were chosen because of the inclusion of a jumping task with change of direction in the test battery, which is a task intended to be included in the late phase of rehabilitation.

Another limitation was that no power calculations were performed for the cross-sectional studies (papers II–IV). However, the recommended guidelines from the COSMIN checklist were followed in papers II–III regarding how many participants to include in evaluations of measurement properties in order to reach good methodological quality (i.e., >50 participants) [94]. Paper IV was an exploratory study in which the cohort from paper III was divided into men and women, thus resulting in small sample sizes in both group. Despite the low sample size, significant sex differences in POE scores were seen, but this result needs to be interpreted with caution and the results need to be verified in a larger cohort.

The face validity was analyzed in papers II–III by discussing the choice of tasks and POEs among small groups of experts of between 3 and 5 people. Focus group discussions with experts are one way to judge whether the POEs and tasks are relevant for the assessment of postural orientation in patients with ACL injury [1,

25]. However, another approach to evaluate content validity is to gather information regarding the choice of tasks and POEs from an independent group of experts, e.g., by sending a questionnaire to several physical therapists from different clinics around the country and asking them to rate the importance of the tasks and POEs independent of each other [1]. This approach can be used in future studies, e.g., for other lower extremity injuries.

The inter-rater reliability was evaluated in papers II–III, but not the intra-rater reliability, which could be seen as a limitation. It is important to determine the measurement error within a rater at different test occasions in order to trust the measurement [25]. However, the reason for not evaluating intra-rater reliability in this thesis was because we were of the opinion that it is more appropriate to first evaluate the validity of the test battery, and then in the future, when there is a valid measure, to conduct a study that is sufficiently powered to evaluate the measurement properties of the reliability domain.

I did not evaluate the responsiveness of the test battery in this thesis, although this is recommended by the COSMIN panel [25]. The study designs of the included studies in this thesis were cross-sectional, and thus the responsiveness of the test battery was not possible to calculate. Future studies are needed to evaluate the ability of the test battery for visual assessment of POEs to detect change over time, e.g., during different phases of rehabilitation in patients with ACL injury.

Another possible limitation is that the visual assessment of POEs was conducted from a 2D perspective, i.e., from a frontal plane camera view, and it is possible that a 2D perspective is not sufficient for some POEs, for example the deviation of trunk in any plane. Studies suggest that the movements in 3D might not be captured in 2D measures [68, 69], and it has been reported that visual assessment of the KMFP POE is valid against 2D knee abduction, but that internal rotation of the hip is the actual movement in 3D [68]. Thus, for a more accurate assessment of the trunk movement, another camera in the sagittal plane, or a 3D motion assessment, might be needed. However, this would lead to a more time-consuming assessment that would affect the clinical usability of the test battery.

Visual assessment is a clinically feasible method to evaluate postural orientation compared with the “gold standard” measurement of 3D motion analysis systems. However, although the number of items to assess in the test battery was reduced (i.e., POEs and tasks), it may still take too much time for clinicians to perform the assessments. To ensure that clinicians will use the test battery for visual assessment of POEs, the method needs further refinements to make it more user friendly and less time consuming. To improve this, future studies can evaluate whether some tasks are more sensitive to detecting change through rehabilitation, compared to others, and if some POEs are redundant.

Clinical relevance and future perspectives

Altered postural orientation, e.g., 3D hip and knee kinematics, is suggested to be a risk factor for ACL injury [19, 21], and therefore postural orientation needs to be evaluated during rehabilitation and before return to sport. Three-dimensional motion analysis systems are the "gold standard" for evaluating postural orientation, however, such equipment is expensive and requires expertise for interpretation of data, which is not available at physical therapy clinics. This thesis contributes with a clinically feasible measure of postural orientation.

The development of a test battery for visual assessment of postural orientation and evaluation of its measurement properties in patients with ACL injury was conducted in this thesis. The final test battery showed good measurement properties, i.e., internal consistency and reliability, suggesting that it can be used to evaluate postural orientation in patients with ACL injury throughout rehabilitation. Further research is needed on measurement properties of the test battery in different populations (e.g., healthy populations and other injuries to the lower extremity).

For progression in rehabilitation, and for return to sport, measures of strength and/or hop performance are commonly used [136-138]. However, systematic reviews report that those measures may not be sufficient to identify patients at risk of re-injury [139, 140]. Clinical guidelines propose that hop performance, strength, and self-reported function as well as evaluations of movement quality should be included in the evaluation of the patient's knee function during rehabilitation of an ACL injury [38, 39], however, no recommended method for evaluation of movement quality has been suggested. Our test battery for visual assessment of postural orientation is a feasible method to use in the clinical setting because it requires no additional equipment than what is expected to found in a physical therapy clinic. Two subscales were developed for the test battery (paper III) so that POEs could be evaluated in different phases of the rehabilitation. The POE subscale ADL includes the SLS, SD, and FL, which are easy tasks that are introduced early in rehabilitation, and the POE subscale Sport includes the tasks SLHD and SH, which are appropriate to add in the late phase of rehabilitation. These tasks are already commonly used in the clinic but have not previously been used for visual assessment of POEs. Given that worse scores on the POE subscale ADL were associated with worse hop performance (in women), the POE subscale ADL may

be used in the clinic to help decide when a patient is ready to progress to jumping tasks. Future longitudinal studies are needed to investigate whether the test battery for visual assessment of POEs may be of value for progression in rehabilitation, and in the decision regarding return to sport. Also, the predictive ability of the test battery needs to be evaluated, such as the risk of injury, subsequent injuries, or diseases.

The use of the test battery for visual assessment of postural orientation, developed in this thesis, could increase the knowledge regarding the patient's knee function, in addition to other commonly used tests (e.g., hop performance and PROMs). This could result in improved outcomes from rehabilitation of ACL injuries, for example with fewer patients returning to sport with undesirable postural orientation. However, this hypothesis needs to be tested in future longitudinal studies.

Conclusions

- The systematic review (paper I) showed that the segment-specific POE KMFP seems to be reliable and valid for use in healthy populations, however, this remains to be determined in injured populations. Measurement properties of visual assessment of other segment-specific POEs were evaluated in too few studies to draw any conclusions, and these need further evaluations. The results from the systematic review also indicate that measurement properties for visual assessment of postural orientation in patients with knee injury remain to be determined.
- A test battery for visual assessment of POEs was developed and evaluated (papers II–III), and the final test battery consisted of 5 functional tasks (single-leg mini squat, stair descending, forward lunge, single-leg hop for distance, and side-hop) and 6 segment-specific POEs (foot pronation, knee medial-to-foot position, femur medial to shank, femoral valgus, deviation of pelvis in any plane, and deviation of trunk in any plane). The final test battery showed good internal consistence, no floor or ceiling effects, and good inter-rater reliability in patients with ACL injury. The results suggest that the final test battery can be used to evaluate postural orientation in patients with ACL injury, both in research and in clinical practice.
- Women with ACLR seem to have worse POE scores in both daily activities and sport-specific tasks compared with men (paper IV). This indicates that postural orientation should be evaluated separately for men and women. Future studies are needed on modifiable factors for POEs, e.g., muscle strength or muscle activation patterns, in men and women with ACL injury in order to design rehabilitation programs aimed at improving postural orientation.
- Worse POE scores were moderately associated with shorter hop distance and fewer side-hops in women, but not in men (paper IV). The POE subscale ADL showed the strongest association with hop performance, and it was suggested that it may be used to help clinicians to decide when it is time to progress to jumping exercises during rehabilitation of ACL injuries.

Acknowledgements

I would like to express my gratitude to all the people that have helped and supported me during this journey. It would never have been possible without you! Special thanks to:

Eva Ageberg, my main supervisor, who introduced research to my when she was my supervisor during my Master's Thesis. Without your enthusiasm and your commitment at the time, I do not think that I would have chosen research as my line of work. Thanks to everything you have taught me about academic writing and for your support and guidance when feeling lost and confused. I hope we can continue our work and collaborate for many years to come.

Mark Creaby, my deputy supervisor, thanks for sharing your knowledge in biomechanics and for your valuable contribution on academic writing, you really have an eye for details which I have gratefully received. And thank you for welcoming me and my family to your lovely country during my research trip to Australia in 2014, it was truly a memorable journey.

Anna Cronström, co-author and colleague, who has been by my side from day one. Thank you for valuable discussions and help in data collection for my studies. This journey would not have been as fun without you in it.

Gustav Nilsson, co-author and clinical colleague, thank you for initiating this project as part of our Master's Thesis and for your valuable input as a clinician.

Kay Crossley, co-author, thank you for sharing your knowledge in physical therapy and movement analysis, and for being a significant contributor to the design of this thesis.

All colleagues in the research group sport sciences (present and past), thanks for valuable and creative discussions during seminars and for all the fun we have had at work and on congress trips. Thanks to Anders Pålsson, Niklas Cederström, Vala Flosadottir, Anna Cronström, August Estberger, Sofia Ryman Augustsson and Jenny Lindell.

Vibeke Horstman, Christel Nielsen, Tommy Schyman and Axel Ström, for statistical advice when needed and for making statistics a little easier to understand.

Marianne Gullberg, for letting me use the Humanities lab for data collection.

My parents, Helene and Arnold Älmqvist for making me who I am today, and for always believing in me and supporting me in every choice I make in life. And thanks to my brother and sister, **David and Maria Älmqvist**, for always believing in me and for letting me know how proud you are.

To my husband Cristian, and our kids Kit and Neo, for your love and support through these years and for giving me perspective on life. I love you to the moon and back.

And thanks to all participants for taking their time to be part of the studies.

At last, to make this thesis possible, I am grateful for the Funding from the Swedish Research Council, the Crafoord Foundation, Skåne Regional Council, the Swedish Rheumatism Association, the Swedish National Centre for Research in Sports, and the Faculty of Medicine of Lund University.

References

1. de Vet HC, Terwee CB, Mokkink LB, Knol DL: **Measurment in Medicine: A Practical Guide**. Cambridge University Press; 2011.
2. Shumway-Cook A, Woollacott HM: **Motor control: Translating Research Into Clinical Practice**. Philadelphia: Wolters Kluwer; 2017.
3. Horak FB: **Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls?** *Age and ageing* 2006, **35 Suppl 2**:ii7-ii11.
4. Dobson F, Hinman RS, Hall M, Terwee CB, Roos EM, Bennell KL: **Measurement properties of performance-based measures to assess physical function in hip and knee osteoarthritis: a systematic review**. *Osteoarthritis and cartilage / OARS, Osteoarthritis Research Society* 2012, **20**(12):1548-1562.
5. Kisner C, Allen C, L., Borstad J: **Therapeutic exercise: foundations and techniques**. Philadelphia: F.A. Davis Company; 2018.
6. Weldring T, Smith SM: **Patient-Reported Outcomes (PROs) and Patient-Reported Outcome Measures (PROMs)**. *Health Serv Insights* 2013, **6**:61-68.
7. Vet H, Terwee C, Mokkink L, Knol D: **Measurement in medicine: a practical guide.** Cambridge, New York: Cambridge University Press; 2011.
8. Bicer EK, Lustig S, Servien E, Selmi TA, Neyret P: **Current knowledge in the anatomy of the human anterior cruciate ligament**. *Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA* 2010, **18**(8):1075-1084.
9. Butler DL, Noyes FR, Grood ES: **Ligamentous restraints to anterior-posterior drawer in the human knee. A biomechanical study**. *The Journal of bone and joint surgery American volume* 1980, **62**(2):259-270.
10. Zantop T, Petersen W, Sekiya JK, Musahl V, Fu FH: **Anterior cruciate ligament anatomy and function relating to anatomical reconstruction**. *Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA* 2006, **14**(10):982-992.
11. Frobell RB, Lohmander LS, Roos HP: **Acute rotational trauma to the knee: poor agreement between clinical assessment and magnetic resonance imaging findings**. *Scandinavian journal of medicine & science in sports* 2007, **17**(2):109-114.
12. Koga H, Nakamae A, Shima Y, Iwasa J, Myklebust G, Engebretsen L, Bahr R, Krosshaug T: **Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball**. *The American journal of sports medicine* 2010, **38**(11):2218-2225.
13. Olsen OE, Myklebust G, Engebretsen L, Bahr R: **Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis**. *The American journal of sports medicine* 2004, **32**(4):1002-1012.
14. Alentorn-Geli E, Myer GD, Silvers HJ, Samitier G, Romero D, Lazaro-Haro C, Cugat R: **Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors**. *Knee surgery,*

sports traumatology, arthroscopy : official journal of the ESSKA 2009, **17**(7):705-729.

15. Murphy DF, Connolly DA, Beynnon BD: **Risk factors for lower extremity injury: a review of the literature**. *British journal of sports medicine* 2003, **37**(1):13-29.
16. Scranton PE, Jr., Whitesel JP, Powell JW, Dormer SG, Heidt RS, Jr., Losse G, Cawley PW: **A review of selected noncontact anterior cruciate ligament injuries in the National Football League**. *Foot & ankle international / American Orthopaedic Foot and Ankle Society [and] Swiss Foot and Ankle Society* 1997, **18**(12):772-776.
17. Orchard JW, Powell JW: **Risk of knee and ankle sprains under various weather conditions in American football**. *Medicine and science in sports and exercise* 2003, **35**(7):1118-1123.
18. Balazs GC, Pavey GJ, Brelin AM, Pickett A, Keblish DJ, Rue JP: **Risk of Anterior Cruciate Ligament Injury in Athletes on Synthetic Playing Surfaces: A Systematic Review**. *The American journal of sports medicine* 2015, **43**(7):1798-1804.
19. Hewett TE, Myer GD, Ford KR, Heidt RS, Jr., Colosimo AJ, McLean SG, van den Bogert AJ, Paterno MV, Succop P: **Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study**. *The American journal of sports medicine* 2005, **33**(4):492-501.
20. Walden M, Hagglund M, Werner J, Ekstrand J: **The epidemiology of anterior cruciate ligament injury in football (soccer): a review of the literature from a gender-related perspective**. *Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA* 2011, **19**(1):3-10.
21. Paterno MV, Schmitt LC, Ford KR, Rauh MJ, Myer GD, Huang B, Hewett TE: **Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport**. *The American journal of sports medicine* 2010, **38**(10):1968-1978.
22. Montalvo AM, Schneider DK, Yut L, Webster KE, Beynnon B, Kocher MS, Myer GD: **"What's my risk of sustaining an ACL injury while playing sports?" A systematic review with meta-analysis**. *British journal of sports medicine* 2019, **53**(16):1003-1012.
23. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE: **Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport**. *Clin J Sport Med* 2012, **22**(2):116-121.
24. Kyritsis P, Bahr R, Landreau P, Miladi R, Witvrouw E: **Likelihood of ACL graft rupture: not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture**. *British journal of sports medicine* 2016, **50**(15):946-951.
25. Mokkink LB, Terwee CB, Patrick DL, Alonso J, Stratford PW, Knol DL, Bouter LM, de Vet HC: **The COSMIN study reached international consensus on**

taxonomy, terminology, and definitions of measurement properties for health-related patient-reported outcomes. *Journal of clinical epidemiology* 2010, **63**(7):737-745.

26. Nagelli CV, Hewett TE: **Should Return to Sport be Delayed Until 2 Years After Anterior Cruciate Ligament Reconstruction? Biological and Functional Considerations**. *Sports medicine (Auckland, NZ)* 2017, **47**(2):221-232.
27. Ageberg E: **Consequences of ligament injury on neuromuscular function and relevance to rehabilitation - using the anterior cruciate ligament-injured knee as model.** *J Electromyogr Kinesiol* 2002, **12**(3):205-212.
28. Hart HF, Culvenor AG, Collins NJ, Ackland DC, Cowan SM, Machotka Z, Crossley KM: **Knee kinematics and joint moments during gait following anterior cruciate ligament reconstruction: a systematic review and meta-analysis**. *British journal of sports medicine* 2016, **50**(10):597-612.
29. Johnston PT, McClelland JA, Webster KE: **Lower Limb Biomechanics During Single-Leg Landings Following Anterior Cruciate Ligament Reconstruction: A Systematic Review and Meta-Analysis**. *Sports medicine (Auckland, NZ)* 2018, **48**(9):2103-2126.
30. Petersen W, Taheri P, Forkel P, Zantop T: **Return to play following ACL reconstruction: a systematic review about strength deficits**. *Arch Orthop Trauma Surg* 2014, **134**(10):1417-1428.
31. Abrams GD, Harris JD, Gupta AK, McCormick FM, Bush-Joseph CA, Verma NN, Cole BJ, Bach BR, Jr.: **Functional Performance Testing After Anterior Cruciate Ligament Reconstruction: A Systematic Review**. *Orthopaedic journal of sports medicine* 2014, **2**(1):2325967113518305.
32. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD: **Risk of Secondary Injury in Younger Athletes After Anterior Cruciate Ligament Reconstruction: A Systematic Review and Meta-analysis**. *The American journal of sports medicine* 2016, **44**(7):1861-1876.
33. Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, Risberg MA: **Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study**. *British journal of sports medicine* 2016, **50**(13):804-808.
34. Culvenor AG, Collins NJ, Guermazi A, Cook JL, Vicenzino B, Khan KM, Beck N, van Leeuwen J, Crossley KM: **Early knee osteoarthritis is evident one year following anterior cruciate ligament reconstruction: a magnetic resonance imaging evaluation**. *Arthritis & rheumatology (Hoboken, NJ)* 2015, **67**(4):946-955.
35. Culvenor AG, Patterson BE, Guermazi A, Morris HG, Whitehead TS, Crossley KM: **Accelerated Return to Sport After Anterior Cruciate Ligament Reconstruction and Early Knee Osteoarthritis Features at 1 Year: An Exploratory Study**. *PM & R : the journal of injury, function, and rehabilitation* 2018, **10**(4):349-356.
36. Øiestad BE, Juhl CB, Eitzen I, Thorlund JB: **Knee extensor muscle weakness is a risk factor for development of knee osteoarthritis. A systematic review and meta-analysis**. *Osteoarthritis and Cartilage* 2015, **23**(2):171-177.

37. Lie MM, Risberg MA, Storheim K, Engebretsen L, Oiestad BE: **What's the rate of knee osteoarthritis 10 years after anterior cruciate ligament injury? An updated systematic review**. *British journal of sports medicine* 2019, **53**(18):1162-1167.
38. Filbay SR, Grindem H: **Evidence-based recommendations for the management of anterior cruciate ligament (ACL) rupture**. *Best Practice & Research Clinical Rheumatology* 2019.
39. van Melick N, van Cingel RE, Brooijmans F, Neeter C, van Tienen T, Hullegie W, Nijhuis-van der Sanden MW: **Evidence-based clinical practice update: practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus**. *British journal of sports medicine* 2016, **50**(24):1506-1515.
40. Smith TO, Postle K, Penny F, McNamara I, Mann CJ: **Is reconstruction the best management strategy for anterior cruciate ligament rupture? A systematic review and meta-analysis comparing anterior cruciate ligament reconstruction versus non-operative treatment**. *The Knee* 2014, **21**(2):462-470.
41. Frobell RB, Roos EM, Roos HP, Ranstam J, Lohmander LS: **A randomized trial of treatment for acute anterior cruciate ligament tears**. *The New England journal of medicine* 2010, **363**(4):331-342.
42. Filbay SR, Culvenor AG, Ackerman IN, Russell TG, Crossley KM: **Quality of life in anterior cruciate ligament-deficient individuals: a systematic review and meta-analysis**. *British journal of sports medicine* 2015, **49**(16):1033-1041.
43. Ageberg E, Thomee R, Neeter C, Silbernagel KG, Roos EM: **Muscle strength and functional performance in patients with anterior cruciate ligament injury treated with training and surgical reconstruction or training only: a two to five-year followup**. *Arthritis and rheumatism* 2008, **59**(12):1773-1779.
44. van Grinsven S, van Cingel RE, Holla CJ, van Loon CJ: **Evidence-based rehabilitation following anterior cruciate ligament reconstruction**. *Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA* 2010, **18**(8):1128-1144.
45. Grindem H, Granan LP, Risberg MA, Engebretsen L, Snyder-Mackler L, Eitzen I: **How does a combined preoperative and postoperative rehabilitation programme influence the outcome of ACL reconstruction 2 years after surgery? A comparison between patients in the Delaware-Oslo ACL Cohort and the Norwegian National Knee Ligament Registry**. *British journal of sports medicine* 2015, **49**(6):385-389.
46. Andrade R, Pereira R, van Cingel R, Staal JB, Espregueira-Mendes J: **How should clinicians rehabilitate patients after ACL reconstruction? A systematic review of clinical practice guidelines (CPGs) with a focus on quality appraisal (AGREE II)**. *British journal of sports medicine* 2020, **54**(9):512-519.
47. Sorensen NL, Hammeken LH, Thomsen JL, Ehlers LH: **Implementing patient-reported outcomes in clinical decision-making within knee and hip osteoarthritis: an explorative review**. *BMC musculoskeletal disorders* 2019, **20**(1):230.

48. Ardern CL, Taylor NF, Feller JA, Whitehead TS, Webster KE: **Psychological responses matter in returning to preinjury level of sport after anterior cruciate ligament reconstruction surgery**. *The American journal of sports medicine* 2013, **41**(7):1549-1558.

49. Ardern CL, Osterberg A, Tagesson S, Gauffin H, Webster KE, Kvist J: **The impact of psychological readiness to return to sport and recreational activities after anterior cruciate ligament reconstruction**. *British journal of sports medicine* 2014, **48**(22):1613-1619.

50. Tengman E, Brax Olofsson L, Stensdotter AK, Nilsson KG, Hager CK: **Anterior cruciate ligament injury after more than 20 years. II. Concentric and eccentric knee muscle strength**. *Scandinavian journal of medicine & science in sports* 2014, **24**(6):e501-509.

51. Reid A, Birmingham TB, Stratford PW, Alcock GK, Giffin JR: **Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction**. *Physical therapy* 2007, **87**(3):337-349.

52. Engelen-van Melick N, van Cingel RE, Tijssen MP, Nijhuis-van der Sanden MW: **Assessment of functional performance after anterior cruciate ligament reconstruction: a systematic review of measurement procedures**. *Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA* 2013, **21**(4):869-879.

53. Wellsandt E, Failla MJ, Snyder-Mackler L: **Limb Symmetry Indexes Can Overestimate Knee Function After Anterior Cruciate Ligament Injury**. *The Journal of orthopaedic and sports physical therapy* 2017, **47**(5):334-338.

54. Hiemstra LA, Webber S, MacDonald PB, Kriellaars DJ: **Contralateral limb strength deficits after anterior cruciate ligament reconstruction using a hamstring tendon graft**. *Clinical biomechanics (Bristol, Avon)* 2007, **22**(5):543-550.

55. Kotsifaki A, Korakakis V, Whiteley R, Van Rossom S, Jonkers I: **Measuring only hop distance during single leg hop testing is insufficient to detect deficits in knee function after ACL reconstruction: a systematic review and meta-analysis**. *British journal of sports medicine* 2019:bjsports-2018-099918.

56. Bennett H, Davison K, Arnold J, Slattery F, Martin M, Norton K: **Multicomponent Musculoskeletal Movement Assessment Tools: A Systematic Review and Critical Appraisal of Their Development and Applicability to Professional Practice**. *The Journal of Strength & Conditioning Research* 2017, **31**(10):2903-2919.

57. Trulsson A, Garwicz M, Ageberg E: **Postural orientation in subjects with anterior cruciate ligament injury: development and first evaluation of a new observational test battery**. *Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA* 2010, **18**(6):814-823.

58. Padua DA, Marshall SW, Boling MC, Thigpen CA, Garrett WE, Jr., Beutler AI: **The Landing Error Scoring System (LESS) Is a valid and reliable clinical assessment tool of jump-landing biomechanics: The JUMP-ACL study**. *The American journal of sports medicine* 2009, **37**(10):1996-2002.

59. Kazman JB, Galecki JM, Lisman P, Deuster PA, O'Connor FG: **Factor structure of the functional movement screen in marine officer candidates**. *Journal of strength and conditioning research / National Strength & Conditioning Association* 2014, **28**(3):672-678.
60. Cook G, Burton L, Hoogenboom B: **Pre-participation screening: the use of fundamental movements as an assessment of function - part 1**. *North American journal of sports physical therapy : NAJSPT* 2006, **1**(2):62-72.
61. Cook G, Burton L, Hoogenboom B: **Pre-participation screening: the use of fundamental movements as an assessment of function - part 2**. *North American journal of sports physical therapy : NAJSPT* 2006, **1**(3):132-139.
62. Frohm A, Heijne A, Kowalski J, Svensson P, Myklebust G: **A nine-test screening battery for athletes: a reliability study**. *Scandinavian journal of medicine & science in sports* 2012, **22**(3):306-315.
63. Harrison E, Duenkel N, Dunlop R, Russell G: **Evaluation of single-leg standing following anterior cruciate ligament surgery and rehabilitation.** *Phys Ther* 1994, **74**(3):245-252.
64. McCunn R, Aus der Funten K, Govus A, Julian R, Schimpchen J, Meyer T: **THE INTRA- AND INTER-RATER RELIABILITY OF THE SOCCER INJURY MOVEMENT SCREEN (SIMS)**. *International journal of sports physical therapy* 2017, **12**(1):53-66.
65. McKeown I, Taylor-McKeown K, Woods C, Ball N: **Athletic ability assessment: a movement assessment protocol for athletes**. *International journal of sports physical therapy* 2014, **9**(7):862-873.
66. Norouzi S, Esfandiarpour F, Mehdizadeh S, Yousefzadeh NK, Parnianpour M: **Lower extremity kinematic analysis in male athletes with unilateral anterior cruciate reconstruction in a jump-landing task and its association with return to sport criteria**. *BMC musculoskeletal disorders* 2019, **20**(1):492.
67. Welling W, Benjaminse A, Seil R, Lemmink K, Gokeler A: **Altered movement during single leg hop test after ACL reconstruction: implications to incorporate 2-D video movement analysis for hop tests**. *Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA* 2018, **26**(10):3012-3019.
68. Ageberg E, Bennell KL, Hunt MA, Simic M, Roos EM, Creaby MW: **Validity and inter-rater reliability of medio-lateral knee motion observed during a single-limb mini squat**. *BMC musculoskeletal disorders* 2010, **11**:265.
69. Creaby M, Le Rossignol S, Conway Z, Ageberg E, Sweeney S, Franettovich Smith M: **Frontal plane kinematics predict three-dimensional hip adduction during running.** *Physical Therapy in Sport* 2017, **27**:1-6.
70. Whatman C, Hume P, Hing W: **Kinematics during lower extremity functional screening tests in young athletes - are they reliable and valid?** *Physical therapy in sport : official journal of the Association of Chartered Physiotherapists in Sports Medicine* 2013, **14**(2):87-93.
71. Onate J, Cortes N, Welch C, Van Lunen BL: **Expert versus novice interrater reliability and criterion validity of the landing error scoring system**. *Journal of sport rehabilitation* 2010, **19**(1):41-56.

72. Graci V, Van Dillen LR, Salsich GB: **Gender differences in trunk, pelvis and lower limb kinematics during a single leg squat**. *Gait & posture* 2012, **36**(3):461-466.
73. Willson JD, Davis IS: **Utility of the frontal plane projection angle in females with patellofemoral pain**. *The Journal of orthopaedic and sports physical therapy* 2008, **38**(10):606-615.
74. Herrington L, Alenezi F, Alzhrani M, Alrayani H, Jones R: **The reliability and criterion validity of 2D video assessment of single leg squat and hop landing**. *J Electromyogr Kinesiol* 2017, **34**:80-85.
75. Harris-Hayes M, Steger-May K, Koh C, Royer NK, Graci V, Salsich GB: **Classification of lower extremity movement patterns based on visual assessment: reliability and correlation with 2-dimensional video analysis**. *Journal of athletic training* 2014, **49**(3):304-310.
76. Whatman C, Hing W, Hume P: **Physiotherapist agreement when visually rating movement quality during lower extremity functional screening tests**. *Physical therapy in sport : official journal of the Association of Chartered Physiotherapists in Sports Medicine* 2012, **13**(2):87-96.
77. Ortqvist M, Mostrom EB, Roos EM, Lundell P, Janarv PM, Werner S, Brostrom EW: **Reliability and reference values of two clinical measurements of dynamic and static knee position in healthy children**. *Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA* 2011, **19**(12):2060-2066.
78. Chmielewski TL, Hodges MJ, Horodyski M, Bishop MD, Conrad BP, Tillman SM: **Investigation of clinician agreement in evaluating movement quality during unilateral lower extremity functional tasks: a comparison of 2 rating methods**. *The Journal of orthopaedic and sports physical therapy* 2007, **37**(3):122-129.
79. Stensrud S, Myklebust G, Kristianslund E, Bahr R, Krosshaug T: **Correlation between two-dimensional video analysis and subjective assessment in evaluating knee control among elite female team handball players**. *British journal of sports medicine* 2011, **45**(7):589-595.
80. Cronstrom A, Ageberg E, Franettovich Smith MM, Blackmore T, Nae J, Creaby MW: **Factors affecting knee abduction during weight-bearing activities in individuals with anterior cruciate ligament reconstruction**. *Physical therapy in sport : official journal of the Association of Chartered Physiotherapists in Sports Medicine* 2019, **38**:8-15.
81. Cronstrom A, Creaby MW, Nae J, Ageberg E: **Gender differences in knee abduction during weight-bearing activities: A systematic review and meta-analysis**. *Gait & posture* 2016, **49**:315-328.
82. Kuenze CM, Trigsted S, Lisee C, Post E, Bell DR: **Sex Differences on the Landing Error Scoring System Among Individuals With Anterior Cruciate Ligament Reconstruction**. *Journal of athletic training* 2018, **53**(9):837-843.
83. Mokkink LB, Terwee CB, Patrick DL, Alonso J, Stratford PW, Knol DL, Bouter LM, de Vet HC: **The COSMIN checklist for assessing the methodological quality of studies on measurement properties of health status measurement instruments: an international Delphi study**. *Quality of life research : an*

international journal of quality of life aspects of treatment, care and rehabilitation 2010, **19**(4):539-549.

84. Nunnally JC, Bernstein IH: **Psychometric theory**, 3rd edn. New York: McGraw-Hill.; 1994.
85. Sim J, Wright CC: **The kappa statistic in reliability studies: use, interpretation, and sample size requirements**. *Physical therapy* 2005, **85**(3):257-268.
86. Landis JR, Koch GG: **The measurement of observer agreement for categorical data**. *Biometrics* 1977, **33**(1):159-174.
87. Fleiss JL, Cohen J: **The Equivalence of Weighted Kappa and the Intraclass Correlation Coefficient as Measures of Reliability**. *Educational and Psychological Measurement* 1973, **33**(3):613-619.
88. Terwee CB, Bot SD, de Boer MR, van der Windt DA, Knol DL, Dekker J, Bouter LM, de Vet HC: **Quality criteria were proposed for measurement properties of health status questionnaires**. *Journal of clinical epidemiology* 2007, **60**(1):34-42.
89. Mokkink LB, Terwee CB, Knol DL, Stratford PW, Alonso J, Patrick DL, Bouter LM, de Vet HC: **The COSMIN checklist for evaluating the methodological quality of studies on measurement properties: a clarification of its content**. *BMC medical research methodology* 2010, **10**:22.
90. Andrade JA, Figueiredo LC, Santos TR, Paula AC, Bittencourt NF, Fonseca ST: **Reliability of transverse plane pelvic alignment measurement during the bridge test with unilateral knee extension**. *Revista brasileira de fisioterapia (Sao Carlos (Sao Paulo, Brazil))* 2012, **16**(4):268-274.
91. Jones D, Tillman SM, Tofte K, Mizner RL, Greenberg S, Moser MW, Chmielewski TL: **Observational Ratings of Frontal Plane Knee Position Are Related to the Frontal Plane Projection Angle but Not the Knee Abduction Angle During a Step-down Task**. *The Journal of orthopaedic and sports physical therapy* 2014, **44**(12):973-978.
92. Nilstad A, Andersen TE, Kristianslund E, Bahr R, Myklebust G, Steffen K, Krosshaug T: **Physiotherapists can identify female football players with high knee valgus angles during vertical drop jumps using real-time observational screening**. *The Journal of orthopaedic and sports physical therapy* 2014, **44**(5):358-365.
93. Downs S, Black N: **The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions.** *J Epidemiol Community Health* 1998, **52**(6):377-384.
94. Terwee CB, Mokkink LB, Knol DL, Ostelo RW, Bouter LM, de Vet HC: **Rating the methodological quality in systematic reviews of studies on measurement properties: a scoring system for the COSMIN checklist**. *Quality of life research : an international journal of quality of life aspects of treatment, care and rehabilitation* 2012, **21**(4):651-657.
95. Ekdahl C, Andersson SI, Svensson B: **Muscle function of the lower extremities in rheumatoid arthritis and osteoarthrosis. A descriptive study of patients in a primary health care district**. *Journal of clinical epidemiology* 1989, **42**(10):947-954.

96. Pfeifer K, Banzer W: **Motor performance in different dynamic tests in knee rehabilitation**. *Scandinavian journal of medicine & science in sports* 1999, **9**(1):19-27.
97. Alkjaer T, Simonsen EB, Peter Magnusson SP, Aagaard H, Dyhre-Poulsen P: **Differences in the movement pattern of a forward lunge in two types of anterior cruciate ligament deficient patients: copers and non-copers**. *Clinical biomechanics (Bristol, Avon)* 2002, **17**(8):586-593.
98. Zatterstrom R, Friden T, Lindstrand A, Moritz U: **Rehabilitation following acute anterior cruciate ligament injuries--a 12-month follow-up of a randomized clinical trial**. *Scandinavian journal of medicine & science in sports* 2000, **10**(3):156-163.
99. Noyes FR, Barber SD, Mangine RE: **Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture**. *The American journal of sports medicine* 1991, **19**(5):513-518.
100. Itoh H, Kurosaka M, Yoshiya S, Ichihashi N, Mizuno K: **Evaluation of functional deficits determined by four different hop tests in patients with anterior cruciate ligament deficiency**. *Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA* 1998, **6**(4):241-245.
101. Gustavsson A, Neeter C, Thomee P, Silbernagel KG, Augustsson J, Thomee R, Karlsson J: **A test battery for evaluating hop performance in patients with an ACL injury and patients who have undergone ACL reconstruction**. *Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA* 2006, **14**(8):778-788.
102. Roos EM, Lohmander LS: **The Knee injury and Osteoarthritis Outcome Score (KOOS): from joint injury to osteoarthritis**. *Health and quality of life outcomes* 2003, **1**:64.
103. Roos EM, Toksvig-Larsen S: **Knee injury and Osteoarthritis Outcome Score (KOOS) - validation and comparison to the WOMAC in total knee replacement**. *Health and quality of life outcomes* 2003, **1**:17.
104. Roos EM, Roos HP, Ekdahl C, Lohmander LS: **Knee injury and Osteoarthritis Outcome Score (KOOS)--validation of a Swedish version**. *Scandinavian journal of medicine & science in sports* 1998, **8**(6):439-448.
105. Mohtadi N: **Development and validation of the quality of life outcome measure (questionnaire) for chronic anterior cruciate ligament deficiency**. *The American journal of sports medicine* 1998, **26**(3):350-359.
106. Kvist J: **Översättning, validitets och reliabilitetstestning av ACL-QOL frågeformulär om livskvalitet efter främre korsbandsskada.** In: *Svensk Idrottsmedicinsl förenings Vårmöte.* Örebro, Sweden 2006.
107. Thomee P, Wahrborg P, Borjesson M, Thomee R, Eriksson BI, Karlsson J: **A new instrument for measuring self-efficacy in patients with an anterior cruciate ligament injury**. *Scandinavian journal of medicine & science in sports* 2006, **16**(3):181-187.
108. Kostogiannis I, Ageberg E, Neuman P, Dahlberg L, Friden T, Roos H: **Activity level and subjective knee function 15 years after anterior cruciate ligament injury: a**

prospective, longitudinal study of nonreconstructed patients. *The American journal of sports medicine* 2007, **35**(7):1135-1143.

109. Collins NJ, Misra D, Felson DT, Crossley KM, Roos EM: **Measures of knee function: International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form, Knee Injury and Osteoarthritis Outcome Score (KOOS), Knee Injury and Osteoarthritis Outcome Score Physical Function Short Form (KOOS-PS), Knee Outcome Survey Activities of Daily Living Scale (KOS-ADL), Lysholm Knee Scoring Scale, Oxford Knee Score (OKS), Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), Activity Rating Scale (ARS), and Tegner Activity Score (TAS)**. *Arthritis care & research* 2011, **63 Suppl 11**:S208-228.
110. Ortqvist M, Iversen MD, Janarv PM, Brostrom EW, Roos EM: **Psychometric properties of the Knee injury and Osteoarthritis Outcome Score for Children (KOOS-Child) in children with knee disorders**. *British journal of sports medicine* 2014, **48**(19):1437-1446.
111. Deeks JJ, Higgins, J. P. and Altman, D. G.: **Chapter 9: Analysing Data and Undertaking Meta-Analyses**. In: *Cochrane Handbook for Systematic Reviews of Interventions: Cochrane Book Series.* edn.: John Wiley & Sons, Ltd, Chichester, UK; 2008.
112. Duval S, Tweedie R: **A Nonparametric "Trim and Fill" Method of Accounting for Publication Bias in Meta-Analysis**. *Journal of the American Statistical Association* 2000, **95**(449):89-98.
113. de Vet HC, Terwee CB, Mokkink LB, Knol DL: **Reliability**. In: *Measurment in Medicine: A Practical Guide.* edn. Cambridge University Press; 2011: 96-149.
114. Cohen J: **Statistical power analysis for the behavioral sciences.**, 2nd edition edn. New Jersey: Lawrence Erlbaum Associates, Inc.; 1988.
115. von Porat A, Holmstrom E, Roos E: **Reliability and validity of videotaped functional performance tests in ACL-injured subjects**. *Physiotherapy research international : the journal for researchers and clinicians in physical therapy* 2008, **13**(2):119-130.
116. Hagglund M, Walden M: **Risk factors for acute knee injury in female youth football**. *Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA* 2016, **24**(3):737-746.
117. Crossley KM, Zhang WJ, Schache AG, Bryant A, Cowan SM: **Performance on the single-leg squat task indicates hip abductor muscle function**. *The American journal of sports medicine* 2011, **39**(4):866-873.
118. Cronstrom A, Ageberg E: **Association between sensory function and medio-lateral knee position during functional tasks in patients with anterior cruciate ligament injury**. *BMC musculoskeletal disorders* 2014, **15**(1):430.
119. Chaudhuri KR, Rizos A, Trenkwalder C, Rascol O, Pal S, Martino D, Carroll C, Paviour D, Falup-Pecurariu C, Kessel B *et al*: **King's Parkinson's disease pain scale, the first scale for pain in PD: An international validation**. *Movement disorders : official journal of the Movement Disorder Society* 2015, **30**(12):1623-1631.

120. Kvist J, Osterberg A, Gauffin H, Tagesson S, Webster K, Ardern C: **Translation and measurement properties of the Swedish version of ACL-Return to Sports after Injury questionnaire**. *Scandinavian journal of medicine & science in sports* 2013, **23**(5):568-575.
121. Choi H, Shin W: **Validity of the lower extremity functional movement screen in patients with chronic ankle instability**. *Journal of Physical Therapy Science* 2015, **27**(6):1923-1927 1925p.
122. Haitz K, Shultz R, Hodgins M, Matheson GO: **Test-retest and interrater reliability of the functional lower extremity evaluation**. *The Journal of orthopaedic and sports physical therapy* 2014, **44**(12):947-954.
123. Ness BM, Taylor AL, Haberl MD, Reuteman PF, Borgert AJ: **Clinical observation and analysis of movement quality during performance on the star excursion balance test**. *International journal of sports physical therapy* 2015, **10**(2):168-177.
124. Ro DH, Lee DY, Moon G, Lee S, Seo SG, Kim SH, Park IW, Lee MC: **Sex differences in knee joint loading: Cross-sectional study in geriatric population**. *Journal of orthopaedic research : official publication of the Orthopaedic Research Society* 2017, **35**(6):1283-1289.
125. Pantano KJ, White SC, Gilchrist LA, Leddy J: **Differences in peak knee valgus angles between individuals with high and low Q-angles during a single limb squat**. *Clinical biomechanics (Bristol, Avon)* 2005, **20**(9):966-972.
126. Baggaley M, Noehren B, Clasey JL, Shapiro R, Pohl MB: **Frontal plane kinematics of the hip during running: Are they related to hip anatomy and strength?** *Gait & posture* 2015, **42**(4):505-510.
127. Trulsson A, Roos EM, Ageberg E, Garwicz M: **Relationships between postural orientation and self reported function, hop performance and muscle power in subjects with anterior cruciate ligament injury**. *BMC musculoskeletal disorders* 2010, **11**:143.
128. Webster KE, Nagelli CV, Hewett TE, Feller JA: **Factors Associated With Psychological Readiness to Return to Sport After Anterior Cruciate Ligament Reconstruction Surgery**. *The American journal of sports medicine* 2018, **46**(7):1545-1550.
129. Casartelli NC, Maffiuletti NA, Brunner R, Buchi M, Sutter R, Pfirrmann CW, Naal FD, Leunig M, Bizzini M: **Clinical Rating of Movement-Pattern Quality in Patients With Femoroacetabular Impingement Syndrome: A Methodological Study**. *The Journal of orthopaedic and sports physical therapy* 2018, **48**(4):260-269.
130. Naili JE, Esbjornsson AC, Iversen MD, Schwartz MH, Hedstrom M, Hager CK, Brostrom EW: **The impact of symptomatic knee osteoarthritis on overall gait pattern deviations and its association with performance-based measures and patient-reported outcomes**. *The Knee* 2017, **24**(3):536-546.
131. Flosadottir V, Roos EM, Ageberg E: **Muscle function is associated with future patient-reported outcomes in young adults with ACL injury**. *BMJ open sport & exercise medicine* 2016, **2**(1):e000154.
132. Ageberg E, Forssblad M, Herbertsson P, Roos EM: **Sex differences in patient-reported outcomes after anterior cruciate ligament reconstruction: data from**

the Swedish knee ligament register. *The American journal of sports medicine* 2010, **38**(7):1334-1342.

133. Tan SH, Lau BP, Khin LW, Lingaraj K: **The Importance of Patient Sex in the Outcomes of Anterior Cruciate Ligament Reconstructions: A Systematic Review and Meta-analysis**. *The American journal of sports medicine* 2016, **44**(1):242-254.
134. Ithurburn MP, Paterno MV, Ford KR, Hewett TE, Schmitt LC: **Young Athletes After Anterior Cruciate Ligament Reconstruction With Single-Leg Landing Asymmetries at the Time of Return to Sport Demonstrate Decreased Knee Function 2 Years Later**. *The American journal of sports medicine* 2017, **45**(11):2604-2613.
135. Marshall BM, Franklyn-Miller AD, Moran KA, King EA, Strike SC, Falvey EC: **Can a Single-Leg Squat Provide Insight Into Movement Control and Loading During Dynamic Sporting Actions in Patients With Athletic Groin Pain?** *Journal of sport rehabilitation* 2016, **25**(2):117-125.
136. Ardern CL, Webster KE, Taylor NF, Feller JA: **Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play**. *British journal of sports medicine* 2011, **45**(7):596-606.
137. Narducci E, Waltz A, Gorski K, Leppla L, Donaldson M: **The clinical utility of functional performance tests within one-year post-acl reconstruction: a systematic review**. *International journal of sports physical therapy* 2011, **6**(4):333-342.
138. Thomee R, Kaplan Y, Kvist J, Myklebust G, Risberg MA, Theisen D, Tsepis E, Werner S, Wondrasch B, Witvrouw E: **Muscle strength and hop performance criteria prior to return to sports after ACL reconstruction**. *Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA* 2011, **19**(11):1798-1805.
139. Webster KE, Hewett TE: **What is the Evidence for and Validity of Return-to-Sport Testing after Anterior Cruciate Ligament Reconstruction Surgery? A Systematic Review and Meta-Analysis**. *Sports Medicine* 2019, **49**(6):917-929.
140. Losciale JM, Bullock G, Cromwell C, Ledbetter L, Pietrosimone L, Sell TC: **Hop Testing Lacks Strong Association With Key Outcome Variables After Primary Anterior Cruciate Ligament Reconstruction: A Systematic Review**. *The American journal of sports medicine* 2019:363546519838794.

Printed by Media-Tryck, Lund 2020 NORDIC SWAN ECOLABEL 3041 0903

Is seeing just believing?

An anterior cruciate ligament (ACL) injury often results in altered postural orientation, which is suggested to be a risk factor for a subsequent injury. The "gold standard" for measuring postural orientation is with three-dimensional motion analysis. However, there is a need for a clinically feasible measure of postural orientation. The results from this thesis indicate that visual assessment of Postural Orientation Errors (POEs) can be used in patients with ACL injury, and that POE scores could be used to help clinicians to decide when it is time to progress to jumping exercises during rehabilitation of ACL injuries.

Jenny Älmqvist Nae (born 1987) completed her bachelor degree in Physical Therapy in 2010 and her Master's degree in Sport Science in 2012, both at Lund University. She has been working part-time as a physical therapist at sports injury clinics since 2010 and she started her PhD studies at the Department of Health Sciences, Lund University in 2013. Since 2017, Jenny has also combined her PhD studies with being a professional triathlete, with gold and silver medals in Swedish Championships 2019.

LUND UNIVERSITY

FACULTY OF MEDICINE

Reasearch group Sport Sciences
Department of Health Sciences

Lund University, Faculty of Medicine
Doctoral Dissertation Series 2020:78
ISBN 978-91-7619-940-4
ISSN 1652-8220