Anterior cruciate ligament injuries in children and adolescents

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Colofon

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Content

Discussion & summary

Appendices

Chapter 1

General introduction and thesis outline

General introduction

Anterior cruciate ligament (ACL) rupture is a severe injury of the paediatric and adolescent knee [1,2]. It may compromise the quality of life, limits physical activity and increases the risk for further injury and early onset osteoarthritis [1,2]. Primary treatment is often non-operative for children with open growth plates [1,2,3]. In case of ACL reconstruction, risk of ACL revision surgery is higher compared to adults [4]. ACL reconstruction in children with open growth plates may result in growth disturbances due to damages of the growth plates [1,2]. Operative treatment on systematic basis of all ACL injuries in this population should therefore be avoided [5,6]. Careful evaluation of the individual patient is necessary. To date, there is however little high-quality evidence to guide decision-making in management of paediatric ACL injuries [1,2,5].

Growth of the knee

Treatment of ACL injuries in skeletally immature children is challenging due to the open growth plates around the knee. Knowledge of the anatomy, development and growth are necessary to treat these children and prevent growth disturbances. The femoral and tibial growth plates are the greatest contributors to the growth of the lower limbs [7]. The distal femoral physis contributes for 37% for the overall leg length, the proximal tibia growth plate for 25% [7]. The final growth spurt before skeletal maturity starts at the onset of puberty, which is approximately at 13 years of bone age for boys and 11 years for girls, as shown in Figure 1 [8]. Growth of the lower limbs will cease stop 2 years and 6 months after the onset of puberty [8].

The last physis to disappear is the femoral physis [9]. For clinical purposes, growth and maturation of the knee can be differentiated in different phases [6,7,10].

- Prepubertal phase
    - Tanner stage 1
    - Skeletal age ≤11 years in girls and ≤12 years in boys
    - High growth potential
- Pubertal phase:
    - Tanner stage ≥2
    - Skeletal age ≥12 years in girls and ≥13 years in boys
    - Decreasing growth potential
- Postpubescent phase:
    - Tanner stage 5
    - Skeletal age ≥14 years in girls and ≥16 years in boys
    - Growth plates closing/closed, no remaining growth around the knee

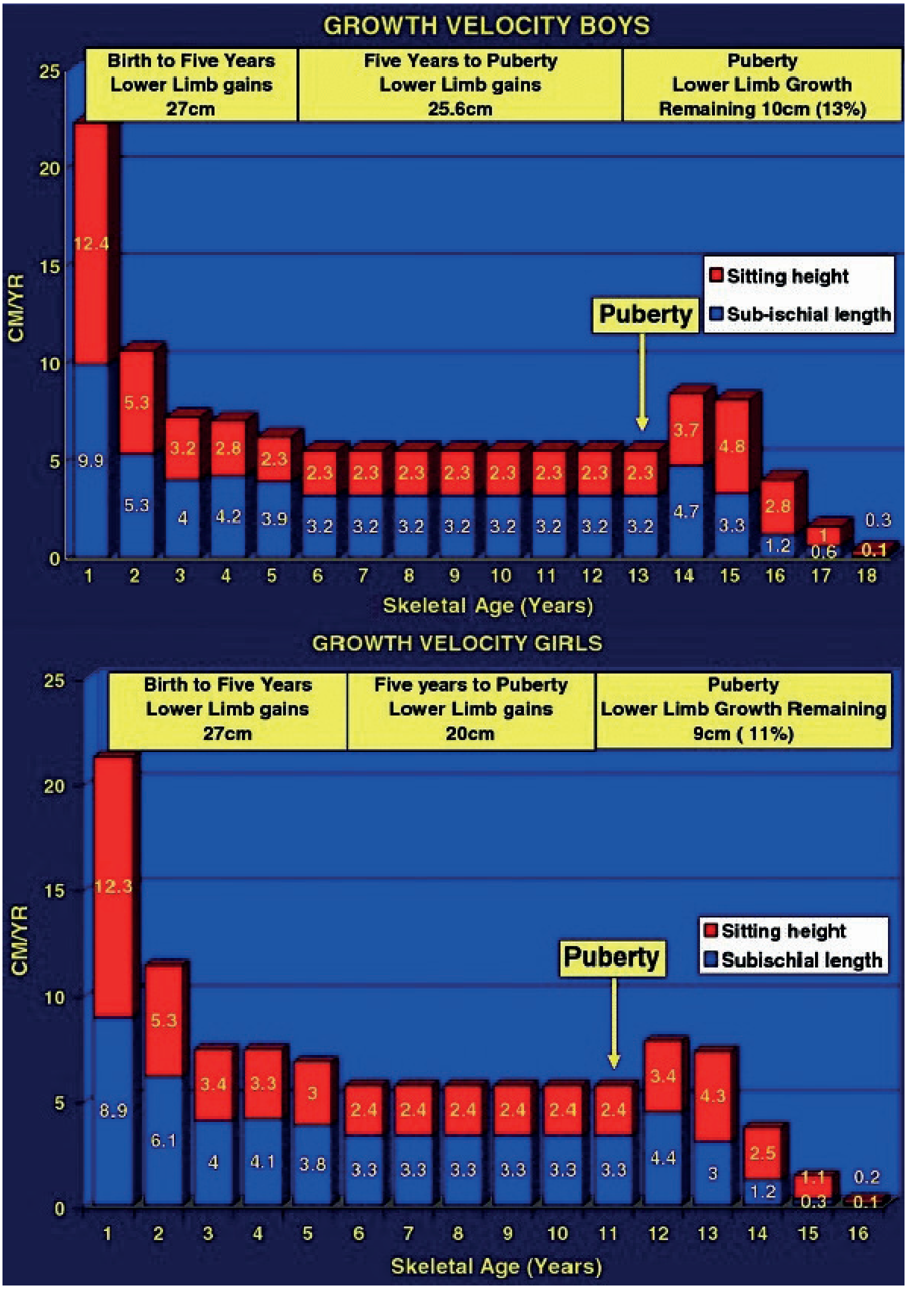

Figure 1. Growth velocities in cm per year for boys and girls, originally published by Kelly et al [8] adjusted to one figure.

The ACL itself shows progressive lengthening without achieving growth peaks during growth of the child [11]. The cross-sectional area of the ACL increases until the age of 11 years in girls and 12 years in boys, stabilizes for three years thereafter and then shows a slight reduction (Figure 2) [11]. This may explain why in the age category of 8-to-14 year-olds avulsion fractures are common, as the ACL area increases progressively before the growth spurt has begun [11]. The discrepancy between height growth and ACL area growth could also justify the progressive increase in the incidence of ACL injury in later adolescence [11]. The inclination angle of the ACL and the roof of the intercondylar notch show progressive verticalisation during growth, which may have consequences for successful ACL graft placement [11].

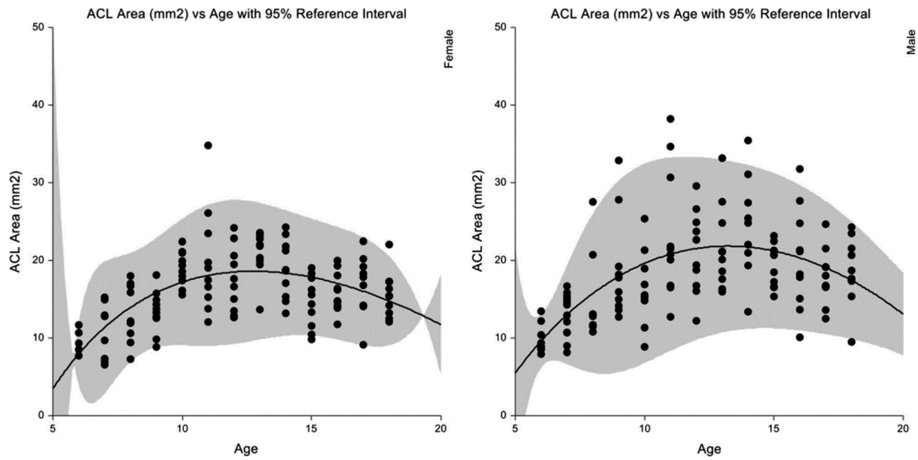

Figure 2. ACL area as a function of patient age and sex. Polynomial regression curves, with corresponding 95% confidence intervals (shaded), by Lima et al. [11]

Epidemiology

The incidence of ACL injuries in children and adolescents is increasing in recent years [12,13,14,15]. In Finland, the incidence increased more than twofold in the adolescent population between 1997 and 2014 [14]. The main reason for this increase, is an increased participation in competitive sports by children, especially girls [14,15,16]. The highest increase in Finland was seen in girls aged 13 to 15 years with a 143% increase in incidence (Figure 3) [14]. The increase among 16 to 17 year-old girls and boys was respectively 81% and 44% (Figure 4) [14]. A large epidemiological study on football (soccer) players in the United States showed that girls were three times more likely to sustain an ACL injury compared to boys [17]. Girl's football (soccer) has the highest ACL injury rate of all sports [18]. These numbers might be especially relevant for the Netherlands, where there is an annual increase of girls' football participation [19]. In the Netherlands, there are currently no epidemiological data on the incidence of ACL injuries in children and adolescents available.

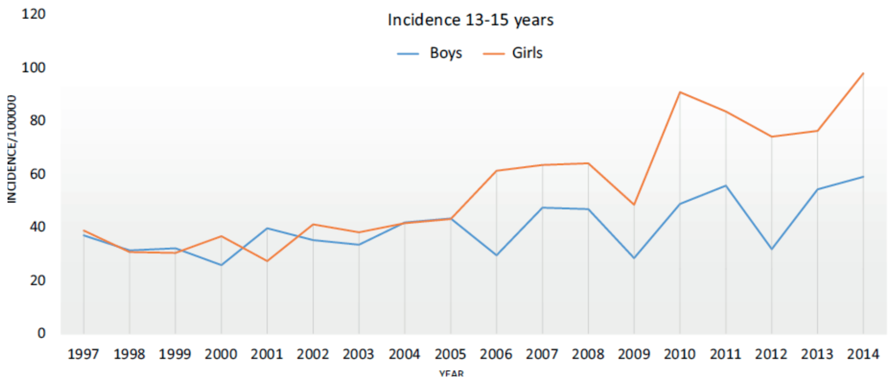

Figure 3. The incidence of ACL rupture in children aged 13–15 by Weitz et al [14].

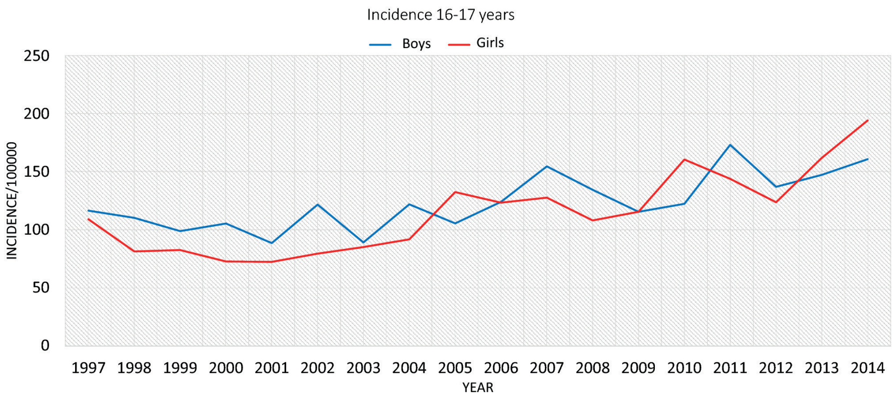

Figure 4. The incidence of ACL rupture in children aged 16–17 by Weitz et al [14].

Prevention

Current evidence shows that ACL injury prevention programs work in skeletally mature patients, resulting in reduced numbers of athletes who sustain a primary ACL injury [2,20-24]. These programs target at movement patterns, which are a key modifiable risk factor for ACL injuries [2,25,26]. Multiple studies have been conducted in adolescents and show that various programmatic components of ACL neuromuscular training are associated with injury reduction [27]. Evidence for skeletally immature children is however currently not available. The effect of an injury prevention program is influenced by the design of the program and the frequency and compliance of which the patient perform the training [2,28,29]. Compliance and adherence of the child, due to age, gender and development, to the training program is one of the biggest challenges, which is also relevant in non-operative or postoperative rehabilitation after ACL injury or reconstruction [2].

Diagnosis

Most ACL injuries in children and adolescents occur during a non-contact trauma: a non-contact valgus or rotational force on a relatively extended knee [6,30,31,32]. Up to 65% of the patients present with an acute haemarthrosis [7,33]. Timely and accurate diagnosis of ACL injuries is of great importance, as missed or delayed diagnosis and treatment increase the risk of meniscal or chondral lesions [31,34-37]. To obtain an accurate diagnosis seems more difficult in children and adolescents compared to adults [2,38]. This difficulty might be due to a greater physiological laxity, a lack of cooperation during physical examination and a more varied differential diagnosis in this age category, which require awareness [38]. There is currently limited evidence on the diagnostic values of the physical examination in children as there are no prospective, diagnostic studies on this topic.

A radiograph should be made to evaluate potential tibial eminence fractures or other child-specific injuries, such as epiphyseal fractures or sleeve fractures of the patella [2]. Tibial eminence fractures and ACL injuries can present with a similar history and physical examination. An MRI is essential in case of suspicion of an ACL injury and to evaluate other intra-articular and soft tissue injuries [6]. The diagnostic performance of (3 Tesla) MRI for detecting ACL injuries are excellent with a sensitivity of 95-99% and specificity of 88-98% in adolescents [39,40]. Diagnostic values in younger patients (<12 years) however are substantially lower compared to adolescents of 12 to 16 years of age (sensitivity 62%, specificity 90%) when using an 1.5 Tesla MRI [38]. Potential explanations for lower diagnostic values in the patients under 12 years of age are inaccuracies due to developmental anatomy, less imaging experience with this age group, smaller anatomic structures, and the high proportion of partial ligament injuries [38].

Another important facet of imaging in this population is to determine whether the child is skeletally immature and to gain knowledge of remaining growth in the lower extremity, as skeletal maturity is important in treatment decision [6]. The radiograph and MRI of the knee provide information on whether the growth plates of the distal femur and proximal tibia are open. It is also important to gain information on whether the child has had the adolescent growth spurt, on the height of the parents and on the Tanner staging [2]. Performing Tanner staging however, is doubtful in this population as preoperative Tanner staging by orthopaedic surgeons is unreliable [41]. The most common method to perform skeletal age assessment is to make a posterior-anterior radiograph of the left hand and wrist and to compare with a skeletal atlas (Greulich and Pyle) [2,42]. Recently, a skeletal age atlas based on an MRI of the knee is validated [9]. This MRI-based atlas provides the possibility to determine skeletal age with the MRI of knee and makes a radiograph of the hand therefore unnecessary.

Treatment

Similar to adults, children and adolescents with an ACL injury can be treated non-operatively and operatively [2]. Opinions on whether primary treatment should be non-operatively or operatively are still a matter of debate within the paediatric and sports medicine orthopaedic community [1]. Weighing the risks and benefits between primary surgical treatment and primary conservative treatment is crucial [1,43]. Protecting the integrity of the knee should be the clinician's primary focus [2]. Decision making depends on several factors, including whether the child is skeletally mature, presence of concomitant injuries that necessitate surgery and the patient's wish to keep on performing pivoting sports [2]. Independent of the chronological age, children with closed growth plates can be treated as adults [2]. Both non-operative and operative treatment have similar goals: to restore a stable knee that enables an active lifestyle and to reduce the risk of further meniscal or chondral injuries, leading to joint degeneration [2].

Non-operative treatment

The key component of both non-operative treatment is rehabilitation [2]. Non-operative treatment is often the treatment of first choice in children with open growth plates, because of the risk of physeal damage during ACL reconstruction [7,44]. For skeletally immature patients without associated injuries or without major instability complaints, non-surgical treatment is a viable and safe treatment option [2].

Rehabilitation for children and adolescents must be performed in close collaboration between the patient, the parents, an experienced physiotherapist and the orthopaedic surgeon [1]. Children are not small adults and can therefore not be expected to perform unsupervised training [1,2]. It is unknown whether the specific milestones of rehabilitation in adults also apply for children. Treatment focus should be mainly on dynamic, multi-joint neuromuscular control. [1,2,45]. Less emphasis should be on muscle strength and hypertrophy training for prepubertal children, because of the physiological and hormonal characteristics of this group [2]. Due to the increase in androgenic hormones, rehabilitation in children after the onset of puberty may be more comparable to rehabilitation in adults, including muscle strength training [2,46]. Current insights in rehabilitation show that rehabilitation should progress through phases based on clinical reasoning, sequential functional achievements and the achievement of functional milestones [1]. Non-surgical treatment should last for at least 3–6 months and after passing functional (return to sport) test criteria, the patient may return to the desired activities [2,47]. Currently, there are no validated non-operative rehabilitation programs for adolescents with ACL injuries and current rehabilitation programs are often based on adult ACL rehabilitation programs.

The effectiveness of brace treatment after ACL injuries in children is unknown. Many clinicians however recommend children to wear a brace during strenuous physical activities [48]. The brace might potentially protect the knee, prevent knee hyperextension or valgus/varus and bring awareness of the injury to others [2].

Operative treatment

Skeletally mature patients can be treated as adults and in case of an ACL reconstruction, an adult ACL reconstruction technique can be used [2]. Children and adolescents with open physes however, are primarily treated non-operatively due to potential post-ACL reconstruction growth disturbances. In the past, those patients were treated often with ACL suture repair, which frequently resulted in unsuccessful outcomes [1]. According to the International Olympic Committee consensus statement on paediatric ACL injuries and Dutch Orthopaedic Society (NOV), there are two main indications for ACL reconstruction in this young population [2,3].

1. Concomitant, repairable injuries that require surgery (for example: bucket handle meniscal tear or osteochondral injury)
2. Recurrent, symptomatic knee giving way after completing high-quality rehabilitation

Several ACL reconstruction techniques are described that potentially minimize the risk of postoperative growth disturbances in skeletally immature patients: transphyseal, physeal-sparing (including all-epiphyseal and over-the-top) and partial transphyseal techniques (Figure 5) [1,3,7]. The tunnels in the transphyseal technique are orientated more vertically and centrally compared to adult ACL reconstruction techniques to reduce the cross-sectional area damage of the physes (Figure 5) [2,7]. The physeal sparing techniques comprise an all-epiphyseal and an extra-epiphyseal technique (over-the-top) [1]. The extra-epiphyseal (over-the-top) (Figure 5) technique consists of a combined intra-articular and extra-articular reconstruction with use of an autogenous iliotibial band. This is fixed to the intermuscular septum on the femoral side and to the periosteum of the proximal tibia [49]. In the all-epiphyseal technique (Figure 5), the tunnels are located in the femoral and tibial epiphyses and there is no drilling through the growth plates [1,6,50]. The partial transphyseal (or "hybrid") technique combines a physeal sparing technique on the femoral side and a transphyseal technique on the tibial side, which intends to provide anatomical reconstruction and minimizing the risk of growth disturbances, and yet being less technically demanding (Figure 6) [51].

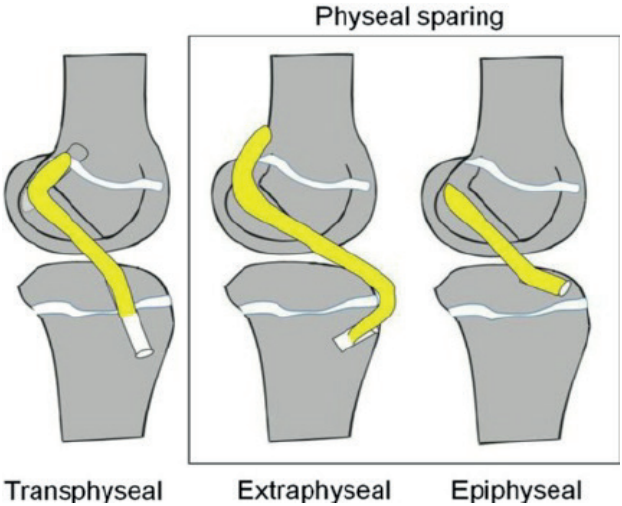

Figure 5. Transphyseal and physeal sparing ACL reconstruction techniques by Janssen et al [1].

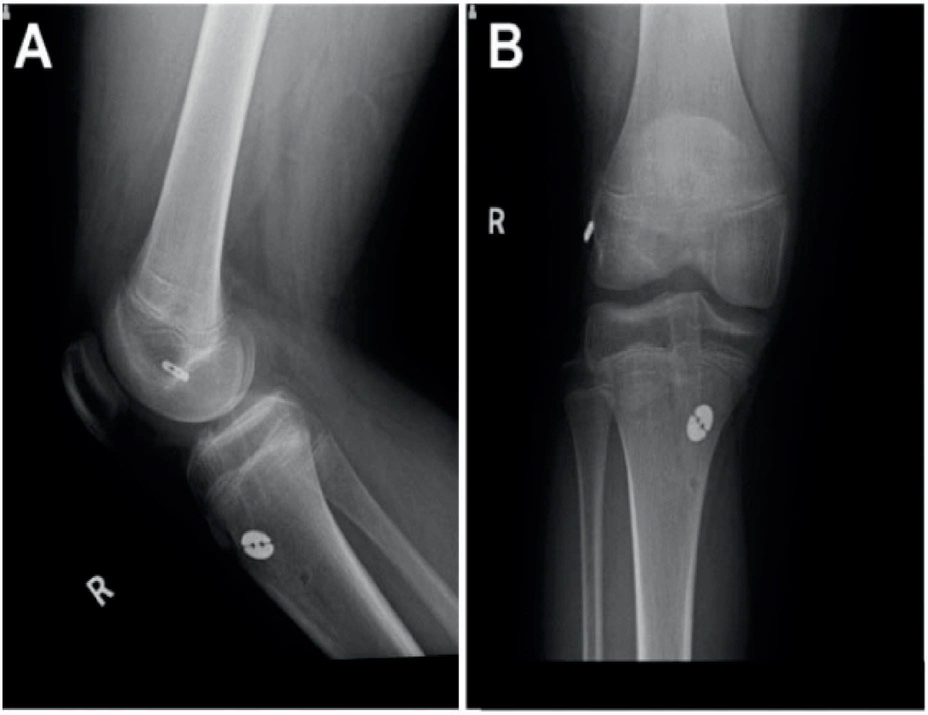

Figure 6. Postoperative radiographs after ACL reconstruction with a hybrid femoral physeal-sparing (all-epiphyseal), tibial transphyseal technique by Wilson et al [51].

Three general rules apply when drilling through the growth plates to prevent growth disturbances [2]:

1. Drilling should not be performed at the periphery of the growth plate or at the perichondral ring
2. Tunnels should be as vertical as possible to reduce the cross-sectional area of damage to the growth plate
3. Tunnels in growth plates should not be filled with hardware, implants or bone, but preferably with soft tissue grafts

Soft tissue grafts can be divided in autograft and allograft. Commonly used autografts for ACL reconstructions are hamstring tendons, bone patella tendon bone graft and quadriceps tendon graft [2]. Hamstring tendon autograft is the most frequently used graft for ACL reconstructions.[2] However in a paediatric population, there are concerns that in some occasions the encountered hamstring graft can be too small to produce a graft with an adequate diameter [52]. Bone-patellar tendon-bone (BPTB) should not be harvested in children with open growth plates, as this may result in damage to tibial tubercle apophysis, leading to a recurvatum deformity [6,7]. Quadriceps and patellar tendon can be harvested without bone block [6]. Also, the iliotibial band is an option as graft material, especially if an extra-epiphyseal, extra-articular technique is performed [6,53]. The use of allografts results in poor clinical outcomes in paediatric ACL reconstructions [2,54].

Clinical Outcomes

Return to sports rate after ACL reconstruction is high [1,55,56]. In a systematic review and meta-analysis was shown that 78.6% return to pre-injury level and 81% to competitive level of sport [55]. Concerning however are the high failure rates and revision rates after ACL reconstruction, especially in children who are exposed to high risk sport activities (pivoting sports, for example football) [1,4,57]. Compared to adults, the revision rate in the 13- to 20-year-old ACL-reconstructed patient is up to 3.5 times higher (Figure 7) [4]. Most revisions are performed in children aged 13-15 years [4,58]. Children also have an increased risk of a contralateral ACL injury [59]. The risk of re-injury is especially high within the first 2 years after ACL reconstruction [60].

Growth disturbances

Growth disturbances are a rare but serious complication [2]. There is a variation in the reported postoperative growth disturbances, ranging from 2% to 24% of the patients [2,61,62]. Current knowledge of the aetiology and of true incidence is limited, as growth disturbances are underreported in literature [61]. A recent ESSKA survey on paediatric ACL injuries showed also that only half of the surgeons reported to follow-up children until skeletal maturity after surgical treatment [61].

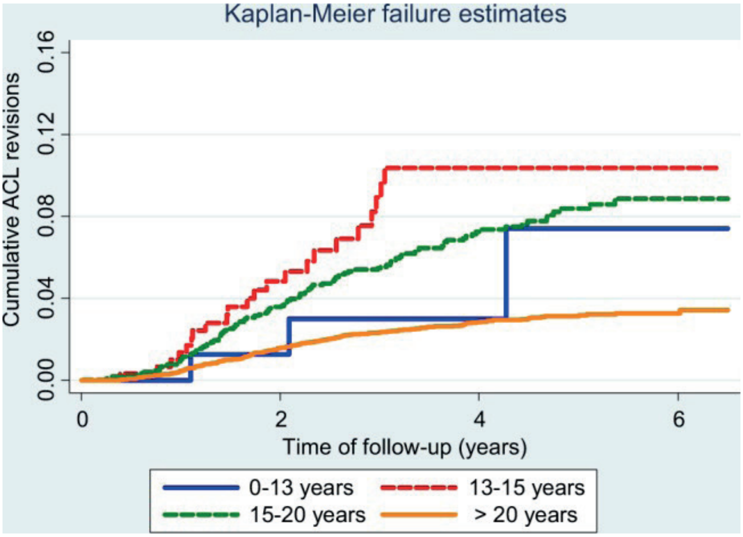

Figure 7. Kaplan-Meier cumulative revision curve of primary anterior cruciate ligament reconstructions in the 4 different age groups of the study, by Faunø et al [4].

Growth disturbances are classified in three categories [2]:

1. Localised bone bridge due to damage of the growth plate, possibly resulting in malalignment
2. Overgrowth due to hypervascularisation
3. Teno-epiphysiodesis effect due to graft tension, possibly resulting in undergrowth

A recent systematic review comparing transphyseal and physeal sparing techniques however, showed no differences in complications such as growth disturbances or graft failure incidence [63].

Long term knee health

Long term knee-health after ACL injury in adolescents is unknown. There is an increased risk of osteoarthritis after ACL injury, which is especially associated with chondral damage, meniscal injury and meniscectomy [1,2,64,65,66]. Meniscectomy or meniscal repair during ACL reconstruction is performed in 39% and 28% of the procedures respectively in patients age 10-14 years [1,15]. It is advised to preserve the meniscus whenever possible, as prior meniscectomy is associated with chondral lesions during ACL reconstruction and prior meniscal repair is not associated with a higher risk on chondral lesions [2,67].

Patient reported outcome measures (PROMs)

PROMs are a valuable tool to assess patients' perceived health condition and treatment results [1,68]. PROMs are used by clinicians to enhance clinical management of individual patients and offer specific benefits since subjective assessment of reduction of symptoms and quality of life avoid observation bias [1,69]. Two types of PROMs can be distinguished: disease-specific and generic PROMs [1,70]. PROMs concerning musculoskeletal conditions often target adult populations, but are also used in paediatric and adolescent populations [70]. Since psychometric properties were determined in an adult population and there might be a lack of comprehensibility of the questionnaire, problems may arise concerning the psychometric properties of the adult PROMs used in children [70,71]. This problem led to the development of paediatric knee-specific PROMs, such as the Pedi-IKDC and KOOS-Child [71,72]. Of which, the Pedi-IKDC and KOOS-Child are translated and validated in Dutch for children and adolescents with knee complaints [73]. An overview of the available knee specific PROMs for clinical and scientific use in ACL ruptured children is lacking.

Physical activity can also be measured as subjective outcome. The level of physical activity is increasingly recognized as both an important prognostic factor and outcome variable in orthopaedics [74]. In Dutch however, there is currently no validated, short and simple physical activity scale for children and adolescents available. The 2018 IOC consensus statement and Paediatric Anterior Cruciate Ligament Monitoring Initiative (PAMI) by ESSKA recommend the use of the Hospital for Special Surgery Paediatric Functional Activity Brief Scale (HSS Pedi-FABS) as a physical activity scale [2,75]. The HSS Pedi-FABS is currently only available in English and Italian [76,77].

Aims and outline of this thesis

There is currently limited evidence in the field of paediatric and adolescent ACL injuries. This thesis focuses on the current state of care of paediatric and adolescent ACL injuries in the Netherlands, diagnostics, preoperative graft planning, predictors for re-injuries, patient reported outcome measures and rehabilitation. The aims of this thesis are to gain evidence on different topics to support clinical decision making.

Part I. Current state of care in the Netherlands

Management of paediatric ACL injuries is a matter of debate in the scientific community and high quality studies are lacking [2,48]. Previous survey on a supranational level (ESSKA) shows a great variability in the treatment of skeletally immature children and in the use of outcome measures and follow-up [48]. In **Chapter 2**, the current state of care for skeletally immature children with ACL injuries in the Netherlands is investigated by performing a survey among members of the Dutch Arthroscopy Society (NVA; Nederlandse Vereniging voor Arthroscopie). It was hypothesized that there would be a great variability in the treatment and follow-up of skeletally immature children with ACL injuries. This study aims to inventory the current state of care for paediatric and adolescent ACL ruptures in the Netherlands. The outcomes of this survey can be used to monitor and give direction to future standards of treatment in the Netherlands.

Part II. Diagnostics and predictors

Diagnosing ACL injuries in children is more difficult compared to adults. There is however limited evidence of the diagnostic values of history taking and physical examination. In **Chapter 3**, the diagnostic values of history taking, physical examination and KT-1000 arthrometer are evaluated by performing a prospective, diagnostic study on children and adolescents with post-traumatic knee complaints. The aim of this study is to determine the diagnostic values of a standardized history taking, physical examination and KT-1000 arthrometer for ACL injuries in children and adolescents.

In case of ACL injury, some children and adolescents undergo ACL reconstruction. Hamstring tendon autograft is most frequently used for ACL reconstruction in children and adolescents [2]. There are concerns however that the tendon dimensions are too small to create a sufficient graft [52]. In **Chapter 4**, the predictability of hamstring tendon length and graft characteristics based on anthropometric values are studied in children. The primary aim of this study is to analyse the preoperative predictability of the ST and G tendon lengths based on anthropometric data in adolescents for the purpose of preoperative graft planning. The secondary aim is to analyse graft characteristics, such as ST or STG graft, length and diameter in a closed socket ACL reconstruction technique.

Re-injuries after ACL injury are high in adolescents compared to adults. Several morphological risk factors of the knee are known to be a risk factor for primary ACL injuries in children and adolescents and for re-injuries in adults after ACL reconstruction. However, there is limited knowledge of knee morphology as risk factor for ACL re-injuries after ACL reconstruction in children and adolescents. In

Chapter 5, in a multi-centre retrospective case-control study, the morphological risk factors of the lateral compartment of the knee are evaluated as risk factors for re-injuries after ACL reconstruction. This study is established by the cooperation between Máxima Medical Centre and Aarhus University Hospital. The aim of this study was to evaluate the tibiofemoral morphology of the lateral knee compartment as risk factor for ACL re-injury as diagnostic tool.

Part III. Outcome measures and (p)rehabilitation

Patient reported outcome measures are used as subjective outcome measure after ACL injury. Adults PROMs are often used for children and adolescents. Adults PROMs are often not validated in a paediatric and adolescent population and there might be problems concerning comprehensibility. There is currently no overview of validated knee-specific PROMs for children and adolescents. In **Chapter 6**, an overview of the available (validated) PROMs for children and adolescents with knee ligament injuries is provided by performing a systematic review. The aim was to create an overview of PROMs for day-to-day practice.

There are currently no short and simple specific physical activity scale for children and adolescents in the Netherlands. The HSS Pedi-FABS is advised by the PAMI to assess the activity level in children and adolescent with ACL injuries. In **Chapter 7**, the HSS Pedi-FABS is translated and transculturally validated in Dutch. The aim was to create the Dutch HSS Pedi-FABS for clinical and scientific use.

Current evidence on non-operative treatment and postoperative rehabilitation after ACL reconstruction in children and adolescents is low. Rehabilitation protocols and return to sport criteria are often based on adult protocols. In **Chapter 8**, an overview is presented on the available tests and criteria for return to sport after ACL injury and ACL reconstruction in children based on a scoping review. Based on this scoping review, evidence based choices for RTS testing can be made.

In **Chapter 9**, a consensus statement is built on (p)rehabilitation and return to sport criteria testing by performing a Delphi consensus study among international paediatric ACL rehabilitation experts. The aim was to develop a practice guideline for paediatric and adolescent ACL rehabilitation which can be used in everyday practice.

Chapter 10. General discussion and valorisation

Finally, in **Chapter 10** the findings of the previous chapters are discussed and current literature is addressed. Final conclusions, recommendations and valorisation are presented in this chapter.

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Part I

Current state of care in the Netherlands

Chapter 2

Current state of care in
the Netherlands

Current State of Care for Paediatric ACL Ruptures in the Netherlands: A Survey

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Abstract

Background: The management of anterior cruciate ligament (ACL) injuries in the skeletally immature patient is an area of controversy. The purpose of this survey is to inventory the current state of care for paediatric ACL injuries in the Netherlands.

Methods: This survey was conveyed by e-mail among all members of the Dutch Arthroscopy Society (Nederlandse Vereniging voor Arthroscopie [NVA]) and promoted on the Web site of the NVA. It was developed by the scientific committee of the NVA by a consensus meeting discussing relevant topics in paediatric ACL injuries.

Results: All members of the NVA received the survey (n = 540). A total of 158 (29%) members responded to the survey, of which 143 were completed. A total of 126 responses were analysed after exclusion. The main finding of this survey is that 78% of the respondents tend to treat children with open physes non-operatively, while 65% tend to treat children with closed physes operatively. The most frequently performed procedure is the transphyseal reconstruction. Many considerations were involved in choosing operative treatment. The postoperative follow-up period varies from less than 1 year (24%) until fully grown (27%).

Conclusions: This survey shows that the current state of care for paediatric ACL injuries is variable and a matter of debate in the Netherlands. Although the response rate seems low, this survey provides an overview of the opinions of specialized orthopaedic surgeons in the Netherlands. The results of this survey led to the development of the national registry for paediatric ACL in the Netherlands.

Introduction

The management of anterior cruciate ligament (ACL) injuries in the skeletally immature patient is an area of controversy [1,2]. Both operative and non-operative treatments can result in complications, such as physeal damage resulting in growth disturbances postoperatively or secondary damage to the meniscus or cartilage in case of non-operative treatment. Opinions on whether paediatric ACL injuries should primarily be treated operatively or non-operatively are still divided [3–5]. Should all children with open physes be treated non-operatively until the physes are closed, or is surgical treatment a viable option in skeletally immature children? In case of operative treatment, which surgical technique should be used to ensure optimal biomechanical positioning of the graft and to prevent physeal injury and graft failure? Which considerations play a role in indicating surgical treatment? What are the formats and requirements for follow-up? All these items are a matter of debate due to a lack of solid scientific knowledge [3].

During the past two decades, there were an increasing number of studies on ACL injuries in skeletally immature children [6]. These studies suggest an increasing trend of ACL injury rates in children, which is also described in a population-based study over a period from 2005 to 2015 in Australia [7]. Whether the incidence is truly increasing because of higher sports participation or whether there is an increase in clinical awareness and advances in diagnostic methods is a matter of debate [6,7].

Studies on the management of children with ACL injury present a low level of evidence [8]. The gold standard of management of skeletally immature children with an ACL rupture has still to be determined and therefore "the best treatment" for the individual skeletally immature patient is so far unknown [2]. A recent, descriptive study by Ekås et al [9] showed that ±50% of the children with primary nonsurgical treatment may cope well and have healthy menisci through adulthood [9]. The other half may need delayed ACL reconstruction [9]. Treatment algorithms for ACL ruptures in skeletally immature children vary around the world and are mainly experience-based [5,6,10,11,12]. With the possible increasing numbers of these injuries and the dilemma that exists between reconstruction and avoidance of physeal injury, an evidence-based approach of this topic is needed [2,13].

This study aims to inventory the current state of care for paediatric ACL ruptures in the Netherlands by conducting a survey among members of the Dutch Arthroscopic Association. The ESSKA paediatric ACL monitoring initiative was created by their international survey awareness on the diversity in clinical practice and the authors hoped that it could serve as a catalyst for international collaborations [6]. The outcomes of this survey can also be used to monitor and give direction to future standards of treatment in the Netherlands. The current national guidelines on ACL injury and treatment in the Netherlands did not include paediatric ACL injuries. The hypothesis therefore is that treatment for skeletally immature children with an ACL injury is heterogeneous.

Materials and Methods

Survey Administration

The survey was administrated by e-mail to all members of the Dutch Arthroscopy Society (Nederlandse Vereniging voor Arthroscopie [NVA]). The Dutch Arthroscopy Society has 540 members, mainly orthopaedic surgeons, but it also includes specialists such as plastic surgeons and veterinarians who do not treat ligament injuries of the knee. Only orthopaedic surgeons are included in the analysis of this survey. A reminder was sent to the members of the NVA who did not respond to the first request to fill in the survey. Besides, the survey was promoted on the Web site of the NVA (https://scopie.org/site/). The responses were analysed on May 1, 2017 (Figure 1).

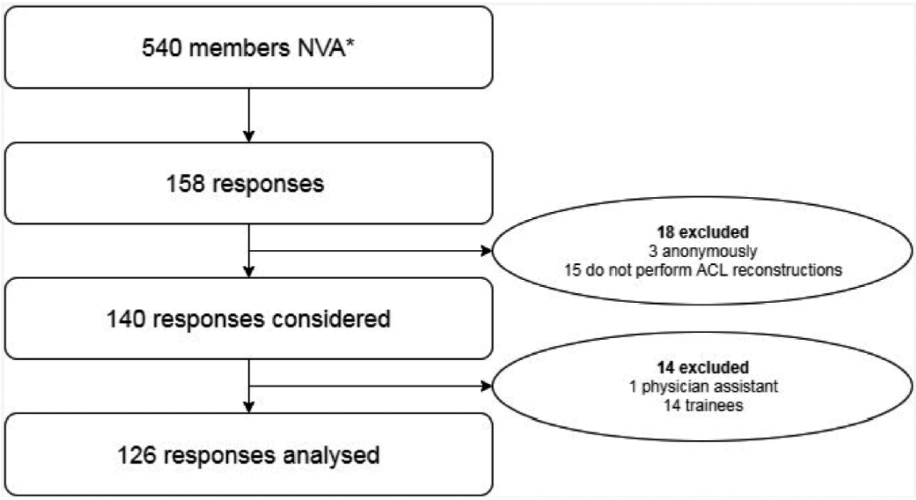

Figure 1. Flowchart of responses to survey of the NVA (Dutch Arthroscopic Society). ACL = anterior cruciate ligament.

Survey Development

The scientific committee of the NVA developed the survey by consensus meeting on the relevant topics in paediatric ACL. The scientific committee of the NVA consists of four experienced arthroscopic orthopaedic surgeons and one clinical epidemiologist and scientific researcher in the field of ACL ruptures. The survey was constructed by a Delphi method and all members approved the final version of the survey. In the final survey, the following topics are included: amount of consultations and reconstructions, management of children with open and closed physes, advices regarding sports, indications for operative treatment, surgical techniques, and postoperative follow-up.

Results

A total of 540 surveys were sent to all members of the NVA. A total of 158 (29%) members responded on the survey, of which 140 were considered for analysis. After exclusion, 126 responses were included for analysis as is shown in Figure 1.

How Many Consultations and Reconstructions Are Yearly Performed?

The number of yearly performed ACL-reconstructions in general (regardless of age) is shown in Table 1. The number of consultations by children in general and by children with open physes are shown in Tables 2 and 3.

Table 1. Number of yearly performed ACL reconstructions in general (n = 126)

ACL reconstructions per year, n	Number (%)
<20	38 (30)
20-50	39 (31)
>50	48 (38)
Unknown	1 (1)

Table 2. Number of consultations of children (including children with open and closed physes) with ACL injury per year (n = 126)

Consultations per year, n	Number (%)
<10	64 (51)
10-50	56 (44)
>50	4 (3)
Unknown	2 (2)

Table 3. Number of consultations of children with open physes with ACL injury per year (n = 126)

Consultations per year, n	Number (%)
<10	100 (79)
10-50	23 (18)
>50	2 (2)
Unknown	1 (1)

How Is the Management of Paediatric ACL Injuries?

In case of open physes, 78% of the children with open physis are primarily treated non-operatively and 22% operatively. In children with a closed physes, 35% are treated primarily non-operatively and 65% operatively. In case of non-operative treatment, the respondents gave different recommendations regarding sports participation (more than one answer allowed). Ranked on frequency, 70% (n = 88) of the respondents recommended to adjust the type of sports, 41% (n = 51) the level of sports, 43% (n = 54) to wear a brace during sports, and 6% (n = 8) to stop sports participation.

In Case of a Concomitant Symptomatic Meniscal Tear, Does This Influence the Decision-Making in Conservative Treatment?

In case of a concomitant, symptomatic meniscal tear, 25% (n = 32) of the respondents stated that this would not influence treatment. 73% (n = 92) responded that this would influence the choice of treatment, of which 5% (n = 5) refers to another specialist, 13%(n = 12) performs an ACL reconstruction, 30% (n = 28) performs a meniscal repair, and 52% (n = 47) performs an ACL reconstruction and meniscal repair. Two (2%) respondents did not fill in an answer to this question.

Which Factors Are Considered Important as Indication for Surgical Treatment?

Different considerations ranked on importance are shown in Table 4.

Table 4. Considerations concerning indications for operative treatment, more than one answer per respondent allowed

Considerations	Number (%)
Concomitant ligament injury	89 (71)
Concomitant meniscal injury	88 (70)
Age of child	74 (59)
Wish to perform sports	72 (57)
Type of sports participation	62 (49)
Level of sports participation	58 (46)
Preference of parents	15 (12)
Degree of instability	8 (6)

Which Surgical Techniques Are Performed in Children with Open Physes?

Of the 126 respondents, 87 (69%) responded to this question in which more than one answer was allowed. In children with open physes, 64% (n = 56) of the respondents perform a transphyseal reconstruction, 28% (n¼ 24) a physeal sparing reconstruction, 20% (n = 17) a transtibial and femoral physeal sparing procedure, and 11% (n = 10) an extra-articular procedure.

In Case of an ACL Reconstruction of Children with Open Physes, What Is the Duration of the Follow-Up Period?

Of the 126 respondents, 27% (n = 34) follow the children until skeletal maturity, 25% (n = 32) for 1 year postoperatively, 7% (n = 9) for 1 to 2 years postoperatively, and 6% (n = 8) for more than 2 years postoperatively. A total of 34% (n = 43) did not complete this question or indicated that the mean follow-up was unknown.

Discussion

The most important finding of this survey is that the majority of the children with open physes are treated non-operatively while most children with closed physes are treated operatively. In case of operative treatment in a child with open physes, 64% of the respondents chose to perform a transphyseal procedure. Another important finding is that many considerations are involved in indicating operative treatment, of which concomitant injury of the menisci or ligaments is most frequently reported.

The majority of the respondents treat fewer than 10 children with an ACL injury per year, and only 3% of clinicians are consulted by more than 50 children per year. On the basis of these data, one can calculate that there are several hundred ACL injuries in children per year in the Netherlands. The exact incidence of ACL injury in children in the Netherlands is unknown however, and there might be a possibility of overestimation of the number of consultations in this survey.

Non-operative treatment is the preferred treatment in skeletally immature injured children for 78% of the respondents. Within the paediatric orthopaedic community, opinions are divided whether paediatric ACL injuries should be treated non-operatively or operatively [12,14]. Comparing two previous surveys from 2002 and 2015, the proportion (34% vs 59%) of orthopaedic surgeons who advocate operative treatment has almost doubled [6,15]. In a recent survey by the PRiSM (Paediatric Research in Sports Medicine) Society, a case of an 8-year-old child with a complete ACL rupture was presented to the respondents [16]. In this survey, only 3% would treat the child non-operatively [16]. Reasons for this increase are development of surgical techniques and a stronger belief in beneficial results from surgical treatments [6]. However, the evidence is low; there are neither high-level evidence studies nor studies that compared results from the past to results from the present [6,17]. In decision-making, weighing risks and benefits between primary non-operative and primary operative treatment is crucial [8].

According to the current survey, the most important considerations for operative treatment were concomitant ligament and meniscus injury, followed by the age of the child, the wish to continue to perform sports, and the type and level of sports participation. The preference of the parents and the degree of instability were deemed less relevant. A consensus meeting of the International Olympic Committee in 2018 stated that there are three indications for ACL reconstruction: repairable concomitant injury that require surgery, recurrent and symptomatic giving way after completing rehabilitation, or unacceptable participation restrictions [1]. It is generally accepted that operative treatment reduces the risk of further damage of the menisci or cartilage in case of persistent instability [3,18]. Non-operative or delayed operative treatment (3–12 months after trauma) may lead to meniscal injury, due to persistent instability [3,11,19]. In conclusion, the goal of operative treatment is to restore stability and protect the knee against future meniscal or chondral lesions [3]. Besides, the wish to return to pre-trauma level and type of sport might be important considerations for operative treatment [1,20].

In case of non-operative treatment, the majority of the respondents advocated adjusting the type of sports to avoid pivoting sports. Recent literature suggests that rehabilitation after ACL injury in children is mainly focused on neuromuscular stimulation and multi-joint functional stability and less on muscular strength and hypertrophy [1,8,21,22]. In the beginning, children should be guarded from performing pivoting activities and advised to wear a brace in sport [22]. Although there are no solid studies on bracing children after ACL injury, a small majority advises to use a brace during sports participation [1,22]. In this survey, the recommendations of the respondents adhere to the current limited scientific evidence for non-operative treatment.

In case of operative treatment, most of the respondents perform a transphyseal repair. Different surgical techniques have been developed to address postoperative complications such as growth disturbances and graft failure [2,23]. A recent systematic review of Pierce et al concluded that there is no difference in clinical outcome in regard to growth disturbances and re-rupture rate between transphyseal and physeal sparing procedures [2]. Theoretical advantages of a transphyseal procedure are a more anatomical ACL reconstruction and more familiarity among surgeons compared with a physeal sparing procedure [2]. One must note, however, that the results of the pooled data were weakened by lack of uniformity among the compared studies [2,3]. To date, there is no convincing evidence to support a specific procedure for paediatric ACL reconstruction [2,3].

There is a variety in the duration of follow-up after ACL reconstruction among respondents in this survey. A third of the respondents did not respond to this item. The follow-up until skeletal maturity is performed by 27% of the respondents. Twenty-five percent of the respondents have a follow-up of less than 1 year postoperatively. These outcomes are similar to the findings in the ESSKA monitoring initiative survey [6]. It is noticeable that most respondents do not follow the children until fully grown considering the risks of postoperative growth disturbances or graft failure [6].

The response rate of 29% (158/540) seems low. However, the NVA is an association of arthroscopy in general. Therefore, not only orthopaedic surgeons specialized in knee arthroscopy are member of this society, but the NVA has a great variation of members, such as orthopaedic surgeons (specialized in knee, shoulder, or any other joint), plastic surgeons, trauma surgeons, and veterinarians. This survey gives an overview of the opinion of the Dutch orthopaedic surgeons who perform ACL reconstructions in general. Besides, the response rate is higher compared with a response rate of 22% in the ESSKA survey, but the total amount of respondents in ESSKA survey was 491 [6]. In contrast to the ESSKA survey, only the responses of orthopaedic surgeons were analysed in this survey and the responses of trainees were excluded.

The questions in this survey are meant to evaluate the treatment of skeletally immature children in general. There is no further specification of the child besides the open physes. For example, one might consider using different surgical techniques based on the estimation of residual growth. Since these questions give an indication of the general treatment of children with open physes, a limitation is that these questions are not case specific and might therefore only give an indication of the techniques that are being used in the Netherlands.

Another limitation of this survey is that the use of patient reported outcome measures (PROMs) is not evaluated. PROMs should be used to gain insight in the patient's perceived treatment results [24,25,26]. In the ESSKA survey, all respondents used PROMs; however, only 15% used child friendly questionnaires [6]. In a recent systematic review, Dietvorst et al [26] showed that the use of adults PROMs in children should be avoided [26]. As the use of PROMs is not evaluated in this survey, no conclusion can be drawn about the use of these PROMs in the Netherlands.

Further research should aim at creating an evidence-based, skeletal, age-specific treatment algorithm. This requires high level studies on non-operative and operative treatments of paediatric ACL injuries. Different operative techniques should be evaluated and developed to minimize graft failure and growth disturbances. Determination of the duration and methods for follow-up must also be established. To evaluate future results of ACL reconstructions in children, there is a necessity for a registry to gain information on outcomes. Currently, a national registry for children with ACL injury is being developed.

Conclusions

This survey shows that the current state of care for paediatric ACL injuries is variable and a matter of debate in the Netherlands. Children with open physes tend to be treated non-operatively, while children with closed physes are operated more frequently. In case of an operative treatment in a child with open physes, a transphyseal ACL reconstruction is most frequently performed. There is variation in the postoperative follow-up period. Further research should be aimed at creating an age-specific treatment algorithm and (inter)national guidelines should be developed. To gain information on future treatment results, a registry is being developed.

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Part II

Diagnostics and predictors

Chapter 3

Diagnostics and predictors

Diagnostic values of history taking, physical examination and KT-1000 arthrometer for suspect anterior cruciate ligament injuries in children and adolescents: a prospective diagnostic study

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Abstract

Background: diagnosing anterior cruciate ligament (ACL) injuries in children and adolescents are more challenging compared to adults. Delayed diagnosis may result in meniscal or chondral injuries. The aim of this study was to determine the diagnostic values of history taking, physical examination and KT-1000 arthrometer for suspect ACL injuries in children and adolescents.

Methods: in this prospective diagnostic study, all children and adolescents (<18 years) with post-traumatic knee complaints presenting at the out-patient department of the Máxima MC were eligible for inclusion. One experienced knee specialised orthopaedic surgeon was blinded and performed history taking, physical examination and KT-1000 arthrometer measurement. All patients had a magnetic resonance imaging (MRI) for the final diagnosis. Diagnostic values of interest were sensitivity, specificity, positive and negative predictive values (PPV and NPV). The outcomes of the KT-1000 arthrometer were drafted in a relative operating characteristics (ROC) curve to determine the optimal cut-off points.

Results: 66 patients were included, of which 50 had an ACL rupture and 16 had no ACL rupture on MRI. Report of a popping sensation during trauma had a specificity and PPV of 100% for diagnosing ACL injuries. The PPV and NPV of the Lachman test (in case of describing end-feel) were 95% and 82%, of the anterior drawer test 87% and 90% and of the pivot shift test 95% and 81% respectively. The optimal cut-off point of the KT-1000 arthrometer at 133 N force was an absolute translation of ≥7mm with a PPV and NPV of 97% and 88% respectively.

Conclusions: report of a popping sensation during trauma has a specificity and PPV of 100% for diagnosing ACL injuries in children and adolescents. Although potentially difficult in children, the Lachman test, anterior drawer test and pivot shift test have a high PPV and NPV when performed by an experienced orthopaedic surgeon. An absolute anterior translation of ≥7mm of the injured knee in the KT-1000 arthrometer at 133 N has the highest diagnostic values of all tests for diagnosing ACL injuries.

Background

Anterior cruciate ligament (ACL) ruptures are a severe injury of the knee for children and adolescents [1]. Paediatric ACL tears are rare, accounting for less than 5% of all ACL injuries, and rarely occur under the age of 9 [1, 2]. Management of paediatric ACL injuries is challenging and a matter of debate due to limited scientific evidence [1, 3]. Diagnosing an ACL injury in children is also more challenging compared to adults [1]. This may be due to difficulty in obtaining an accurate history, greater physiological joint laxity and lack of cooperation during physical examination [1, 4, 5]. Besides, skeletally immature children may sustain different knee injuries than adults, such as an epiphysiolysis or sleeve fracture of the patella, and the frequency of specific injuries is different within adolescent age categories [1, 6]. A missed or delayed diagnosis and treatment of an ACL rupture in children and adolescents increase the risk of -irreparable- meniscal lesions or chondral lesions [7-11]. Besides, a false positive diagnosis might result in unnecessary referrals to orthopaedic surgeons and magnetic resonance imaging (MRI).

There is currently limited evidence on the diagnostic values of history taking and physical examination in children as there are no prospective, diagnostic studies on this topic. In their retrospective study, Kocher et al [4] determined the diagnostic accuracy of the physical examination in children with intra-articular disorders of the knee necessitating an arthroscopic evaluation, including ACL, meniscal and chondral injuries [4]. The sensitivity and specificity of the physical examination for diagnosing an ACL injury were respectively 81.3% and 90.6% [4]. History taking and ACL injury specific tests, such as the Lachman test, anterior drawer test, pivot shift test or the KT-1000 arthrometer have not been evaluated for diagnosing ACL injuries in children and adolescents specifically [4, 12-16].

The aim of this study is to determine the diagnostic values of a standardized history taking, physical examination and KT-1000 arthrometer for suspect ACL injuries in children and adolescents. It is hypothesized that children and adolescents report similar anamnestic items as adults, but due to greater physiological laxity and paediatric specific injuries, the diagnostic values of physical examination are lower than those reported in literature for adults.

Methods

Study design

In this prospective diagnostic study, all children and adolescents (<18 years) with post-traumatic knee complaints presenting consecutively between 2017 and 2021 at the out-patient clinic of an experienced knee specialized orthopaedic surgeon (RJ) were eligible for inclusion. There were no restrictions on time interval between trauma and consultation nor on referral. Patients who had undergone surgical treatment for the knee complaints or for whom the reason for referral was known were excluded. The orthopaedic surgeon was blinded for the reason of referral and for prior diagnostic outcomes including physical examinations, radiographs and MRI's. A standardized history taking and physical examination including the KT-1000 arthrometer was performed by the orthopaedic surgeon. All patients had an MRI of the affected knee before or after the consultation.

Tests

A complete history taking on the trauma and post-traumatic complaints was performed in all patients. As this study aims at diagnostic values of history taking for suspected ACL injuries, three common symptoms were registered [17,18]:

- Q1: Did you experience a popping sensation in the knee during trauma?
- Q2: Was there acute post-traumatic effusion of the knee?
- Q3: Do you have complaints of instability (giving way) of the knee?

During history taking, patients were invited to explain all aspects of their complaints, symptoms and injury mechanism by open questions. Specific details such as a popping sensation, post-traumatic effusion and/or feeling of instability were additionally asked if not previously mentioned.

Physical examination was performed in a standard manner according to International Knee Documentation Committee (IKDC) 2000 knee ligament standard evaluation form [1, 19, 20]. Tests of interests were the Lachman test, anterior drawer test and pivot shift test [1, 19, 20]. An increased translation compared to the contralateral side was defined as a positive outcome. After the physical examination, the orthopaedic surgeon indicated for whether the patient was suspect for an ACL injury based on the outcomes of history taking and physical examination.

After the physical examination, the KT-1000 arthrometer was used to quantify the anterior-posterior laxity of both knees. The KT-1000 arthrometer is an objective instrument that measures anterior tibial translation relative to the femur and is often used as dichotomous outcome tool, but not as continuous outcome variables [21]. The KT-1000 arthrometer is strapped to the leg, the tibia is pulled anteriorly with 67 N, 89 N and 133 N and the amount of anterior translation (mm) is measured [21]. Anterior translation of the injured and non-injured knee was measured and compared. The anterior translation of the target knee, measured in mm at 133 N force, was the outcome of interest, as normative data of this force are published in children and adolescents [22]. Outcomes at 67 N and 87 N were also gathered in order to compare the diagnostic capacities of the three different forces. Unfortunately, the KT-1000 arthrometer was only available at one of the two out-patient departments in which the orthopaedic surgeon was consulted.

MRI

The MRI was used as a reference test, as an MRI is less invasive than arthroscopy and the sensitivity and specificity for detecting ACL injuries are 95% and 88% in children and adolescents [23]. All patients had an MRI of the knee before or after the consultation. The outcomes of the MRI were analysed by a radiologist who was not aware of the study. ACL injuries defined as full and partial ACL ruptures on MRI were the primary outcome of interest, in addition other ligament, meniscal and chondral injuries or fractures were recorded. Outcomes of the MRI were compared to outcomes of surgery on ACL injuries and meniscal injuries, in case when the patient did not have another trauma in between the MRI and surgery.

Statistical analyses

Baseline characteristics were calculated for the study population. Sensitivity, specificity, positive predictive values (PPV) and negative predictive values (NPV) including the 95%-confidence intervals (95%-CI) were calculated as diagnostic values for the questions during history taking and the laxity tests during physical examination. Moreover, the final judgement on suspicion of ACL injury after history taking and after physical examination was evaluated. Clinically relevant diagnostic pathways based on the PPV and NPV were illustrated. The diagnostic values were calculated for the KT-1000 arthrometer. The outcomes were drafted in a Receiver Operating Characteristic (ROC) curve and the Area Under the Curve (AUC) was calculated for the KT-1000 arthrometer at 67 N, 87 N and 133 N. The Youden index were calculated for absolute and relative (difference between injured and control leg) anterior translations. Differences in anterior tibial translation between patients legs were calculated with the Wilcoxon signed rank test and between ACL injured and non-ACL injured children with the Mann-Whitney U test. Differences between complete and partial ACL injured children were calculated for history taking and physical examination based on cross tabs and Chi square, Fisher's exact test or linear-by-linear association.

Based on preliminary results of this study on the prevalence of ACL injuries, the requirement of minimal sample size was calculated based on Bujang et al [24]. Based on the prevalence of 70-80% and prior published sensitivity and specificity of diagnostic tests [25], the minimum sample size was calculated to consist of 60 patients, of which 48 patients having an ACL injury [24]. Due to the population size and skewness of data, medians and interquartile ranges were used to describe the central tendency. Statistical analyses were performed by using SPSS (version 22.0.0, IBM, Chicago, IL, USA). Significance was set at p=0.05.

Ethical approval

The study is approved by the local ethical committee of Máxima Medical Centre [N.17.020]. All included participants and their parents or legal guardians (if necessary) gave informed consent.

Results

Sixty-seven patients were eligible for inclusion. One patient gave no consent for participation and was therefore excluded. The baseline characteristics of the 66 included patients are shown in Table 1. Age ranged from 7 to 17 years. All patients had post-traumatic knee complaints after a sports injury. 76% of the patients had an ACL injury. Of the 66 patients, 26 patients had a MRI before consultation, for which the orthopaedic surgeon was blinded. All other patients had a MRI after the consultation. All ACL injuries on MRI were confirmed during arthroscopy and all patients who underwent surgery for other indications had an intact ACL. There were 14 meniscal injuries diagnosed during ACL reconstruction, of which 8 meniscal injuries were prior diagnosed on MRI. Mean interval between MRI and ACL reconstruction for patients with meniscal injury was 186 days.

Table 1. Baseline characteristics of the study population.

	Patients (n=66)	
Age, y medians [IQR]	14	[12.5-15]
Gender, n female (%)	34	(52)
BMI, kg/m^2 medians [IQR]	19.7	[17.7-22.3]
Open physes, n (%)	41	(62)
Previous knee complaints, n yes (%)	7	(11)
Time since trauma, weeks median [IQR]	22	[8-55]
Type of trauma, n (%)		
Non-contact	48	(73)
Contact	16	(24)
Missing	2	(3)
Injuries, n (%)*		
ACL injuries	**50**	**(76)**
Complete ACL rupture	45	(68)
Partial ACL rupture	5	(8)
Other injuries		
MCL injuries	1	(2)
LCL injuries	1	(2)
PCL injuries	1	(2)
Patellar dislocations	2	(3)
Meniscal injuries	12	(18)
Cartilage injuries	4	(6)
Osgood Schlatter	1	(2)
No injuries	9	(14)
Referral, n (%)		
General physician	24	(36)
Emergency department	8	(12)
Second opinion^	34	(52)

"ACL = Anterior Cruciate Ligament"; "BMI = Body Mass Index"; "IQR = Interquartile Range"; "LCL = Lateral Collateral Ligament"; "MCL = Medial Collateral Ligament"; "MRI = Magnetic Resonance Imaging"; "PCL = Posterior Cruciate Ligament"; *injuries diagnosed with history taking, physical examination or imaging. ^from orthopaedic surgeons or sports medicine doctors.

History taking and physical examination

The diagnostic values of the questions (Q) during history taking are shown in Table 2. With the information gathered during history taking the orthopaedic surgeon misclassified 8 of 66 patients, resulting in a PPV of 89% and NPV of 83%. A popping sensation during trauma has a PPV of 100% and therefore diagnosis of an ACL injury is certain in case of a popping sensation. The NPV is 39% however, no popping sensation does therefore not rule out an ACL injury. Different diagnostic pathways are shown in Figure 1 based on having experienced a popping sensation during trauma.

Outcomes during history taking were similar between complete and partial injured children. Complaints of instability were however significantly different, as 96% of the children with a complete ACL injury had complaints of instability compared to 50% of the children with a partial ACL injury (p=0.045).

Table 2. Diagnostic values of the questions during history taking.

	TP	FP	TN	FN	Sensitivity % (95%-CI)	Specificity % (95%-CI)	PPV % (95%-CI)	NPV % (95%-CI)
Q1: Popping sensation^	24	0	16	25	49 (35-63)	100 (81-100)	100 (86-100)	39 (25-54)
Q2: Acute effusion	49	12	4	1	98 (92-100)	25 (9-49)	80 (69-89)	80 (37-99)
Q3: Instability (giving way)	46	5	11	4	92 (82-97)	69 (45-88)	90 (80-96)	73 (49-91)
Suspected for ACL injury*	48	6	10	2	96 (88-99)	63 (38-83)	89 (79-95)	83 (57-97)

"ACL = Anterior Cruciate Ligament"; "CI = Confidence Interval"; "FN = False Negative"; "FP = False Positive; "NPV = Negative Predictive Value"; "PPV = Positive Predictive Value"; "Q = Question"; "TN = True Negative"; "TP = True Positive".

^in one case the popping sensation was not described; *suspicion of ACL injury after history taking.

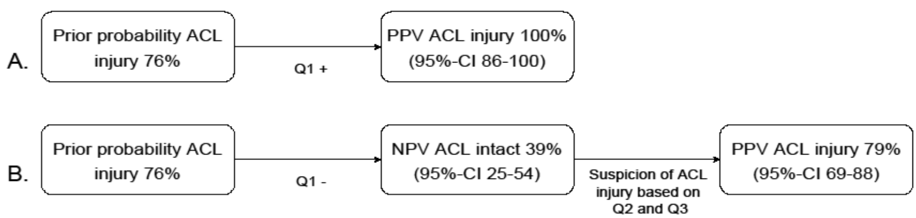

Figure 1. Different diagnostic pathways based on a popping sensation. A. PPV of a positive popping sensation during history taking. B. PPV of suspicion of ACL injury after history taking despite no popping sensation during trauma. "ACL = Anterior Cruciate Ligament"; "CI = Confidence Interval"; "NPV = Negative Predictive Value"; "PPV = Positive Predictive Value".

Diagnostic values of the physical examination tests are shown in Table 3. In 6 patients the end-feel during Lachman test was not described and in one patient the results of the anterior drawer test were not described. The pivot shift could not be performed in 9 patients due to pain or problems in relaxation. After gathering information from both history taking and physical examination the orthopaedic surgeon correctly classified 63 of the 66 patients, as is shown in Figure 2.

Outcomes of Lachman test, end-feel, anterior drawer test and pivot shift test were significantly different in complete ACL injured versus partial ACL injured children. Lachman and anterior drawer were 6-10mm or >10mm in 98% and 82% of the complete injured children compared to 25% and 25% of the partially ACL injured children (p=.001 and p=.039). All partially injured patients had a hard endpoint during Lachman test, compared to 2% of the complete ACL injured children (p=.000). None of the partially ACL injured children had a pivot shift of more than glide (1+). 78% of the completely ACL injured children had a pivot shift of clunk (2+) or more (p=.004).

Table 3. Diagnostic values of laxity tests.

	TP	FP	TN	FN	Sensitivity % (95%-CI)	Specificity % (95%-CI)	PPV % (95%-CI)	NPV % (95%-CI)
Lachman test	49	10	6	1	98 (92-100)	38 (17-62)	83 (72-91)	86 (51-99)
Soft end-feel during Lachman test	41	2	14	3	93 (83-98)	88 (66-98)	95 (86-99)	82 (60-95)
Anterior drawer test	48	7	9	1	98 (91-100)	56 (32-78)	87 (76-94)	90 (63-99)
Pivot shift test	39	2	13	3	93 (83-98)	87 (62-96)	95 (86-99)	81 (58-95)
Suspected for ACL injury*	49	2	14	1	98 (90-100)	88 (64-98)	96 (87-99)	93 (70-99)

"ACL = Anterior Cruciate Ligament"; "CI = Confidence Interval"; "FN = False Negative"; "FP = False Positive; "NPV = Negative Predictive Value"; "PPV = Positive Predictive Value"; "TN = True Negative"; " TP = True Positive".

*suspicion of ACL injury after history taking and physical examination.

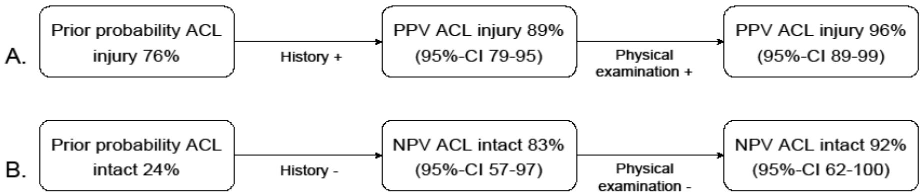

Figure 2. Different diagnostic pathways based on the suspicion after history taking and physical examination on ACL injuries.

A. PPV based on the suspicion of ACL injuries after history taking and physical examination. B. NPV based on no suspicion of ACL injuries after history taking and physical examination. "ACL = Anterior Cruciate Ligament"; "CI = Confidence Interval"; "NPV = Negative Predictive Value"; "PPV = Positive Predictive Value".

KT-1000 arthrometer

A total of 40 patients were examined with a KT-1000 arthrometer at 133 N, of which 21 patients were also tested at 67 N and 87 N force. Of the 26 patients who were not examined with the KT-1000 arthrometer, 7 patients were not able to tolerate the KT-1000 arthrometer due to pain (5 patient with ACL injury and 2 patient without ACL injury). The legs of 3 patients were too small to fit in the KT-1000 arthrometer (2 patients with ACL injury and 1 without ACL injury) and 16 patient could not be examined with the KT-1000 arthrometer due to absence of the KT-1000 arthrometer at the location of the out-patient department visit (11 patients ACL injury and 5 patients without ACL injury). Group of partial ACL injuries was too small for subsequent analysis. Median anterior translations in the KT-1000 arthrometer are shown in Table 4.

Table 4. Median anterior translations of the tibia in the KT-1000 arthrometer at 133 N for the injured and control leg for patients with and without ACL injuries.

	Median anterior translation of the tibia in mm [IQR]		
	ACL injuries (n=32)	**No ACL ruptures (n=8)**	**P-value**
Injured leg	10 [8.3-12.0]	5.0 [2.0-5.8]	>.001
Control leg	5.0 [3.0-7.0]	5.0 [2.0-5.0]	0.361
P-value	>.001	1.000	

"ACL = Anterior Cruciate Ligament"; "IQR = Interquartile Range"; "mm = millimetres"; "N = Newton".

The diagnostic performance of the KT-1000 arthrometer at 133 N is shown in Figure 3 for the absolute translation for the injured leg (3.1) and relative translation (difference between legs) (3.2). The AUC of the KT-1000 arthrometer at 133 N for relative translations was higher (0.973) compared to measurements at 67 N (0.953) and 87 N (0.947). The AUC for absolute translations were for 67 N, 87 N and 133 N respectively 0.920, 0,947 and 0,920. The Youden indexes at 133 N were higher than at 67 N and 87 N. Based on the Youden index, there is one optimal cut-off point for the absolute translation of the injured leg and two cut-off points for the relative translation, as is shown in Table 5. A relative translation of ≥1mm resulted in a slightly lower PPV, but higher NPV compared to the cut-off of ≥4mm.

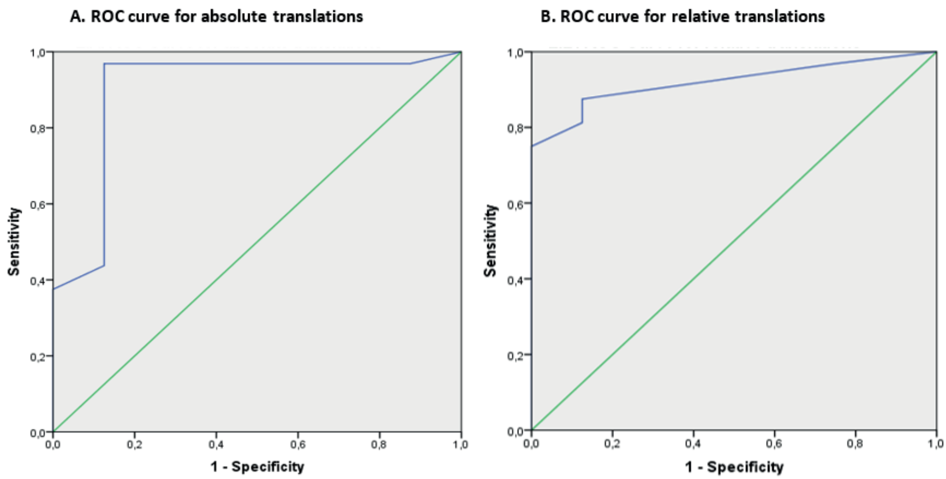

Figure 3. Receiver Operating Characteristics (ROC) curve for outcomes the KT-1000 arthrometer at 133 N for absolute anterior translations of the injured leg (3.A) and relative translations (3.B).

Table 5. Optimal cut-off points of absolute and relative anterior tibial translation in the KT-1000 arthrometer at 133 N.

Anterior tibial translation in millimetres (mm)		Sensitivity% (95%-CI)	Specificity% (95%-CI)	PPV % (95%-CI)	NPV % (95%-CI)	Youden Index
Absolute (injured leg)	7	97 (84-99)	88 (53-98)	97 (84-99)	88 (53-98)	0.84
Relative (injured - control leg)	1	88 (72-95)	88 (53-98)	97 (83-99)	64 (35-84)	0.75
	4	75 (58-87)	100 (68-100)	100 (86-100)	50 (28-72)	0.75

"CI = Confidence Interval"; "mm = millimetres", "NPV = Negative Predictive Value"; "PPV = Positive Predictive Value".

Discussion

The most important finding is that report of a popping sensation during trauma has a specificity and PPV of 100% for diagnosing ACL injuries in children and adolescents. The Lachman test, anterior drawer test and pivot shift test have a high PPV and NPV when performed by an experienced orthopaedic surgeon. An absolute anterior translation of ≥7mm of the injured knee in the KT-1000 arthrometer at 133 N force is the most accurate test with a PPV of 97% and NPV of 88%. The KT-1000 arthrometer is therefore the most accurate clinical test to diagnose an ACL injury.

A missed or delayed diagnosis and treatment of an ACL rupture in children and adolescents increase the risk of an (irrepairable) meniscal lesion or chondral lesions [7-11]. Diagnosing an ACL injury in children however, can be more challenging compared to adults [1]. It is therefore important, especially in (primary) health care settings with a low prevalence of paediatric ACL injuries and professionals with limited experience in performing ACL stability tests, to screen for potential ACL injuries and to refer early to a specialized orthopaedic surgeon [14]. In adults, Geraets et al [26] showed that for primary health care professionals only history taking is valuable when diagnosing ACL ruptures, while for orthopaedic surgeons diagnosis became more accurate when adding physical examination to medical history taking [26]. In the current study, report of a popping sensation resulted in a specificity and PPV of 100% with the 95%-CI of the specificity ranging from 81% to 100%. A report of a popping sensation did not necessitate additional examination to diagnose an ACL injury. A popping sensation is therefore a valuable diagnostic outcome for referral to an orthopaedic surgeon. However, careful physical examination is still essential as concomitant injuries might be present necessitating early treatment, such as a medial collateral ligament injury. Besides, the actual PPV in primary health care settings and general orthopaedic clinics might be lower as the prevalence of ACL injuries is lower [17].

In contrast to children and adolescents, the Lachman test, anterior drawer test and pivot shift test have been evaluated in an adult population before [25, 27]. In the most recent meta-analysis the Lachman and pivot shift tests showed a pooled sensitivity of respectively 89% (95%-CI 67-98%) and 79% (95%-CI 63-91%) in adults [25]. Compared to these diagnostic values in adults, the sensitivity of the Lachman test and pivot shift are higher in the current study. One would expect that the diagnostic values of tests would not be as high as in adults, due to specific issues in a paediatric and adolescent population, such as lack of patient cooperation and relaxation during examination, increased physiological laxity and the more varied differential diagnoses [1, 4, 5]. In the current study however, all tests were performed by a highly specialized orthopaedic surgeon in a setting with a high prevalence of ACL injuries in children. Experience level is a factor that might affect the reproducibility of the physical examination tests [25, 26]. This experience factor, combined with other factors, such as the size of the examiner hands, chronicity of the lesion and associated injuries, may also contribute to the variability of diagnostic values in literature [25, 26].

In order to objectify the anterior translation of the tibia, instrumented tests, such as the KT-1000 arthrometer, have been proposed to diagnose ACL injuries and to assess stability after ACL reconstruction [28]. In their systematic review and meta-analysis on the diagnostic values of arthrometers for diagnosing ACL injuries, van Eck et al [28] found that the KT-1000 arthrometer at maximal manual force had the highest diagnostic values with a sensitivity of 93% and a specificity of 93%, although no cut-off value is presented [28]. The KT-1000 arthrometer is often used as dichotomous outcome diagnostic tool, measuring a difference of 2-3mm between the legs (relative translation) [21]. The current study found that a relative translation at 133 N force had a greater AUC compared to 67 N and 87 N, although the AUC at 87 N was higher than at 133 N for absolute translations. The Youden indexes were highest for 133 N of force, these cut-offs were therefore used for analyses on diagnostic values. An absolute translation of ≥7mm of the injured leg had a sensitivity of 97% (95-CI 84-100%) and a specificity of 88% (95%-CI 47-100%) and showed higher diagnostic values compared to cut-off values of relative translation (difference between injured and control leg). Interestingly, the often used cut-off values of a relative translation of 2 or 3mm were not an optimal cut-off point in the current study, as both 1mm and 4mm relative translations had higher diagnostic values [21]. The absolute translation as a cut-off seemed to be most useful for diagnosing ACL injuries. However, absolute anterior translation should always be interpreted with caution as gender, pubertal growth phases and greater physiological joint hypermobility have influences on laxity and the contralateral leg should therefore always be evaluated [22, 29]. A limitation of KT-1000 arthrometer was that some children were too small to fit in the arthrometer or were unable to undergo the test due to fear or pain.

This study had certain limitations. The first limitation is that the MRI is used as reference test. Arthroscopy is regarded as the gold standard, but rarely used as diagnostic tool [30]. Diagnosis of ACL injuries on MRI is however highly accurate in children and teenagers and is less invasive, as was confirmed in the current study [23]. The MRI was therefore chosen as the reference test in the current study. Interestingly, half of the meniscal injuries were missed on MRI and found during

ACL reconstruction in this study. The second limitation is that the Máxima Medical Centre is a tertiary referral centre for paediatric ACL injuries and the prevalence of ACL injuries was therefore high. This also resulted in a low prevalence of non-ACL injured patients, resulting in a relatively wide 95%-CI for specificity and NPV of some tests. Although the orthopaedic surgeon was blinded for the referral and MRI outcomes, one might expect that the high prevalence of ACL injuries potentially affected blinding as there was already a high suspicion of ACL injuries, especially when patients were referred from other hospitals. The third limitation was the population size of 66 children, which is smaller than some of the previous studies [4, 16]. However, the current study included a relatively large amount of children with ACL injuries and is the first study that evaluated history taking, ACL stability tests and KT-1000 meter in this population. The population consisted of a few partially ACL injured children, which was a limitation in analysing differences between complete and partial ACL injuries. Final limitation was that joint hyperflexibility (for example Beighton scale) was not measured during physical examination. Previous study by Falciglia showed that KT-1000 laxity measurements were greater in adolescents with signs of physiological joint hyperflexibility [22].

Conclusions

Report of a popping sensation during trauma has a specificity and PPV of 100% for diagnosing ACL injuries in children and adolescents. Although potentially difficult in children, the Lachman test, anterior drawer test and pivot shift test have a high PPV and NPV when performed by an experienced orthopaedic surgeon. An absolute anterior translation of ≥7mm of the injured knee in the KT-1000 arthrometer at 133 N has the highest diagnostic values of all clinical tests for diagnosing ACL injuries.

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Chapter 4

Diagnostics and predictors

Height is a predictor of hamstring tendons length and closed socket anterior cruciate ligament reconstruction graft characteristics in adolescents

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In review at BMC Musculoskelet Disord.

Abstract

Background: Knowing the potential hamstring tendon length is relevant for planning ligament reconstructions in children and adolescents, as it is not uncommon to encounter small hamstring tendons intraoperatively. The aim of this study is to predict semitendinosus and gracilis tendon length based on anthropometric values in children and adolescents. The secondary aim is to analyse hamstring tendon autograft characteristics in a closed socket anterior cruciate ligament reconstructions and to evaluate the relationship with anthropometric variables.

Methods: This observational study included two cohorts of adolescents undergoing ligament reconstructions between 2007-2014 and 2017-2020. Age, gender, height and weight were recorded preoperatively. Semitendinosus and gracilis tendon length and graft characteristics were measured intraoperatively. Regression analysis was performed on tendon length and anthropometric values. Subgroup analyses of the closed socket ACL reconstruction were performed and the relation between anthropometric values and graft characteristics were analysed.

Results: The population consisted of 171 adolescents from 13 to 17 years of age, with a median age of 16 years [IQR 16-17]. The median semitendinosus tendon length was 29 cm [IQR 26-30] and gracilis tendon length was 27 cm [IQR 25-29]. Height was a significant predictor of semitendinosus and gracilis tendon length. Subgroup analysis of the closed socket ACL reconstructions showed that in 75% of the procedure, the semitendinosus tendon alone was sufficient to create a graft with a minimum diameter of 8.0 mm. Additional use of the gracilis tendon was more often necessary in females and patients of shorter height.

Conclusions: Height is a significant predictor of semitendinosus and gracilis tendon length in adolescents between 13 and 17 years of age and outcomes are similar to data in adults. In 75% of the closed socket ACL reconstructions, the semitendinosus tendon alone is sufficient to create an adequate graft with a minimum diameter of 8mm. Additional use of the gracilis tendon is more often necessary in females and shorter patients.

Introduction

Anterior cruciate ligament (ACL) injury in children and adolescents is a severe injury of the knee [1]. The treatment goal is to restore a stable, well-functioning knee and prevent further chondral or meniscal injury [1]. The three indications for an ACL reconstruction are a concomitant and repairable meniscus injury, failed non-operative treatment or unacceptable sports restrictions [1].

The ACL reconstruction technique for children and adolescents depends on skeletal maturity and is also surgeon dependent [1,2]. However, general principles, such as the use of a well-positioned (soft-tissue) autograft with an adequate size, diameter and fixation for ACL reconstruction in adults also apply for the younger patient population [1,3]. Desired graft length depends on the type of ligament reconstruction, operative technique, for example full tunnels versus closed-sockets techniques, and fixation methods [4]. However, the graft diameter is important regardless of the technique, as a diameter of less than 8 mm is related to higher revision rates within the age category of 20 years and younger [5-11].

Quadrupled hamstring autograft is most commonly used as soft tissue graft for ACL reconstructions in children [3]. Both semitendinosus (ST) as semitendinosus-gracilis (STG) grafts are used for ACL reconstructions. In some children, the harvested hamstring graft can be too small to produce a graft with an adequate specifications [8]. Preoperative knowledge of potential tendon dimensions could assist in graft planning for knee ligament surgery, as complex knee ligament reconstructions require specific tendon length and diameter [12]. Various studies on the anthropometric predictability of tendon dimensions have been conducted in adults, reporting that height is a predictor of hamstring tendon length [12-14]. To this date, one study evaluated the predictability of hamstring tendon dimensions in children and adolescents, which aimed at the cross-sectional area (CSA) of the hamstring tendons [15]. Other studies evaluated the relationship of anthropometric values or magnetic resonance imaging (MRI) measurements with the diameter of a hamstring tendon autograft for a specific ACL reconstruction technique, but did not analyse the length of the hamstring tendons itself [16,17,18]. Predictability of hamstring tendon length in a paediatric and adolescent population has not been studied to this date, despite that tendon length is also an important aspect to be able to obtain the desired graft dimensions.

The primary aim of this study is to analyse the preoperative predictability of the ST and G tendon lengths based on anthropometric data in adolescents. The secondary aim is to analyse graft characteristics, such as ST or STG graft, length and diameter in a closed socket ACL reconstruction technique. The first hypothesis of this study is that the ST and G tendon length can be predicted by anthropometric variables, such as height. The second hypothesis is that graft characteristics, such as additional use of G tendon for graft (ST versus STG graft), can also be predicted by height due to the predictability of tendon length by height.

Materials and methods

In this retrospective study, consecutive adolescent patients with ACL rupture, scheduled for ACL reconstruction between 2007-2014 and 2017-2020, were eligible for inclusion. The patients included between 2007 and 2014 were also part of the data analysed in the study by Janssen et al.[12] and in the current study a subgroup analysis on the younger patients (<18 years) of that cohort was performed [12]. From 2017, a closed socket technique (All-Inside, Arthrex®, Naples, USA) was used for ACL reconstructions. Anthropometric values, hamstring tendon lengths and graft characteristics were recorded again from 2017. All patients (< 18 years) undergoing primary reconstruction with hamstring tendon autografts were eligible for inclusion. Exclusion criteria were ACL reconstruction with other types of allo- or autografts, previous harvest of the ipsilateral hamstring tendon, congenital limb deficiency that would affect total body weight and neuromuscular disorders. Preoperatively gender, age, height and weight of the patient were recorded as anthropometric variables.

Two orthopaedic surgeons (RJ and MvdB) performed all procedures using the same technique. From 2007 to 2014, a STG autograft with WasherLoc™ (Zimmer Biomet®, Warsaw, Indiana, USA) was used as the primary graft for a tunnel ACL reconstruction. The methodological description of that period has been published previously [12,19].

From 2017, a closed socket technique (All-Inside, Arthrex®, Naples, USA) was used to reconstruct the ACL in young ACL reconstruction patients with the ST as autograft type of choice. The ST tendon was harvested and prepared in a standardized fashion according to the previous study [12,19]. The available length of each tendon was measured with a ruler and recorded in cm, rounded off to the nearest 0.5 cm. A provisional ST graft was then created and the length and diameter of the graft were measured. The diameter of the hamstring graft was measured by soft tissue graft caliper (Arthrex®, Naples, Florida, USA) with 0.5-mm increments between holes and the length of the graft is measured with a ruler. In case of insufficient graft diameter of the ST graft, the G tendon was also harvested. The primary goal was to create a hamstring autograft with a minimum length of 6 to 6.5 cm and diameter of ≥8 mm, preferably as a 4-strand ST graft (4-ST). In order to create a 4-ST graft of 6 cm, a minimum ST tendon length of 24 cm was necessary. Depending on length of the tendons and/or diameter of the graft, strand variations of the graft are possible with or without the use of the G tendon. The possible variations were a 3-strand ST, 4-strand ST, 5-strand ST(G), 6-strand STG, 7-strand STG or 8-strand STG graft.

The Institutional Review Board (IRB) of The Medical Ethical Committee Máxima Medisch Centrum determined that this study was not subjected to the guidelines of the Medical Research Involving Human Subjects Acts (WMO) (N20.038).

Statistical analysis

Descriptive analyses were used to describe the groups based on the ACL reconstruction technique. Baseline parameters were compared between groups by medians of the Mann Whitney U test after tests for normality for the continuous variables and Chi square test for gender. Multivariate linear regression analyses were performed to analyse the predictability of the ST and G tendon length with the following anthropometric parameters: gender, age, height, weight and BMI. As a minimum of 24 cm ST tendon length was necessary to create a standard 4-ST graft, the division between significant anthropometric values and ST tendon length of 24 cm was analysed. Additional analyses were performed on the 2017-2020 closed socket technique subgroup. A logistic regression analysis was performed to analyse the necessity for additional use of the G tendon in the 2017-2020 group. Data analysis was performed in SPSS Statistics version 22.0 (IBM, Armonk, New York, USA). Significance is set at ≤0.05 in all analyses.

Results

A total of 171 patients were included for analysis, of which 99 patients were included in the period from 2007-2014 and 72 patients from 2017-2020. See Table 1 for baseline characteristics and Figure 1 for the age distribution. The height, weight and BMI of 2 patients were unknown and of 1 patient the ST length was unknown.

Table 1. Characteristics of the study population. BMI = body mass index; G = gracilis; IQR = Interquartile range; ST = semitendinosus; STG = semitendinosus-gracilis.

	Total	**2007-2014**	**2017-2020**	
	N=171 Median [IQR]	**N=99 Median [IQR]**	**N=72 Median [IQR]**	**p-value**
Age (years)	16.0 [16.0-17.0]	16.0 [16.0-17.0]	16.0 [15.0-17.0]	0.114
Gender, female%	47%	47%	49%	0.931
Height (cm)	174 [168-182]	174 [168-183]	172 [168-182]	0.354
Weight (kg)	65.0 [60.0-73.5]	65.0 [61.0-74.0]	65.0 [58.0-72.0]	0.388
BMI (kg/m^2)	21.5 [19.8-23.8]	21.5 [20.1-23.7]	21.4 [19.5-24.0]	0.664
ST length (cm)	29.0 [26.0-30.1]	29.0 [27.0-31.0]	28.5 [26.0-30.0]	0.238
G length (cm)	27.0 [25.0-29.0]	28.0 [25.0-29.5] N=99	24.0 [23.0-27.0] N=18	0.003

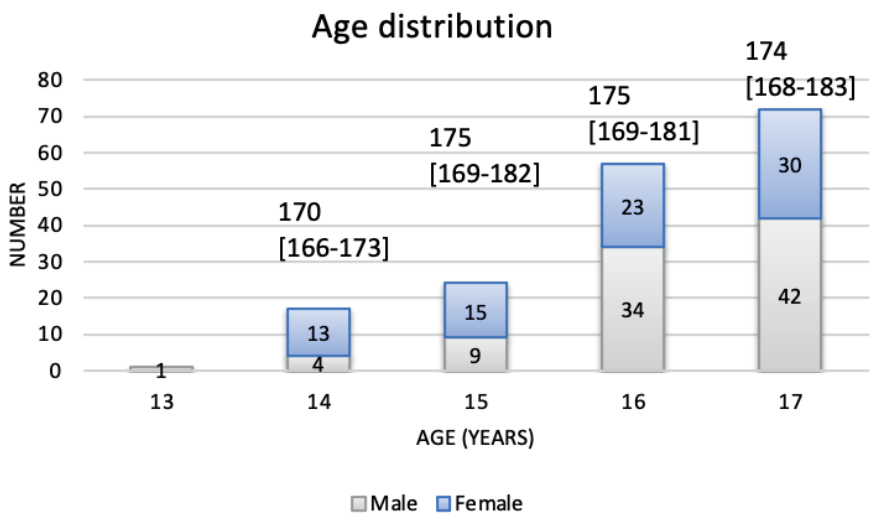

Figure 1. Age distribution of females and males. Numbers above columns represent median height in cm [IQR] within the age-group.

Prediction of tendon lengths

The multivariate linear regression analyses in the total group on the ST and G tendon lengths are shown in Table 2. Height is a predictor for both the ST and G tendon length. For each centimetre increase in height, the predictive length of the ST and G tendon increase 0.18 cm and 0.14 cm respectively.

Table 2. Multivariate linear regression analysis of anthropometric values and ST or G length. CI = confidence interval.

Multivariate						
	Semitendinosus tendon length			**Gracilis tendon length**		
Model	Regression coefficients (95% CI)	P-value	R^2	Regression coefficients (95% CI)	P-value	R^2
Constant	0.702 (-11.848; 13.252)	0.912		5.223 (-12.456; 22.921)	0.559	
Age (years)	-0.135 (-0.551; 0.281)	0.522		-0.164 (-0.807; 0.408)	0.616	
Gender (female)	-0.876 (-1.978; 0.225)	0.118	0.337	-0.619 (-2.132; 0.894)	0.420	0.212
Height (cm)	0.180 (0.115; 0.245)	<0.001		0.140 (0.053; 0.226)	0.002	
Weight (kg)	-0.016 (-0.059; 0.028)	0.476		0.004 (-0.054; 0.062)	0.898	

In order to create a standard 4-ST graft, the required ST tendon length was 24 cm. In Table 3 the division between ST tendon lengths of 24 cm or more and height categories are shown, as height was a significant predictor of ST tendon length.

Table 3. Relation of height categories and ST tendon length; ST = semitendinosus.

	ST tendon length	
Height (cm)	<24cm N (%)	≥24cm N (%)
<160	4 (44)	5 (56)
160-170	5 (13)	33 (87)
170-180	3 (4)	65 (96)
≥180	0 (0)	53 (100)

Closed socket subgroup analysis

In the 2017-2020 group, 75% of the closed socket ACL reconstructions were performed with a ST tendon autograft only. In 18 (25%) cases, an additional G tendon autograft was necessary to achieve adequate graft dimension. Patients with a STG graft were significantly more often female, were shorter and lighter and had shorter ST tendons as is shown in Table 4.

Four of the 72 patients (6%) had a graft diameter of less than 8 mm (all had 7.5 mm), which were all ST grafts and these graft configurations were accepted intra-operatively. Four strand ST graft was used most frequently. In case of using an STG graft, a six strand variation was used most frequently.

Table 4. Characteristics of patient with a ST and STG graft from the 2017-2020 closed socket group. BMI = body mass index; G = gracilis; IQR = Interquartile range; NA = not applicable; ST = semitendinosus; STG = semitendinosus-gracilis.

	Patients with ST graft	**Patients with STG graft**	
	N=54 Median [IQR]	**N=18 Median [IQR]**	**P-value**
Age (years)	16.0 [15.0-17.0]	16.0 [15.8-17.0]	0.402
Gender, female%	41%	72%	0.021
Height (cm)	175 [169-182]	170 [165-175]	0.032
Weight (kg)	65.0 [60.0-74.0]	58.5 [53.5-67.8]	0.021
BMI (kg/m^2)	21.8 [19.6-24.1]	20.4 [19.1-23.1]	0.352
ST length (cm)	29.0 [26.0-30.0]	25.8 [24.0-28.1]	0.001
G length (cm)	NA	24.0 [23.0-27.0]	NA
Graft diameter (mm)	8.5 [8.0-9.0]	8.5 [8.0-9.0]	0.568
Strand type % (n)			
3-strand	2% (1)	0% (0)	
4-strand	85% (46)	0% (0)	
5-strand	13% (7)	0% (0)	
6-strand	0% (0)	73% (13)	
8-strand	0% (0)	22% (4)	
10-strand	0% (0)	6% (1)	

The results of the univariate logistic regression analyses of height and additional G tendon use as hamstring autograft is shown in Table 5. The STG group consisted of 18 patients and therefore no stable multivariate model could be created. Due to the significance of height in previous analyses, height was chosen as a factor of interest. According to the univariate logistic regression analysis, patient's height is a statistically relevant predictor for additional need for the G tendon as autograft.

Table 5. Univariate logistic regression analysis of height and additional G tendon use (0= no additional G tendon use; 1= additional G tendon use). CI = confidence interval.

Univariate			
Model	Regression coefficient (95% CI)	P-value	Nagelkerke R^2
Constant	11.514	0.056	0.095
Height (cm)	-0.073 (0.868-0.996)	0.038	

Patients with an STG graft were significantly more often females. Differences in height and weight could therefore be the result of differences in gender between groups. Males had a significantly greater median height than females (180 cm [IQR 175-185] versus 168 cm [165-170], p-value <0.001). Males also were heavier than females (68 kg [60-79] versus 63 kg [55-67], p=0.009). Univariate logistic regression analysis of height and additional G tendon use within females (n=35, of which n=13 having a STG graft) showed no statistically significant value of height as is shown in Table 6.

Table 6. Univariate logistic regression analysis of height and additional G tendon use (0= no additional G tendon use; 1= additional G tendon use) within the female subgroup. CI = confidence interval.

Univariate			
Model	Regression coefficient (95% CI)	P-value	Nagelkerke R^2
Constant	12.202	0.264	0.056
Height (cm)	-0.076 (0.815-1.053)	0.244	

Discussion

Height is a significant predictor of ST and G tendon length in the age category of 13 to 17 years. Knowing the potential ST and G tendon length is relevant for planning the hamstring tendon autograft for ligament reconstructions in adolescents [8,12]. Complex knee ligament reconstructions require specific tendon lengths to create the desired graft dimensions and there are concerns that in some adolescents, the harvested hamstring graft can be too small to produce a graft with an adequate diameter [8,12]. To this date, no study previously analysed the prediction of hamstring tendon lengths focusing on an adolescent population. The results of this current study are in accordance with the first hypothesis and the study by Janssen et al., which showed that for each increase in 1 cm in body height, the ST and G length increase respectively with 0.20 cm and 0.16 cm in a population with a mean age of 28.7 years [12].

Age was no predictor for tendon lengths in the multivariate regression analyses. However, the great majority of the population were 16 and 17 year-olds and may therefore (almost) have reached final height [20]. It is however not known whether the increase in height of 4 cm between 14 and 17 year-olds would result in an (relatively equal) increase in hamstring tendon lengths, as the increase in height is not only caused by growth of the lower extremities, but also by spinal growth. Besides, there is limited evidence of the development of human tendons in vivo [21]. Current available evidence shows that throughout childhood and adolescence, the tendons seem to adapt in size and structure as the musculotendinous structures develop [22-25]. The influence of growth on hamstring tendon lengths has not been evaluated previously. However, the influence of growth on Achilles and patellar tendon lengths have been studied and showed that the lengths of both tendons in 14 year-olds boys are similar to adults [27,27].

Current ACL reconstruction techniques allow the use of multiple-stranded hamstring autografts and depending on the reconstruction technique, different socket/ tunnel lengths require different graft lengths [12]. For example, in order to create a 4-strand ST with a minimum length of 60 mm, a minimum ST tendon length of 24 cm (4 x 60 mm) is necessary. In 44% of the patients with a height of <160 cm the ST tendon was shorter than the required 24 cm. It is necessary in those cases to harvest an additional G tendon, as a 3-ST graft in most cases did not reach the required diameter. A recent systematic review showed that the hamstring tendon graft diameter should be ≥7mm, but a threshold towards larger graft diameters should be considered for patients younger than 20 years [28]. High graft failure rates are problematic in this young population [29]. A graft diameter of less than 8 mm is related to higher revision rates within the age category of 20 years and younger [5-11]. For each increase of 0.5 mm in diameter within the 7.0 to 9.0 mm range, the likelihood of a revision was 0.82 lower [11]. It is therefore important to reduce the risks of graft failure by creating a graft with an adequate length and diameter [9]. Preoperative prediction of tendon length might therefore help in preparing the graft for ligament reconstructions.

In the current cohort of the closed socket technique, 25% of the reconstructed ACL autografts required an additional G tendon to create a graft of sufficient diameter. All STG grafts had a diameter of more than 8 mm and did not need augmentation of contralateral hamstring tendon autograft or allograft. This finding is somehow similar to the outcomes of the study by Stergios et al [30], who found that the ST tendon alone was insufficient to create a 4-strand graft with a minimum diameter of 7 mm in one in five adult patients [30]. In the current study, logistic regression analysis showed that additional use of the G tendon can be predicted by height, which was in accordance with the second hypothesis. However, as there were significantly more females in the STG group who were significantly smaller than males, subgroup analysis of females showed no significant effect of height. The effect of height on additional use of the G tendon might be explained by the findings that more females needed an additional G tendon and females were smaller than males. This is in line with previous literature showing that females more often had an inadequate ST tendon length to create a ST 4-strand graft and alternative graft options should be considered [18,30].

This study has several limitations. The first limitation is that the diameter of the tendons is not measured, although most likely both tendon length and diameter contribute to graft size. Recent studies showed that anthropometric data and CSA measurements of hamstring tendon on MRI are correlated to the diameter of hamstring grafts [17,18,31]. Another limitation of this study is that, similar to the study by Calvo et al. [16], measurements were based on chronological age and not on physiological age [16]. The number of children with remaining growth of the lower extremity is therefore not known. Besides, leg length was not measured in this study and could therefore not be analysed as predictive factor. Future research should aim at skeletally immature children specifically of which bone age and remaining growth of the lower extremity is known. Finally, this study population consisted of Caucasian adolescents. Chiang et al. concluded in their study that Caucasian patients had significantly longer hamstring tendons compared to Chinese Han population [12,1]. The outcomes of this study might therefore not be extrapolated to adolescents of other ethnicities.

Conclusions

Height is a significant predictor of ST and G tendon length in adolescents between 13 and 17 years of age and outcomes are similar to data in adults. In 75% of the closed socket ACL reconstructions, the ST tendon alone is sufficient to create an adequate graft with a minimum diameter of 8 mm. Additional use of the G tendon is more often necessary in females and shorter patients.

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Chapter 5

Diagnostics and predictors

Lateral tibiofemoral morphometry does not identify risk of re-ruptures after ACL reconstruction in children and adolescents

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Abstract

Purpose: Anterior cruciate ligament (ACL) ruptures in children and adolescents are a severe injury to the knee. Children and adolescents have an increased risk of re-ruptures after ACL reconstruction. Recent studies in adults focussed on tibiofemoral morphological relations as a risk factor for re-ruptures after ACL reconstruction. The purpose of this study is to evaluate tibiofemoral morphology of the lateral compartment of the knee as risk factor for ipsi- and contralateral (re-)ruptures in children and adolescents.

Methods: This case control study matched cases with ACL ipsilateral re-ruptures and contralateral rupture 1:1 to controls without a (re-)rupture after ACL reconstruction. MRI measurements included: lateral tibial slope, meniscal bone angle, lateral femoral condyle index (LFCI) and the Porto Ratio. Differences among groups were compared and diagnostic performances were assessed.

Results: Medical files of 492 patients from two tertiary referral centres for ACL reconstructions between 2008 and 2019 were screened for ACL re-ruptures. A total of 33 ipsilateral and 29 contralateral re-injured patients were included. No significant differences were found between the ipsi- and contralateral case and controls. The total re-injured population had a significant greater lateral tibial slope compared to controls (5^0 versus 4^0, p=0.048). The area under the curves, as a value for diagnostic performance, were not significantly different from 0.5.

Conclusions: The investigated parameters of the lateral compartment of the knee were not found to be significant risk factors for ipsilateral graft ruptures and contralateral ACL ruptures. The total reinjured population had a significant greater lateral tibial slope compared to controls and slopes ≥ 7˚ were associated with re-injuries. The lateral tibial slope was however not a discriminative factor for identifying risk of re-ruptures.

Introduction

As the age of onset for anterior cruciate ligament (ACL) ruptures in children decreases, the incidence of ACL ruptures in children increases [1,34]. ACL injuries are a severe injury to the paediatric knee [2]. A primary concern after ACL reconstruction in children and adolescents is the increased risk of ipsilateral graft ruptures and contralateral ACL ruptures [2,9,19,21,34]. It is therefore important to be aware of potential morphological risk factors in light of other intrinsic and extrinsic risk factors, such as an increased body mass index (BMI) and sports participation, that can potentially identify children prone for re-ruptures [23].

Previous studies reported several morphological risk factors for primary ACL ruptures in children and adolescents [6,7,8,22,32]. Risk factors in children include an increased medial and lateral tibial slope, narrower notch width, increased size of tibial eminence and patella alta [6,7,8,22,32]. The tibial slope has been studied previously as a morphological risk factor for re-ruptures or revisions in children and adolescents [5,12,26].

Recently, the morphology of the lateral compartment of the knee gained more interest in relation to ACL (re-)ruptures in adults, as it may play an important role in the pivot shift phenomenon and knee kinematics [10,14,24,27,31]. The lateral tibial slope and meniscal bone angle have been identified as risk factors for re-ruptures in adults [4,13,16,27]. Studies on the lateral femoral condyle shape were somewhat contradictory [14,17,24]. Pfeiffer et al [24] showed that an increased posterior femoral depth, defined as an increased femoral condyle ratio, is associated with an increased risk of primary and contralateral ACL injuries [24]. This might be due to a greater anisometry in flexion because of increased length of anterolateral and lateral structures, resulting in laxity near full extension, which is the point where most non-contact ACL injuries occur [24,25]. Hodel et al [14] however, showed that a decreased lateral femoral condyle index (LFCI), resulting in a more spherical shape of the femur, is associated with an increased risk of primary ACL injuries [14]. A decreased lateral femoral condyle index consists of a smaller posterior flexion circle and therefore a more prominent anterior part of the condyle, resulting in excessive gliding of the flat surface of the condyle over the convex tibial plateau [14]. Besides, patients with a decreased LFCI in combination with an increased lateral tibial slope and lateral tibial height are at higher risk for an ACL rupture and re-rupture [14]. Another study on tibiofemoral morphometric relations reported that an increased Porto ratio is a risk factor for primary ACL injury [10]. These results might suggest that bony morphology of both the femoral condyle and tibial plateau play an important role in knee kinematics and the Pivot-Shift magnitude and risk of ACL injuries [10,14,18].

The aim of this study was to evaluate the tibiofemoral morphology of the lateral knee compartment on magnetic resonance imaging (MRI) as risk factors for ipsilateral graft rupture and contralateral ACL rupture after ACL reconstruction in children and adolescents in a case control study. The hypothesis was that an increased lateral tibial slope, a decreased femoral flat surface, a decreased meniscal bone angle and a decreased lateral femoral condyle index were morphological risk factors for ipsilateral graft ruptures and contralateral ACL ruptures in children and adolescents after ACL reconstruction.

Methods

Patients

The study design was a case control study and approved by both the local medical ethical committee Máxima Medical Centre [L19.047] and Aarhus University Hospital. A retrospective chart review was conducted for children and adolescents (< 18 years old) who underwent primary ACL reconstruction at the Máxima MC Eindhoven, The Netherlands and Aarhus University Hospital, Denmark. Inclusion and exclusion criteria are shown in Table 1.

Table 1. In- and exclusion criteria for cases and controls.

Inclusion criteria		Exclusion criteria
Cases	**Controls**	**Overall**
Age < 18 years*	Age < 18 years*	Absence of preoperative MRI or impossibility to perform measurements on the MRI due to the absence of slices or insufficient quality
Primary ACL reconstruction	Primary ACL reconstruction	Absence of preoperative information required for matching
Re-rupture: ipsilateral graft rupture or contralateral ACL rupture	No ipsi- or contralateral ACL injury	Revision due to infection
	Minimum follow-up of 1 year	

*< 18 years at time of primary ACL reconstruction

The cases were matched to the controls according to gender, age, height, weight and surgical technique. Matching on surgical technique consisted of adult surgical technique versus surgical technique for open physes (all-epiphyseal, transphyseal, hybrid), graft use and concomitant anterolateral ligament (ALL) reconstruction. Control patients of the MMC were contacted by telephone to reassure there was no re-rupture or contralateral ACL injury. Control patients of AUH were not contacted, due to the organisation of the electronic patient files which include all hospitals in Jutland, Denmark. Consultations in other hospitals for re-rupture or contralateral ACL injury could therefore be found in the electronic patient files. After matching, the study consisted of two separate populations: (1) the ipsilateral ACL graft rupture cases and their matched controls, and (2) the contralateral ACL rupture cases and their matched controls.

A total of 492 medical files of children and adolescents after primary ACL reconstruction were screened. After exertion of the in- and exclusion criteria, 33 patients were included for having an ipsilateral graft re-rupture, and 29 patients for having a contralateral ACL rupture (Figure 1). Patients screened for the re-rupture groups who did not meet the inclusion criteria were most often excluded because there was no pre-operative MRI available. Patients in the control group who did not meet the inclusion criteria usually lacked a follow-up period of 12 months or in some cases the pre-operative MRI was unavailable.

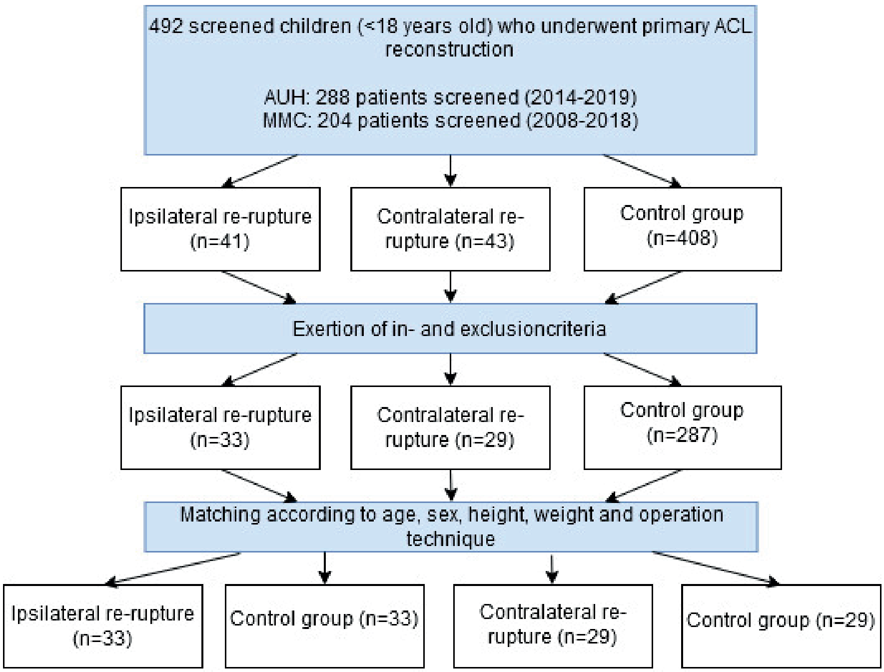

Figure 1. Flow chart of patient in- and exclusion; "ACL = Anterior Cruciate Ligament", "AUH = Aarhus University Hospital", "MMC = Máxima Medical

MRI measurements

As many patients were secondary referrals to our clinics, preoperative MRI's of the primary ACL rupture were performed with many different types of MRI's. The measurements regarding morphologic characteristics were performed using the preoperative MRI's of the primary ACL rupture. MRI's were imported in Agfa Healthcare IMPAX version 6.6.1.3004 (Agfa Health-Care®, Mortsel, Belgium) to perform the measurements. Measurements were performed on sagittal images on the Proton Density Weighted (PDW) series. Coronal series were necessary to determine the positioning of the correct slice for the measurements of the lateral compartment.

Tibia

The tibial parameters of interest were the tibial slope, the meniscal bone angle and the anterior-posterior depth of the tibial plateau (Figure 2). First the tibial axis was measured by the method of Hudek [15]. Then, the centre of the lateral compartment was determined based on the AP slices as stated by Hodel et al [14]. Measurements of the tibial slope were performed following the method by Hodel et al [14], the meniscal bone angle by Sauer et al [27,30], the AP depth of the tibia by Shaw et al [28].

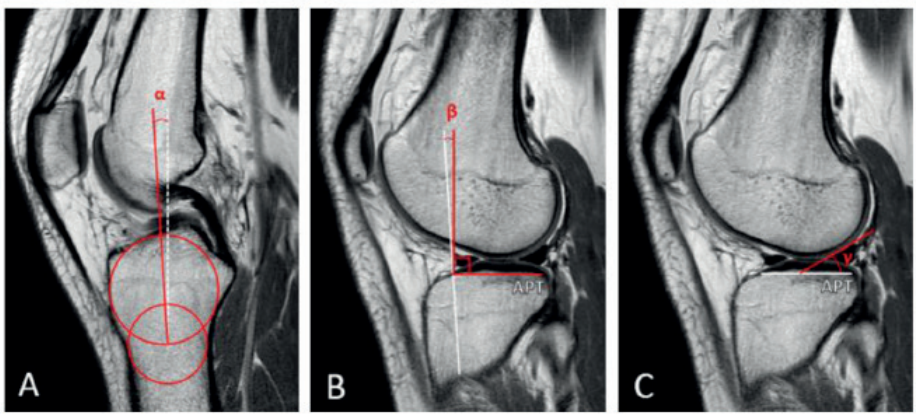

Figure 2. MRI measurements of the tibia. A The longitudinal tibial axis (α) is drawn. B After drawing the AP depth of the tibial plateau [APT], α is used to determine the tibial slope (β). C The meniscal bone angle (γ) is drawn using the APT.

Femur

The measurements of the femur were performed on the same slice as the measurements on the tibia. Parameters of interest of the femur were the diameter of the anterior extension circle, posterior flexion circle and the flat surface (Figure 3). The measurements of the circles were performed following the methods by Hodel et al [14]. The flat surface was measured according to the method by Vasta et al [31].

Indices

The lateral femoral condyle index (LFCI) is calculated by dividing the diameter of the posterior flexion circle by the diameter of the anterior extension circle (Figure 3) [14]. Second, the Porto ratio is calculated by dividing the flat femur surface (Figure 3) by the AP depth of the tibial plateau (Figure 2B) [31].

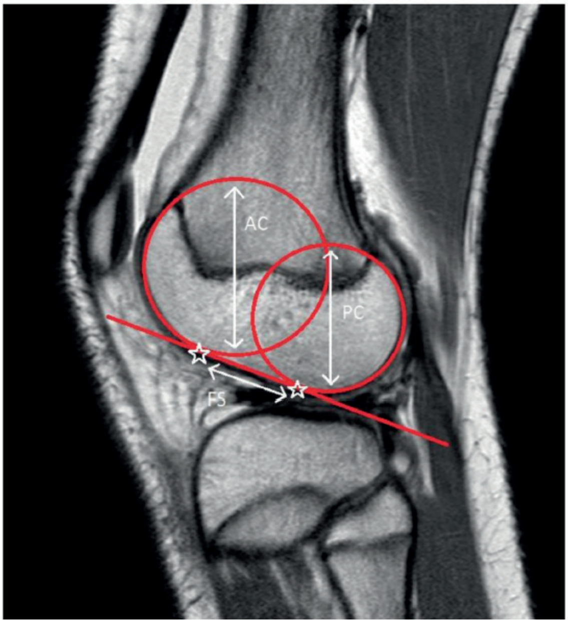

Figure 3. MRI measurements of the femur. The anterior "extension" circle [AC] and posterior "flexion" circle [PC] are drawn [14]. A line tangent to both circles determines the flat surface (FS) [31].

Inter- and intra-observer reliability

To determine the inter- and intra-observer reliability, all measurements were performed on twenty randomly selected MRI's from the pre-matched research population. Two blinded reviewers (M.D., S.V.) performed the measurements independently to determine the interobserver reliability. Both of the reviewers repeated all twenty measurements 1 week later to determine the intra-observer reliability.

Statistical analysis

The inter- and intra-observer reliability were determined by calculating the Intraclass Correlation Coefficient (ICC) with a 95%-Confidence Interval (CI). Normality of continuous data was tested using with Shapiro Wilk test. Differences in baseline characteristics between the ipsilateral and contralateral re-injured patients were tested by means of Mann-Whitney U or unpaired t-tests.

A sample size calculation was based on outcomes of the lateral tibial slope in the study by Jaecker et al [16]. (mean (SD) lateral tibial slope in graft failure patients 7.3° (3.3) versus controls 4.5° (3.2)), as the tibial slope was determined as the potential most important risk factor. A paired t-test sample size estimation in G*Power resulted in a group size of 26 patients (correlation of 0.01, α of 0.05 and power of 0.85).

All statistical analyses on morphological risk factors were performed both separately for the ipsilateral graft rupture and contralateral ACL rupture group and their matched control group, as well as for the total ACL re-rupture group and the total group of matched controls. The data within these analyses was approached as paired as a results of matching. Depending of distribution of continuous data the paired t-test or Wilcoxon signed rank test was used. Categorical data were analysed by means of Wilcoxon signed rank test or McNemar test.

For each parameter, the receiver operating characteristic (ROC) curve, the area under the curve (AUC) and its 95% CI were calculated. The AUC represents the diagnostic accuracy of the measurements, ranging from 0 to 1.0 (perfect test), with 0.5 as cut-off for no discrimination capacity. A 2-sided binomial z test was performed to determine the statistical significance of the AUC. Statistical analyses were computed using SPSS version 22. The significance level was set at 0.05.

Results

Inter- and intra-observer reliability

All measurements showed good to excellent inter- and intra-observer reliability (Table 2).

Table 2. Inter- and intra-observer reliability of morphological parameters*

	Inter-observer reliability	Intra-observer reliability	
		(M.D.)	(S.V)
Lateral tibial slope	0.93 (0.83-0.97)	0.90 (0.75-0.96)	0.90 (0.75-0.96)
Meniscal bone angle	0.90 (0.75-0.96)	0.95 (0.87-0.98)	0.95 (0.88-0.98)
AP tibia depth	0.99 (0.63-0.94)	0.96 (0.90-0.99)	0.97 (0.93-0.99)
Femur flat surface	0.90 (0.74-0.96)	0.88 (0.69-0.95)	0.92 (0.79-0.97)
Lateral femoral condyle index	0.77 (0.42-0.91)	0.77 (0.42-0.91)	0.76 (0.39-0.91)
Porto ratio	0.86 (0.66-0.95)	0.89 (0.72-0.96)	0.91 (0.78-0.97)

* Values are presented as intraclass correlation coefficient (95% CI). AP = anterior-posterior; CI = confidence interval.

Patients

The demographic characteristics of the ipsilateral and contralateral matches are shown in Table 3. There were no differences in the baseline characteristics between the re-injured patients and control patients for both groups, indicating a successful matching process. There were no differences in age, height, weight and BMI between the ipsilateral and contralateral reinjured patients. There were, however, significantly more males in the ipsilateral graft rupture group and more females in the contralateral ACL group (respectively 70% and 66%, p = 0.01). There were no statistically significant differences in the time to re-rupture and surgical technique between the ipsi- and contralateral injured patients.

Table 3. Demographic characteristics ipsilateral and contralateral matches

	Ipsilateral			Contralateral		
	Injured (33)	**Control (33)**	**P-value**	**Injured (29)**	**Control (29)**	**P-value**
Age, years (mean SD)	14.5 (1.7)	14.5 (1.8)	0.414	14.9 (2.0)	15.1 (1.4)	0.180
Gender, n female (%)	10 (30)	10 (30)	1.000	19 (66)	19 (66)	1.000
Weight, kg (mean SD)	63 (18)	61 (13)	0.401	62 (11)	64 (9.7)	0.085
Height, cm (mean SD)	171 (12)	171 (12)	0.760	172 (9.0)	171 (9.3)	0.635
BMI, kg/m^2 (mean SD)	21 (4.2)	21 (2.7)	0.438	21 (3.1)	22 (2.2)	0.094
Time to rerupture			n.a.			n.a.
<1 year	5	n.a.		1	n.a.	
1-2 years	12	n.a.		15	n.a.	
>2 years	16	n.a.		12	n.a.	
Follow-up duration controls, years (mean SD)	n.a.	4.3 (2.3)	n.a.	n.a.	4.2 (2.3)	n.a.
Surgical technique			0.059			0.705
Adult	17	16		21	22	
Hybrid	12	16		5	6	
Transphyseal	4	1		2	1	
All-epiphyseal	0	0		1	0	
Graft type			0.317			1.000
HS	32	33		29	29	
BPTB	1	0		0	0	
QT	0	0		0	0	
Allograft	0	0		0	0	
Primary ALL reconstruction			1.000			1.000
Yes	1	0		1	2	
No	32	33		28	27	

ALL = anterolateral ligament; BPTB = bone patella tendon bone; cm = centimetres; HS = hamstring; kg = kilograms; LCL = lateral collateral ligament; m = metre; MCL = medial collateral ligament; n.a. = not applicable; PCL = posterior cruciate ligament; QT = quadriceps tendon; SD = standard deviation

Morphological risk factors

There were no statistically significant differences between the measurement of the lateral side of the knee in both the ipsilateral and the contralateral matches, as shown in Table 4. Analysis of the total group of re-ruptures (ipsilateral graft and contralateral ACL) and their matches showed that the reinjured patients had a significant greater tibial slope ($p = 0.048$). Analyses of the degree of tibial slope and the association with re-injuries showed that a tibial slope ≥ 7˚ was associated with re-injuries, as significantly more patients with a slope of ≥ 7˚ had re-injuries ($p=0.023$).

Table 4. MRI parameters in the ipsilateral and contralateral group, shown as median [IQR]

	Ipsilateral			**Contralateral**			**Total**		
	Re-injured (33)	**Controls (33)**	**P-value**	**Re-injured (29)**	**Controls (29)**	**P-value**	**Re-injured (62)**	**Controls (62)**	**P-value**
Tibial slope (^{0})	5 [2-8]	3 [2-6]	0.233	5 [4-7]	5 [3-6]	0.104	5 [3-8]	4 [2-6]	0.048
Meniscal bone angle (^{0})	24 [22-28]	25 [22-29]	0.941	27 [23-30]	27 [24-30]	0.739	26 [23-29]	26 [23-29]	0.779
AP depth tibia (mm)	30 [29-37]	32 [29-35]	0.821	32 [30-36]	33 [30-35]	0.968	32 [29-36]	32 [30-35]	0.913
Flat surface femur (mm)	21 [18-25]	19 [16-25]	0.215	25 [19-27]	25 [19-28]	0.909	24 [18-26]	22 [18-27]	0.401
LFCI	0.75 [0.66-0.81]	0.72 [0.67-0.76]	0.257	0.71 [0.67-0.75]	0.71 [0.66-0.75]	0.907	0.73 [0.67-0.79]	0.71 [0.66-0.76]	0.302
Porto ratio	0.66 [0.55-0.77]	0.61 [0.48-0.73]	0.397	0.79 [0.66-0.84]	0.76 [0.61-0.84]	0.899	0.74 [0.60-0.82]	0.69 [0.57-0.80]	0.431

AP = anterior-posterior; IQR = interquartile range; LFCI, lateral femoral condyle index; mm = millimetres; MRI = magnetic resonance imaging.

Diagnostic performance of MRI measurements

In Table 5, the AUC's for each measurement is shown. None of the AUC showed significant difference from 0.5.

Table 5. Area under the curve (AUC) for each parameter in the ipsi- and contralateral and total group.

	Ipsilateral		Contralateral		Total	
	AUC	**95%-CI**	**AUC**	**95%-CI**	**AUC**	**95%-CI**
Tibial slope	0.578	0.436-0.719	0.590	0.442-0.738	0.589	0.488-0.690
Meniscal bone angle	0.495	0.353-0.637	0.477	0.327-0.627	0.485	0.382-0.587
AP tibia depth	0.507	0.364-0.650	0.520	0.369-0.671	0.502	0.399-0.605
Flat surface femur	0.566	0.426-0.707	0.475	0.325-0.625	0.519	0.416-0.621
Lateral femur condyle index	0.588	0.449-0.728	0.507	0.356-0.657	0.549	0.447-0.651
Porto ratio	0.574	0.434-0.714	0.529	0.378-0.680	0.545	0.443-0.647

AP = anterior-posterior; AUC = area under the curve; CI = confidence interval

Discussion

The most important finding of the present study is that the morphological measurements of the lateral compartment of the knee are not found to be statistically significant risk factors for ipsilateral graft ruptures and contralateral ACL ruptures in children and adolescents. The total re-injured population had a significant greater lateral tibial slope compared to controls and tibial slopes of ≥ 7˚ were associated with re-injuries. Tibial slope was however not identified as discriminative factor for identifying the risk of re-injuries.

The only morphological measurement of the lateral compartment of the knee previously investigated as a risk factor for re-ruptures in adolescents is the tibial slope [5,12,26]. Outcomes of these studies showed different results [5,12,26]. In contrast to the current study, two studies previously reported tibial slope as a risk factor for re-ruptures after ACL reconstruction [12,26]. Salmon et al [26] found that the sagittal tibial slope on radiographs is a strong predictor for ipsilateral graft ruptures and contralateral ACL injury after reconstruction and has even more negative effects in adolescents compared to adults [26]. Grassi et al [12] found that a steep medial tibial plateau slope is associated with a higher risk of contralateral ACL injury within 2 years after ACL reconstruction [12]. Cooper et al [5] found no association between revision of ACL and medial and lateral posterior tibial slope, although extreme measurements of the lateral posterior tibial slopes were associated with ACL revision surgery [5]. As in the study by Cooper et al [5], in the current study higher degrees of tibial slope were associated with re-injuries [5]. Differences in outcomes between studies should be interpreted in light of the multifactorial causes for ACL (re-)ruptures, as besides to morphological factors, other intrinsic and extrinsic factors are known to be risk factors for ACL (re-)injury [11,23]. Caution should also be taken when comparing outcomes from different studies, due to various measurement methods, alternative case definitions (graft failure versus revision) and variations in follow-up and return to sports timing [5,31].

The role of several other morphological measurement of the lateral compartment of the knee as risk-factors for re-ruptures had been investigated in adults. Differences in the current study focussing on adolescent compared to the in literature known outcomes in adults were found. Previous studies reported the lateral tibial slope as a risk factor for re-ruptures after ACL reconstruction in adults, which is in contrast to the outcomes of the current study [4,13,16]. A decreased meniscal bone angle was associated with ipsilateral re-ruptures after ACL reconstruction in adults [27]. However, in the current study, there was no difference in the meniscal bone angle between re-injured and control patients. Variations in the shape of the femoral condyle were not associated with a risk of re-ruptures, which is in accordance with the study by Hodel et al [14], but in contrast to the study by Pfeiffer et al [24]. In the study by Hodel et al [14], a decreased LFCI measured on MRI, resulting in a more spherical condyle, was associated with higher risk on primary ACL ruptures compared to controls [14]. The LFCI was however not different between patients with re-ruptures and no re-ruptures after ACL reconstruction [14]. In the study by Pfeiffer et al [24], the lateral femoral condyle ratio (LFCR), measured on radiographs, was significantly higher in patients with contralateral re-ruptures compared to patients without re-ruptures after ACL reconstruction [24]. Interestingly, Hodel et al [14] reported that patients with a decreased LFCI in combination with an increased lateral tibial slope and lateral tibial height are at higher risk for an ACL rupture and re-rupture [14]. A specific tibiofemoral morphological outcome, the Porto ratio, was previously investigated as a risk factor for primary ACL injuries, but not as a risk factor for re-ruptures [10]. In the current study, the Porto ratio was also not identified as a risk factor for re-ruptures. Comparing these study outcomes in adults with outcomes in children and adolescents is difficult due to different intrinsic and extrinsic factors. With regard to the risk of re-ruptures, it is known that children and adolescents have an increased risk compared to adults [2,3,9]. Furthermore, it is known that certain morphological parameters might change during growth, such as the medial and lateral tibial slope [6]. In contrast with adults, not morphological parameters but rather other factors associated with multifactorial nature of the risk for re-ruptures might play a more prone role in adolescents [23].

Certain demographic differences were found in this study between females and males. The ipsilateral graft rupture group consisted of 70% males, the contralateral ACL rupture group 66% females. The percentage of males with ipsilateral graft ruptures is in accordance with the study by Astur et al [3]. Salmon et al [26] also showed that adolescent males have an increased risk of graft failure, compared to adults and females [26]. Previous reports on gender distribution in contralateral ACL ruptures show variable results [11,20,29,33].

An important limitation of this study is the inability to investigate other possible relevant parameters, such as the intercondylar notch width. The intercondylar notch was found to be a statistically significant risk factor for primary ACL rupture in children [8]. The current study did not include this parameter, as a notch plasty is performed during ACL reconstructions in some patients to prevent graft failure. The preoperative notch might therefore have different characteristics compared to the postoperative notch. It seemed therefore inappropriate to investigate the preoperative notch shape as a risk factor for graft ruptures.

Compared to previous studies on this topic, the current study also had several strengths. The current study has a relatively large population of re-ruptures due to the combined analyses of the patients of Aarhus University Hospital and Máxima MC, both PAMI (Paediatric ACL Monitoring Initiative) participating centres [21]. Furthermore, the study population also contained a relatively large number of skeletally immature children with an ACL reconstruction technique for open physes. Other studies of morphological risk factors on re-ruptures focussed on the tibial plateau, as the current study intended to evaluate tibiofemoral morphological relations [5,12,26]. Another methodical strength is that measurements were performed on MRI. As stated by Dare et al [6], measurements of bony morphology in children on MRI is superior to standard radiographs, as the subchondral bone in skeletally immature children do not adequately represent the articular surface [6].

The clinical relevance of this study is that the investigated morphological parameters of the lateral compartment of the knee were not found to be significant risk factors for ipsilateral graft ruptures and contralateral ACL ruptures after ACL reconstruction in children and adolescents. Although not discriminative for identifying re-injuries, tibial slopes $\geq 7^\circ$ were associated with re-injuries. Future studies should focus on morphological risk factors in a more multifactorial role of intrinsic and extrinsic factors, including also postoperative rehabilitation and type of sports participation.

Conclusions

The investigated morphological parameters of the lateral compartment of the knee were not found to be significant risk factors for ipsilateral graft ruptures and contralateral ACL ruptures in children and adolescents. The total reinjured population had a significant greater lateral tibial slope compared to controls and slopes ≥ 7˚ were associated with re-injuries. The lateral tibial slope was however not a discriminative factor for identifying risk of re-ruptures.

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Part III

Outcomes measures and (p)rehabilitation

Chapter 6

Outcomes measures and (p)rehabilitation

PROMs in paediatric knee ligament injury: use the Pedi-IKDC and avoid using adult PROMs

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Abstract

Purpose: The aim of this systematic review was to present an evidence-based overview of psychometric properties of patient-reported outcome measures (PROMs) for children with knee ligament injury.

Methods: A systematic search of literature was performed in PubMed, EMBASE and Cochrane databases. The inclusion criteria were diagnostic studies evaluating psychometric properties (validity, reliability, responsiveness) and comprehensibility of PROMs as well as studies including children (age < 18 years) with knee ligament injury. The systematic review was performed following the PRISMA statement.

Results: Ten studies were included. Eight studies evaluated psychometric properties of PROMs, and two studies analysed comprehensibility of PROMs. The Pedi-IKDC has been evaluated in four studies and has acceptable psychometric properties. The KOOS-Child is evaluated in one study and has acceptable psychometric properties. The use of adult PROMs in children causes problems in comprehensibility.

Conclusions: The Pedi-IKDC is an adequate PROM for children with knee ligament injuries. It is valid, reliable and responsive. The KOOS-Child might be an alternative PROM for the Pedi-IKDC, but has only been evaluated in one study. The clinical relevance of the present systematic review is that adult versions of PROMs are not recommended in children and adolescents.

Introduction

Knee injuries in children are rare, but the incidence increases with the rise in sports participation [13,26]. This epidemiological trend has also been described for injuries of the anterior cruciate ligament (ACL), with an increase in ACL reconstructions in the paediatric and adolescent patient population from 36.1–49.2 per 10.000 to 40.0–53.7 between 2007 and 2011 [5,26]. This increase in number of paediatric knee injuries warrants objective evaluation by patient-reported outcome measures (PROMs).

PROMs are the patient's perceived health condition and treatment results [3]. Despite being developed for research purposes, clinicians use PROMs to enhance clinical management of individual patients by observing complaints over the time and evaluation of treatment results [1]. PROMs offer the advantage of preventing observation bias of subjective assessment of symptoms and quality of life by the clinician [1]. PROMs are also used for the evaluation of different clinical practices, quality assessment and registries [11].

There are two types of PROMs: disease-specific and generic PROMs [1]. Disease-specific PROMs focus on symptoms and impact on function of a specific condition [1]. Generic PROMs measure general aspects such as self-care and mobility [1]. PROMs concerning musculoskeletal conditions often target adult populations but are also being used in paediatric populations [19]. Problems arise with the use of adult PROMs in children, since psychometric properties were determined in an adult population. Furthermore, data suggested a lack of comprehensibility when the (adult) Knee injury and Osteoarthritis Outcome Score (KOOS)—a frequently used PROM in knee injuries—was used in children [20]. As a result, a KOOS-Child was developed as PROM for children with knee injuries between 10 and 16 years of age [20]. The adult International Knee Documentation Committee Subjective Knee Form (IKDC), which assesses the patient's perspective on knee injuries, has also been modified in a child version [12]. PROMs in children with knee injuries need to be valid (does the PROM measure what it intends to measure?), reliable (does the PROM produce similar outcomes on repeated measurements in similar conditions?), responsive (does the PROM detect changes over time?) and comprehensible (do the children understand the PROM?).

The aim of this systematic review is to present an overview of psychometric properties and methodological quality of PROMs developed for children with knee ligament injury. The hypothesis is that specific paediatric PROMs have better psychometric properties and comprehensibility in children compared to adult PROMs. To our knowledge, there is no previous systematic review on the psychometric properties of PROMs in children with knee ligament injury. Such an overview will facilitate clinicians to make evidence-based selection of PROMs for children in daily practice.

Materials and methods

This systematic review was performed following the Preferred Reporting Items for Systemic Reviews and Meta-Analysis (PRISMA) statement [16].

Protocol

A systematic review protocol was made and registered at the International Prospective Register of Systematic Reviews (PROSPERO). The protocol can be accessed at http://www.crd.york.ac.uk/PROSPERO/display_record.asp?ID=CRD42016047318. This protocol provides the methods of this systematic review, including the search, inclusion and exclusion criteria and outcome.

Eligibility criteria

Studies were eligible if they met the following criteria:

- Studies including children and adolescents (< 18 years) with ligament injury of the knee. Excluded were adults (> 18 years of age) and studies involving patients with non-ligament knee injuries.

- Reported psychometric properties as defined in the COSMIN criteria: validity (both content and construct validity), reliability (test–retest, measurement error), responsiveness and interpretability (including floor and ceiling effects) [24]. The secondary outcome is children's comprehensibility (addressing the meaning of words and phrases) of the PROM.

- Diagnostic studies, including cohort studies and cross-sectional studies. The minimum level of evidence was 4 (case–control studies). Papers written in English, Dutch or German were included.

Search strategy

At 9 September 2016, an independent information specialist searched PubMed (Medline), EMBASE and Cochrane databases. All published articles up to 9 September 2016 were considered eligible. Search items included synonyms of the keywords "knee", "ligament injury", "paediatric", "adolescent", "questionnaire", "validity", "reliability" and "responsiveness". The electronic search strategy is shown in Appendix 1.

Study selection

Two independent researchers (MD and BvG) screened the abstracts for eligibility. A full-text version was reviewed of these eligible studies. All references of these studies were screened for additional eligible articles. Any disagreements between the reviewers were resolved by discussion. In case of non-consent, a third reviewer was involved (RJ). The PRISMA flow chart is presented in Figure 1.

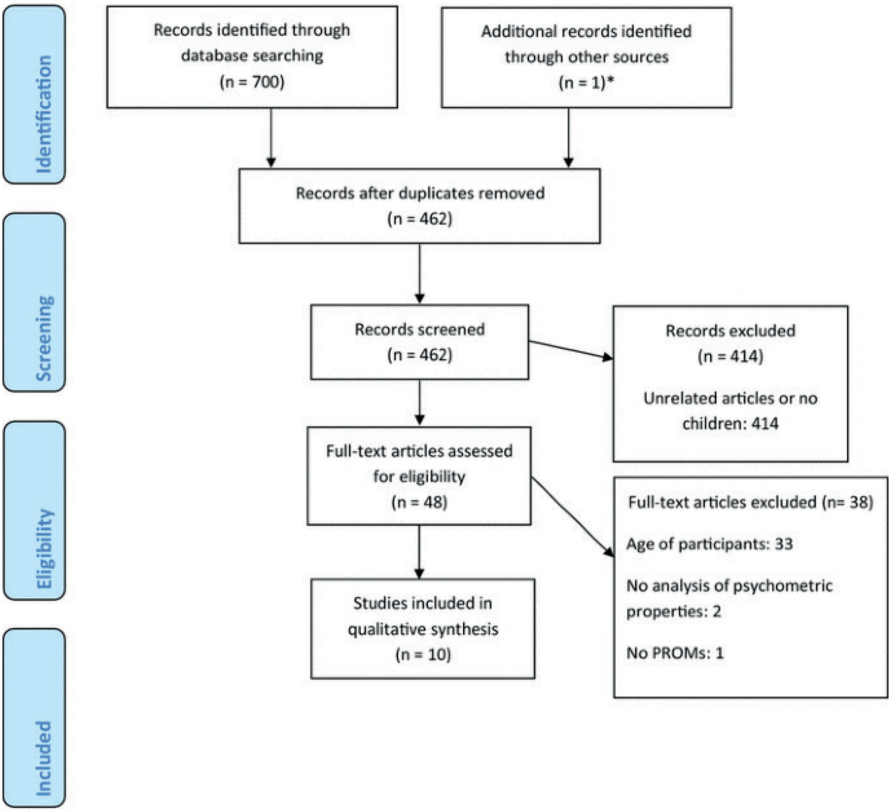

Figure 1. Flow chart of study selection according to the PRISMA statement

* additional record identified by searching through Google Scholar

6

The following PROMs were evaluated in the included studies:

- Pedi-IKDC, including a Danish translation (Paediatric International Knee Documentation Committee Subjective Knee Form) [2,10,12,18].
- IKDC (International Knee Documentation Committee Subjective Knee Form) [9,21].
- KOOS-Child (Knee injury and Osteoarthritis Outcome Score for Children) [19].
- KOOS (Knee injury and Osteoarthritis Outcome Score) [20].
- SANE (single assessment numeric evaluation) [22].
- Marx Activity Scale [23].

Patient-reported outcome measures

The Pedi-IKDC is a modified version of the original IKDC, developed for children. The Pedi-IKDC contains 18 items [12]. Based on the original IKDC, the measurement is a knee-specific outcome score for symptoms, function and sport activities in patients with a variety of knee conditions [21]. The validity, reliability and responsiveness of the IKDC have been established in the adult population [21].

The KOOS-Child is the first paediatric PROM designed to evaluate self-reported knee function [19,20]. The KOOS-Child includes sports- and knee-related quality of life subscales. It addresses five domains including: pain, other symptoms, activities of daily living, sports and recreation and knee-related quality of life [20].

The SANE consists of only one question, grading the knee from 0 to 100 points [22]. The SANE rating is a qualitative assessment of symptoms and function. It evaluates work, sports and activities of daily living allowing patients to weigh the importance of each knee-related activity to their needs and interests [22].

The Marx Activity Scale consists of four questions regarding the frequency of running, cutting, decelerating and pivoting in the past year [23]. The Marx Activity Scale has been previously validated in sports medicine in an adult population [23].

Data collection process

One author (MD) extracted all relevant data. The data included specific details of the PROM, population, age, sex, injuries, interventions, study methods, follow-up period and outcomes of interest to the review question and research objectives.

Methodological quality

The methodological quality of the measurement properties was assessed by two independent reviewers (MR and MvdS), using the COSMIN checklist [25]. A methodological quality score for each measurement property was obtained by registering the lowest rating of any item within the property (worse score counts) [25]. Scores were defined as poor, fair, good or excellent. Disagreement between the reviewers was resolved through discussion.

Quality of psychometric properties

The assessed psychometric properties of the PROMs were validity, reliability, responsiveness, interpretability and comprehensibility. The definitions by Terwee et al [24] were used to determine the quality of the PROM. Scores were defined as positive rating "+", indeterminate rating "?" or negative rating [24].

Results

Study characteristics

The characteristics of the 10 included studies are presented in Table 1. The number of patients ranged between 30 and 673, with age ranging from 10 to 18 years. Seven of eight included quantitative studies were cohort studies [8,12,18,19,21,22,23]. Two of 10 studies had a qualitative design [9,20].

Table 1. Study characteristics.

Study	Study design	Patients, n	Age, years	Female, n (%)	Type of injury	Type of PROM	Follow-up
Boykin [2]	Cross sectional	135	15.3 (IQR 13.1–17.2)	55 (40.7)	ACL	Pedi-IKDC	NA
Iversen [9]	Qualitative	30	10–18	15 (50)	Knee injuries, not specified	IKDC	NA
Jacobsen [10]	Prospective cohort	99	14 (range 10–18)	49 (49.5)	ACL 56 ACL and MCL 3 Non-ligament injury 40	Danish Pedi-IKDC	4 months (range 3–12 months)
Kocher [12]	Prospective cohort	589	14.6 (SD 2.5)	301 (51.1)	ACL 129 PCL 4 MCL 13 LCL 2 Non-ligament injury 441	Pedi-IKDC	Non-operative 17 days (range 3–67 days); Post-operative 7.6 months (SD 7.5 weeks)
Oak [18]	Cohort	100	15.9 (SD 1.4)	64 (64)	ACL 18 (post-op) ACL injury 15 MCL injury 1 PCL injury 1 LCL 1 (post-op) Non-ligament injury 64	Pedi-IKDC Adult-IKDC	NA
Örtqvist [19]	Prospective cohort	115	13 (SD 1.9)	64 (55.7)	ACL injury 19 PCL injury 1 Non-ligament injury 95	KOOS-Child	3 months
Örtqvist [20]	Qualitative	34	14 (range 10–16)	17 (50)	ACL injury 11 Non-ligament injury 23	KOOS	NA
Schmitt [21]	Cohort	673	14.2	361 (53.6)	Ligament sprain, reconstruction or avulsion 83 Non-ligament injury 590	IKDC	NA
Shelbourne [22]	Cohort	766	< 18	NA	ACL injury (post-op)	SANE	NA
Shirazi [23]	Cohort	62	14.6	23 (37.1)	Knee injury, not specified	Marx Activity Scale	NA

Abbreviations: ACL anterior cruciate ligament, PCL posterior cruciate ligament, MCL medial collateral ligament, LCL lateral collateral ligament, SD standard deviation, (Pedi-) IKDC (Paediatric) International Knee Documentation Commee Subjective Knee Form, KOOS-(Child) Knee injury and Osteoarthritis Outcome Score (-Child), SANE single assessment numeric evaluation, SD standard deviation, IQR interquartile range, NA not applicable

Methodological quality

Appendix 2 shows the scores on the different items according to the COSMIN criteria. Table 2 presents the overall scores of methodological quality of the individual studies, according to worse score counts. The methodological quality of content validity ranged from poor to excellent and construct validity from poor to good. The reliability and responsiveness scores scored poor or fair.

Table 2. Methodological quality of individual studies according to the COSMIN checklist (worse score counts) [25].

PROM	Study	Methodological quality of psychometric properties				
		Validity		**Reliability**	**Responsiveness**	
		Content validity	**Construct validity**	**(Test–retest) Reliability**	**Measurement error**	
Pedi-IKDC	Boykin [2]		Poor			
	Jacobsen [10]	Poor		Fair	Fair	Fair
	Kocher [12]	Fair	Fair	Fair		Poor
	Oak [18]		Fair			
IKDC	Schmitt [21]		Poor			
KOOS-Child	Örtqvist [19]		Good	Poor	Poor	Fair
KOOS	Örtqvist [20]	Excellent				
SANE	Shelbourne [22]		Poor			
Marx Activity Scale	Shirazi [23]			Poor		

Iversen et al [9] are not included in this table, since no psychometric properties are determined, but the focus was on comprehensibility (Pedi-) IKDC (Paediatric) International Knee Documentation Committee Subjective Knee Form, KOOS-(Child) Knee injury and Osteoarthritis Outcome Score (-Child), SANE single assessment numeric evaluation

Psychometric properties

Appendix 3 shows the results of the psychometric properties of each PROM per study. Table 3 presents the results of the quality of the psychometric properties based on positive, negative or indeterminate ratings according to Terwee et al [24]. If determined, reliability of the investigated PROMs was rated positively. In the eight studies investigating validity, six times a positive rating was found and three times validity was not confirmed. Also responsiveness yielded mixed results, namely one positive and two indeterminate ratings. The Pedi-IKDC and Marx Activity Scale had significant ceiling effects in contrast to the KOOS-Child.

Table 3. Quality of psychometric properties according to checklist Terwee et al [24].

PROM	Study	Quality of psychometric properties					
		Validity		Reliability		Responsive-ness	Interpretability
		Content validity	Construct validity	(Test–retest) Reliability	Measurement error		Floor and ceiling effect
Pedi-IKDC	Boykin [2]		–				
	Jacobsen [10]	+		+	+	+	
	Kocher [12]	–	+	+		?	–
	Oak [18]		+				
IKDC	Schmitt [21]		+				
KOOS-Child	Örtqvist [19]		+	+	+	?	+
KOOS	Örtqvist [20]	+					
SANE	Shelbourne [22]		–				
Marx Activity Scale	Shirazi [23]			+			–

Iversen et al [9] are not included in this table, since no psychometric properties are determined. (Pedi-) IKDC (Paediatric) International Knee Documentation Committee Subjective Knee Form, KOOS (-Child) Knee injury and Osteoarthritis Outcome Score (-Child), SANE single assessment numeric evaluation

+ = positive rating; – = negative rating; ? = indeterminate rating

Comprehensibility

The comprehensibility of PROMs by children (IKDC and KOOS) was evaluated in two studies [9,20]:

- Iversen et al [9] determined the comprehensibility of the IKDC among 30 children aged 10–18 years. Children had difficulty comprehending the adult IKDC. Therefore, adjustment was necessary, resulting in the development of the Pedi-IKDC [9].

- Örtqvist et al [20] evaluated the comprehensibility of the KOOS in 34 patients with a mean age of 14 years. Eleven of the 34 patients had an ACL injury. The (adult) KOOS was not well understood by children, and modifications were deemed necessary. This led to the development of the KOOS-Child [20].

Discussion

The most important finding of the current systematic review was that specific paediatric PROMs need to be used in children. The most frequently studied PROM was the Pedi-IKDC, which has been evaluated in four studies [2,10,12,18]. It has acceptable psychometric properties. The KOOS-Child has been evaluated in one study and appears to be valid and reliable. In general, a greater variety of psychometric properties has been tested in the Pedi-IKDC or KOOS-Child, compared to the IKDC, SANE or Marx Activity Scale. The use of adult PROMs might cause problems concerning comprehensibility.

The limited comprehensibility of the adult IKDC and KOOS by children led to the development of the Pedi-IKDC and KOOS-Child by using cognitive interviews [9,20]. Iversen et al [9] concluded that younger children had difficulty using five-point responses [9]. Children experienced the most difficulty in understanding the items "current" and "prior" function [9]. Children also had difficulty in comprehending as well as answering the adult IKDC [9]. Therefore, modifications concerning directions (time frames), definitions and formatting were needed to ensure comprehensibility and validity in children [9]. In contrast to the comprehensibility of the IKDC, most children understood how to use the 5-point Likert response scale in the KOOS [19]. However, many children found the instructions confusing and found several items irrelevant [20]. Örtqvist et al [20] also concluded that modifications of the KOOS were necessary for comprehensibility. Modifications concerning instructions, item and response format, mapping and layout were made [20].

Most articles included in this review determined psychometric properties of the Pedi-IKDC [2,10,12,18]. Overall, they presented good reliability and an acceptable validity and responsiveness. One needs to note the significant ceiling effect in the study by Kocher et al [12]. This has recently been confirmed in a study on normative data of the Pedi-IKDC by Nasreddine et al [17]. The psychometric properties were similar among the different studies. Irrgang et al [7,8] have demonstrated that the outcome of the Pedi-IKDC was similar to the outcome of the IKDC in an adult population. In summary, the Pedi-IKDC is a well-studied PROM in children with knee ligament injuries and shown to be valid, reliable and responsive.

The (adult) IKDC is commonly used as PROM in clinical studies to evaluate the patients' perspective on treatment results in children [6,14]. The IKDC has only been evaluated in a paediatric population in one study by Schmitt et al [21]. The authors described a good construct validity of the adult IKDC if used in a paediatric population. However, the methodological quality of this study is poor and no other psychometric properties were assessed [21]. Furthermore, the known concerns on comprehensibility of the IKDC in children warrant the use of the Pedi-IKDC in paediatric and adolescent populations.

The KOOS-Child was the first PROM for children with knee injuries designed to evaluate self-reported knee function. It was developed due to problems concerning comprehensibility of the adult KOOS by children [19,20]. The original KOOS has not been evaluated in a paediatric population. The KOOS-Child has only been evaluated in one study by Örtqvist et al [19] and appears to be valid and reliable, although the methodological quality of the subscales in reliability was poor. There were no significant ceiling or floor effects [19]. This current review shows comparable psychometric properties of the KOOS-Child to the original adult KOOS [4,19]. The KOOS-Child might be an alternative for the Pedi-IKDC for children with knee ligament injuries.

The SANE consists of only one question, grading the knee from 0 to 100 points, and addresses symptoms, functions, daily activities and psychological factors [22,27]. Only one study reported the methodological quality of SANE in children, but merely addressed construct validity [22]. The methodological quality of this study was poor, and the construct validity had a negative rating [22]. The present review does not recommend to the use of SANE as PROM for children with knee ligament injuries.

The Marx Activity Scale is a validated scale to evaluate activity level for adults in sports medicine [15,23]. One study was included in the current review evaluating the test–retest reliability of the Marx Activity Scale in children [23]. The test–retest reliability was high, but the methodological quality of this study was poor. There was also a significant ceiling effect of 53.2%. The scale was less reliable in patients younger than 14 years, possibly related to the problems concerning comprehensibility. No information was available on validity and responsiveness in a paediatric population [23]. In summary, the Marx Activity Scale has not yet been shown to be an adequate PROM to evaluate activity levels in children.

The interpretation of this systematic review has some limitations. The overall methodological quality of the included studies was poor, according to the COSMIN criteria. One needs to consider that the overall quality according to COSMIN is determined by the lowest score counts. This influences the quality ratings. For example, the study by Örtqvist et al [19], nearly all items scored "excellent" but only one item scored "poor". As a result, the overall quality assessment of this study is "poor" according to the COSMIN criteria. Methodologically, the worst count method is valid. In daily practice however, it might neither be desirable nor possible for validation studies to achieve an excellent score on all items. There are no valid alternative rating systems for the COSMIN criteria available for rating PROMs.

Another limitation is that patients with a variety of knee injuries were included in this systematic review. The outcomes are therefore not solely based on children with ligamentous injury. It must be noted however that the majority of included children in the 10 studies did have a ligamentous injury. Therefore, the current review is the best available evidence-based approach to choose a PROM for children with knee ligament injury.

A potential source of bias in young children is the fact that parents are often involved in explaining questions even though they are not allowed to answer for the patients [12,21,23]. Children's self-reports are not equal to reports by proxy respondents [21]. Therefore, a parent's report of function cannot be substituted for the child's report [21]. In studies concerning PROMs in children, one needs to consider this "proxy-problem" to be a potential bias.

Future studies regarding the psychometric properties of PROMs in children are necessary to determine age-specific outcome measurements. The current systematic review provides an evidence-based overview of the current value of PROMs for children with knee ligament injuries and can be used to select paediatric PROMs in the clinical setting.

Conclusions

The Pedi-IKDC is an adequate PROM for children with knee ligament injuries. It is valid, reliable and responsive. The KOOS-Child might be an alternative PROM for the Pedi-IKDC, but has only been evaluated in one study. The clinical relevance of the present systematic review is that adult versions of PROMs are not recommended in children and adolescents.

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Appendix 1 – Search strategy

Embase.com 310 results

('knee injury'/exp OR (((knee* OR acl OR anterior-cruciate-ligament* OR pcl OR posterior-cruciate-ligament* OR menisc* OR patella*) NEAR/3 (injur* OR rupture* OR tear* OR dislocat* OR luxat* OR trauma* OR defect*))):ab,ti) AND ('questionnaire'/exp OR 'musculoskeletal disease assessment'/exp OR 'scoring system'/de OR (questionnaire* OR score* OR scale*):ab,ti) AND (child/exp OR adolescent/exp OR adolescence/exp OR pediatrics/exp OR childhood/exp OR 'child development'/de OR 'child growth'/de OR 'child health'/de OR 'child health care'/exp OR 'child care'/exp OR 'childhood disease'/exp OR 'pediatric ward'/de OR 'pediatric hospital'/de OR 'adolescent disease'/de OR (adolescen* OR infan* OR newborn* OR (new NEXT/1 born*) OR baby OR babies OR neonat* OR child* OR kid OR kids OR toddler* OR teen* OR boy* OR girl* OR minors OR underag* OR (under NEXT/1 (age* OR aging)) OR juvenil* OR youth* OR kindergar* OR puber* OR pubescen* OR prepubescen* OR prepubert* OR pediatric* OR paediatric* OR school* OR preschool* OR highschool*):ab,ti) AND ('sensitivity and specificity'/exp OR 'validation study'/exp OR 'validity'/exp OR 'diagnostic accuracy'/de OR 'reliability'/exp OR reproducibility/de OR 'observer variation'/de OR (sensitivit* OR specificit* OR validit* OR validat* OR accura* OR reliab* OR reponsiv* OR reproducib* OR Comprehensib* OR variabil* OR ((observer OR intraobserver OR interobserver) NEAR/3 variation) OR consisten* OR test-retest OR (compar* NEAR/3 (analy*))):ab,ti)

Medline Ovid 388 results

Cochrane 2 results

Appendix 2. Methodological quality according to COSMIN criteria [25]

	Boykin [2]	**Jacobsen [10]**	**Kocher [12]**	**Oak [18]**	**Örtqvist 1 [19]**	**Örtqvist 2 [20]**	**Schmitt [21]**	**Shelbourne [22]**	**Shirazi [23]**
	Pedi-IKDC				**KOOS-Child**	**KOOS**	**IKDC**	**SANE**	**Marx Activity Scale**
B Reliability									
1		good	good		excellent				good
2		fair	fair		excellent				fair
3		good	good		good				excellent
4		excellent	excellent		excellent				excellent
5		good	good		excellent				good
6		excellent	excellent		excellent				excellent
7		good	excellent		excellent				fair
8		excellent	excellent		excellent				excellent
9		good	fair		poor				poor
10		excellent	excellent		excellent				excellent
11		excellent	good		good				good
12		NA	NA		NA				NA
13		NA	NA		NA				NA
14		NA	NA		NA				NA
C Measurement error									
1		good			excellent				
2		fair			excellent				
3		good			good				
4		excellent			excellent				
5		good			excellent				
6		excellent			excellent				
7		good			excellent				
8		excellent			excellent				
9		excellent			poor				
10		excellent			excellent				
11		excellent			excellent				
D Content validity									
1		excellent	fair			excellent			
2		excellent	excellent			excellent			
3		fair	good			excellent			
4		poor	fair			excellent			
5		excellent	excellent			excellent			
F Hypothesis testing									
1	good		good	good	excellent		good	good	

	Boykin [2]	Jacobsen [10]	Kocher [12]	Oak [18]	Örtqvist 1 [19]	Örtqvist 2 [20]	Schmitt [21]	Shelbourne [22]	Shirazi [23]
	Pedi-IKDC				**KOOS-Child**	**KOOS**	**IKDC**	**SANE**	**Marx Activity Scale**
2	fair		fair	fair	excellent		excellent	fair	
3	excellent		excellent	excellent	excellent		excellent	excellent	
4	fair		excellent	fair	excellent		poor	poor	
5	good		excellent	good	good		good	good	
6	good		good	excellent	excellent		good	good	
7	excellent		excellent	excellent	excellent		excellent	excellent	
8	poor		good	good	excellent		excellent	poor	
9	excellent		excellent	excellent	excellent		fair	fair	
10	good		good	fair	excellent		good	fair	
I Responsiveness									
1		good	good		excellent				
2		fair	fair		excellent				
3		good	good		good				
4		excellent	excellent		excellent				
5		excellent	excellent		excellent				
6		excellent	good		good				
7		excellent	excellent		excellent				
8			fair		fair				
9			good		excellent				
10			good		excellent				
11			poor		excellent				
12			NA		good				
13			excellent		excellent				
14		excellent	fair		NA				
15		excellent	NA		NA				
16		excellent	NA		NA				
17		NA	NA		NA				
18			NA		NA				

Empty cells indicate that this property was not assessed. NA=Not Applicable; (Pedi-)IKDC=(Pedi-) International Knee Documentation Committee Subjective Knee Form; KOOS-(Child)=Knee injury and Osteoarthritis Outcome Score (-Child); SANE=Single Assessment Numeric Evaluation.

Appendix 3. 'Overview of outcomes of psychometric properties'

		Validity	
PROM	**Article**	**Content validity**	**Construct validity (hypothesis testing)**
Pedi-IKDC	Boykin [2]	X	7/12 significant correlated with CHQ
	Jacobsen [10]	Determined	X
	Kocher [12]	Determined	All hypotheses significant 9/12 significant correlated with CHQ
	Oak [18]	X	R2=92% (with IKDC adult version)
IKDC	Schmitt [21]	X	ICC=0.83 (PedsQL)
KOOS-Child	Örtqvist [19]	No	All hypotheses significant
KOOS	Örtqvist 2 [20]	Determined	X
SANE	Shelbourne [22]	X	ICC=0.637-0.652 with IKDC & CKRS
Marx Activity Scale	Shirazi [23]	X	X

		Responsiveness
PROM	**Article**	
Pedi-IKDC	Boykin [2]	X
	Jacobsen [10]	AUC 0.70
	Kocher [12]	Significant increase (effect size 1,39; standardized response mean 1,35)
	Oak [18]	X
IKDC	Schmitt [21]	X
KOOS-Child	Örtqvist [19]	Significant correlation with CHQ
KOOS	Örtqvist 2 [20]	X
SANE	Shelbourne [22]	X
Marx Activity Scale	Shirazi [23]	X

		Reliability		
PROM	**Article**	**(Test-retest) reliability**	**Measurement error**	
			Agreement	**Reliability**
Pedi-IKDC	Boykin [2]	X	X	
	Jacobsen [10]	ICC=0.9	4.1 (SDC 11.3)	ICC 0.9
	Kocher [12]	ICC=0.91 (95%-CI 0.86-0.95)	X	
	Oak [18]	X	X	
IKDC	Schmitt [121]	X	X	
KOOS-Child	Örtqvist [19]	Cronbach's α = 0.59-0.90	5.3-8.1 (SDC 14.6-22.6)	ICC 0.78-0.91
KOOS	Örtqvist 2 [20]	X	X	
SANE	Shelbourne [22]	X	X	
Marx Activity Scale	Shirazi [23]	Cronbach's α = 0.964	X	

Chapter 7

Outcomes measures and (p)rehabilitation

Translation and transcultural validation of the Dutch hospital for special surgery paediatric functional activity brief scale (HSS Pedi-FABS)

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Abstract

Background: There is a need for a validated simple Dutch paediatric activity scale. The purpose was to translate and transculturally validate the Dutch Hospital for Special Surgery Paediatric Functional Activity Brief Scale (HSS Pedi-FABS) questionnaire in healthy children and adolescents.

Methods: The original HSS Pedi-FABS was translated forward and backward and was transculturally adapted after performing a pilot study among children and professionals. The final version of the Dutch HSS Pedi-FABS was validated in healthy children and adolescents aged 10 to 18 years old. Children who had any condition or injury limiting their normal physical activity were excluded. The interval between the first questionnaire T0 (HSS Pedi-FABS, Physical Activity Questionnaire for children or adolescents (PAQ-C/A) and Tegner activity scale) and the second questionnaire T1 (HSS Pedi-FABS) was 2 weeks. Construct validity, interpretability and reliability were evaluated. Content validity was evaluated through cognitive interviews among a smaller group of children and through a questionnaire among professionals.

Results: To evaluate content validity, 9 children and adolescents were interviewed, and 30 professionals were consulted. Content validity among professionals showed a relevance of less than 85% for most items on construct. However, content validity among children was good with a 92% score for item relevance. Readability was scored at a reading level of 11- to 12-year-olds. The validation group consisted of 110 healthy children and adolescents (mean age of 13.9 years ±2.6). Construct validity was considered good as 8 out of 10 hypotheses were confirmed. The Dutch HSS Pedi-FABS showed no floor or ceiling effect. Analysis of the internal consistency in the validation group resulted in a Cronbach's alpha of 0.82. Test-retest reliability was evaluated among 69 children and adolescents and revealed an Intraclass Correlation Coefficient (ICC) of 0.76.

Conclusions: The Dutch HSS Pedi-FABS showed good psychometric properties in a healthy Dutch paediatric and adolescent population. Limitations of the current Dutch HSS Pedi-FABS are content validity on construct of items reported by professionals.

Background

Physical activity provides important health benefits for children and adolescents. Unfortunately, injuries related to physical activity are common, especially in single sports specialization[1,2,3]. With 42,000 sports and physical activity-related injuries seen among 5–14 year-old children in Dutch hospitals every year, sports injuries are a substantial public health issue [1,4].

The level of physical activity is increasingly recognized as both an important prognostic factor and outcome variable in orthopaedics [5]. A simple validated outcome measure is important to determine physical activity in children and adolescents. Physical activity can be assessed with both objective and subjective measures. Objective measures such as accelerometers and heartrate monitors provide highly reproducible and accurate data on physical activity but are often rather expensive, time-consuming, and may require technical expertise [6]. Self-reported measures, such as questionnaires, are often used to assess physical activity in children and adolescents because of their advantages, such as low costs, minimal participant burden, and easy administration. However, problems may arise with the length of the questionnaire, understanding the questions, or accurately recalling physical activity especially in a young target population [7].

Multiple self-reported activity scales already exist in the orthopaedic field [8,9]. However, current scales are often aimed at children with a specific disability [8]. The existing activity scales for children are long, time consuming and specific to activity, sport and/or joint [7,8,10]. Long questionnaires may lead to questionnaire fatigue [8,11]. Global use of activity-specific scales may also be limited due to cultural biases [8,12,13]. Moreover, a recent review by Hidding et al [14] argued that there is a lack of physical activity questionnaires with excellent validity and reliability [14]. To date, the Physical Activity Questionnaire – Children or Adolescent (PAQ-C and PAQ-A) are the only validated Dutch questionnaires to assess physical activity in children and adolescents [14,15]. These questionnaires have 9 to 10 items including a checklist of 23 sports and are therefore long and time-consuming. In 2013, the Hospital for Special Surgery Paediatric Functional Activity Brief Scale (HSS Pedi-FABS) was developed to assess the physical activity level in children and adolescents aged 10 to 18 years old [8]. The HSS Pedi-FABS is a simple, validated paediatric activity scale, which may be useful to evaluate physical activity level as a prognostic factor in clinical outcome research [16]. It has excellent scale reliability, robust construct validity, and shows no floor or ceiling effects [8]. Besides, the HSS Pedi-FABS has recently been recommended by the 2018 International Olympic

Committee (IOC) consensus statement and will be used as activity-rating scale in the Paediatric Anterior Cruciate Ligament Monitoring Initiative (PAMI) [17]. This European initiative launched by the European Society for Sports Traumatology, Knee Surgery and Arthroscopy (ESSKA) aims to create a pan-European system to collect and analyse data to provide stronger scientific evidence in paediatric ACL injury treatment [17,18,19]. Yet, the HSS Pedi-FABS is currently available in English and Italian [8,18]. Therefore, it is crucial to transculturally validate the Dutch HSS Pedi-FABS. It is hypothesized that the Dutch HSS Pedi-FABS has adequate psychometric properties in a healthy paediatric and adolescent population, comparable to the psychometric properties of the original HSS Pedi-FABS [8].

Methods

Translation procedure

Translation of the original HSS Pedi-FABS, which is published by Fabricant et al [8], was performed using a forward-backward translation procedure [20] The HSS Pedi-FABS was translated from English into Dutch by two native Dutch speakers. Translations were compared, discrepancies between them were discussed and a preliminary version of the Dutch HSS Pedi-FABS was established. Subsequently, this preliminary version was translated back into English by two independent English native speakers who were unfamiliar with the original questionnaire. The translated version was compared to the original version of the HSS Pedi-FABS to check for similar item content. Differences and inconsistencies were discussed and adjustments were made to form the pre-final version. This pre-final version was evaluated as a pilot among children and professionals for cross-cultural adaptation which resulted in minor adjustments. The developer of the original HSS Pedi-FABS was consulted to discuss cross-cultural adaptations [8]. Finally, the Department of Patient Communication at the Máxima Medical Centre evaluated this pre-final version. Some linguistic adjustments were made, and the final version of the Dutch HSS Pedi-FABS was established.

Participants

The study population consisted of the content validity group and the validation group. The content validity group consisted of two subgroups: target population and professionals. Participants of the content validity target population were recruited at a sports club and through a personal network. Physically active children aged 10 to 18 years old were included in this group. Professionals from relevant disciplines were recruited from four Dutch teaching hospitals: Máxima Medical Centre Eindhoven/

Veldhoven, VieCuri Hospital Venlo, Maastricht University Medical Centre and Erasmus University Medical Centre Rotterdam. The validation group was recruited through primary and secondary schools in the Netherlands and at the out-patient department of the paediatric orthopaedic clinic at the Máxima Medical Centre and Erasmus University Medical Centre. Children or adolescents aged 10 to 18 years were included in this group. Children who had any condition or injury limiting their normal physical activity were excluded.

Study procedure

Figure 1 shows the study procedure of the translation and validation of the Dutch HSS Pedi-FABS. After translation, content validity was assessed through cognitive interviews in participants representing the target population and through questionnaires in professionals [21]. Interpretability and construct validity were evaluated within the validation group. Participants received an information letter together with a set of questionnaires at school (T0). Assistance in completing the questionnaire by the parents was allowed for any reason. If the participants completed the baseline questionnaires, they were asked to fill out the Dutch HSS Pedi-FABS again by email or post 2 weeks later (T1) and answer the anchor question "Did your level of physical activity change since you completed the previous questionnaires (± 2 weeks ago)?". Responses of participants reporting stable level of activity were used to assess reliability of the Dutch HSS Pedi-FABS.

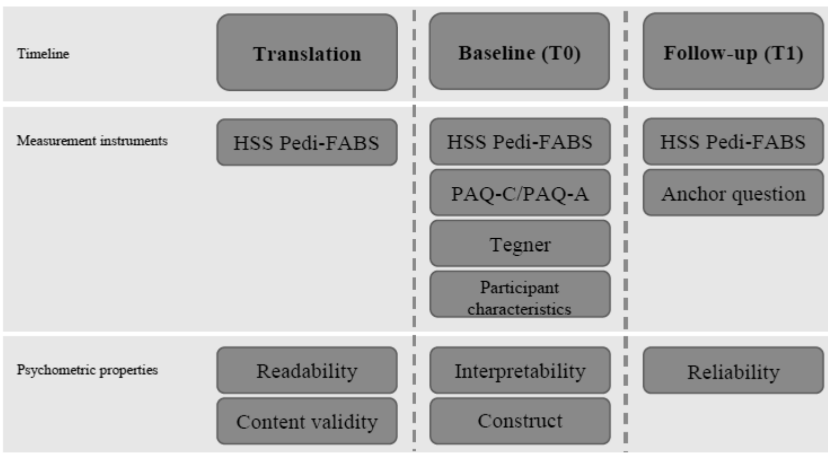

Figure 1. Study procedure.

"HSS Pedi-FABS = Hospital for Special Surgery Paediatric Functional Activity Brief Scale"; "PAQ-C/A = Physical Activity Questionnaire – Children or Adolescents".

Questionnaires

At baseline (T0), children and adolescents within the validation group completed the HSS Pedi-FABS, PAQ-C or PAQ-A, Tegner activity scale, and questions concerning age, school, self-reported weekly participation in sports and self-reported level of competition.

The HSS Pedi-FABS questionnaire is an 8-item metric to assess physical activity in children and adolescents between 10 and 18 years old [8]. The questionnaire consists of 6 Likert-based items regarding frequency of activities, one item on the level of sports and one item on supervision [8,18]. Scores range from 0 to 30, with a higher score indicating more physical activity [8,18].

The PAQ-C and PAQ-A are the only validated Dutch questionnaires to assess physical activity in children and adolescents [14,15]. The PAQ-C was originally designed for children aged 8 to 14 years and consists of 10 questions [15]. The PAQ-A was designed for adolescents aged 14 to 20 years and consists of 9 questions [15]. Both PAQ questionnaires contain one question in the form of a checklist of common sports and activities which are scored on frequency of participation [15]. Subsequently, the mean is calculated which results in the total score ranging from 1 (low activity) to 5 (high activity) [15].

Although the Tegner activity scale is not validated in the paediatric population, it is often used as an activity scale for children and adolescents [22]. The Tegner activity scale is a 1-item activity scale ranging from 0 (no activity) to 10 (high activity) and is widely used as an activity rating system for a variety of knee disorders [13,23,24].

Readability

Readability of the Dutch HSS Pedi-FABS was assessed with the Dutch version of the Flesch reading ease (FRE) test [25]. A score of 0 reflects academic language while a score of 100 reflects the reading level of children in 4th grade (age 9–10 years). The aim was to attain a readability score between 60 and 80 points, which reflects the reading level of children aged 11 to 13 years old.

Content validity

Target population

Relevance, comprehensiveness and comprehensibility were evaluated through cognitive interviews with children [26]. All interviews were conducted by one researcher (TK) and were audio-recorded for transcription. A semi-structured interview guide was used containing predefined probe questions which addressed comprehension of the instructions, items, recall period, and response options [27]. All items of the HSS Pedi- FABS were also rated on relevance, and participants were asked to suggest potential missing concepts. Parents were not asked for input on the scale. Interviews were transcribed verbatim and analysed by one researcher (TK) using ATLAS.ti version 8.4 (Scientific Software Development GmbH, Berlin, Germany). Cognitive codes were applied using the Problem Classification Coding Scheme (CCS), which consists of five categories: comprehension and communication; memory retrieval; judgement and evaluation; response selection; and other (see Supplementary file 1) [28]. A sixth category containing four codes was added to determine relevance.

Professionals

Professionals from relevant disciplines (orthopaedic surgeons, residents in orthopaedic surgery, physiotherapists, sports physicians, rehabilitation physicians, and trauma surgeons) rated the relevance and comprehensiveness of the Dutch HSS Pedi-FABS. A questionnaire was used to evaluate the relevance of each item for both the target population and the construct; the response options and recall period were rated on appropriateness. Comprehensiveness was addressed by asking whether important concepts or items were missing in the questionnaire.

Items were considered relevant for the target population or construct if at least 85% of professionals rated them as relevant. Content validity of the Dutch HSS Pedi-FABS was rated as sufficient if at least 85% of the items were considered relevant by both professionals and participants [21].

Interpretability

Interpretability was assessed by examining the distribution of HSS Pedi-FABS scores at T0, including the mean and standard deviation (SD). Moreover, floor and ceiling effects were evaluated and considered present if more than 15% of the participants scored either the lowest or highest score possible [8,21,29]. A positive rating of interpretability of the HSS Pedi-FABS was given if floor and ceiling effects were absent.

Construct validity

Hypothesis testing was used to assess construct validity; criterion validity was not evaluated since no gold standard is available for questionnaires on physical activity. Hypotheses were defined about the relationship between the HSS Pedi-FABS and outcome measures which measure either the same or a different construct (convergent or discriminative validity, respectively). These hypotheses were formulated by a panel consisting of experts and based on the study of Fabricant et al [8].

To evaluate convergent validity, a correlation of r ≥ 0.50 was expected between the HSS Pedi-FABS scores and a) the PAQ scores (total), b) PAQ-C scores, c) PAQ-A scores, d) the Tegner activity score, e) self-reported hours of weekly participation in sports, and f) the level of competition, all assessed at baseline (T0). Age and BMI were expected not to correlate (< 0.30) with scores of the HSS Pedi-FABS which reflects divergent validity. Correlations of the hypotheses confirming convergent validity should be at least 0.1 higher than the correlations that indicate discriminative validity [26]. The latter was operationalized as two hypotheses: hypotheses conforming convergent validity should be at least 0.1 higher than age (hypothesis 9) and BMI (hypothesis 10). Construct validity of the HSS Pedi-FABS was considered good if at least 75% of the predefined hypotheses were confirmed [21].

Reliability

Internal consistency, test-retest reliability and measurement error were evaluated as measurement properties of reliability [21]. All participants within the validation group were included for analysis of internal consistency. All participants who completed the baseline questionnaires were invited to complete the Dutch HSS Pedi- FABS a second time 2 weeks (T1) after completion of T0. Only participants who reported no change in their activity pattern during the interval period were included in the test-retest analysis.

Comparison between HSS Pedi-FABS versions

The psychometric properties of the original, the Italian and Dutch HSS Pedi-FABS were compared.

Statistical analysis

Statistical analyses were performed with IBM SPSS Statistics 24. Descriptive statistics were used to describe baseline characteristics of the participants. The aim was to include at least 7 participants and 30 professionals to evaluate relevance and to ensure excellent content validity [21,26]. To assess construct validity, interpretability, and reliability, at least 100 participants needed to be included in the validation group [26]. Shapiro-Wilk test was used as test for normality of the baseline characteristics and HSS Pedi-FABS outcomes in the validation group [30]. Spearman rank correlations were calculated to assess construct validity. To determine internal consistency, Cronbach's alpha was calculated. Test-retest reliability was evaluated by means of a two-way random effects model of Intraclass Correlation Coefficient (ICC) in absolute agreement. Cronbach's alpha and ICC coefficients of 0.70 or higher are considered to reflect good reliability [20]. The Standard Error of Measurement (SEM) was calculated as $SEM = SD * \sqrt{(1 - reliability)}$, where the ICC reflects reliability [21,31]. The Smallest Detectable Change (SDC) was defined as 1.96 * √2 * SEM [32]. The significance level was set at 5% for all statistical analyses.

Ethical approval

This validation study was approved by the local Medical Ethics Committee (METC) of the Máxima Medical Centre [N18.168] and Erasmus University Medical Centre [MEC-2020-0278]. The developer of the original HSS Pedi-FABS was informed and gave permission for publication of the Dutch HSS Pedi-FABS. All participants gave written informed consent and their parents or legal guardians if necessary (in case of age < 16 years).

Results

The content validity population consisted of 9 participants. A total of 132 children and adolescents were included for the validation study, of which 22 participants reported a condition or injury limiting their normal physical activity and were excluded for analysis. In Table 1, the characteristics of the content validity population and validation population are shown. 39.1% of the children received assistance from parents in completing the questionnaires, of which 73% was aged 10 to 12 years. The reasons or types of assistance by the parents were not evaluated.

Table 1. Baseline characteristics of the content validity population and the validation population at T0 and T1.

	Content validity	Validation	
	Participants (n = 9)	**T0 Participants (n = 110)**	**T1 Participants (n=69)**
Age, mean ± SD, y	13.4 ± 2.4	13.9 ± 2.6	13.7 ± 2.5
Sex, No. (%)			
Female	7 (78)	60 (55)	38 (51)
Male	2 (22)	50 (46)	37 (49)
BMI, mean ± SD, kg/m^2	19.4 ± 2.3	18.3 ± 2.7	18.1 ± 2.8
Weekly participation in sports at a sports club, mean ± SD, h		4.3 ± 3.1	4.0 ± 2.9
Weekly participation in sports without sports club, mean ± SD, h		4.3 ± 4.3	4.0 ± 2.3
Days per week with at least one hour of physical activity, No. (%)			
Almost never		1 (1)	0 (0)
1 day per week		3 (3)	3 (4)
2 days per week		3 (3)	2 (3)
3 days per week		15 (14)	9 (12)
4 days per week		11 (10)	5 (7)
5 days per week		22 (20)	15 (20)
6 days per week		24 (22)	18 (24)
Every day		30 (27)	22 (30)
Missing		1 (1)	1 (1)
Competition level, No. (%)			
Recreational		34 (31)	23 (32)
Regional		64 (58)	45 (63)
National		5 (5)	3 (4)
International/elite		3 (3)	1 (1)
Missing		4 (4)	3 (4)

"BMI = body mass index"; "h = hours"; "No. = number"; "SD = standard deviation"; "y = years".

Readability

The readability level was estimated at 71 which corresponds to a readability level of 11- to 12-year-old children.

Content validity

Target population

The interviews (n = 9) yielded 32 different codes, 28 as defined in the CCS and 4 extra codes to evaluate the relevance of each item (Supplementary file 1). In total, 127 times a code was applied; 54 times this was a relevance code and 73 times a code from the CCS (Table 2). Considering the relevance of the items, 92.3% (50/54) was considered relevant by the participants of which 69% (37/54) was evaluated as highly relevant; in three cases (5.6%) it was unclear whether the item was considered relevant and only once an item was indicated as not relevant (1.9%). Over half of the applied codes from the CCS (45/73) were classified in the comprehension and communication category (Table 2). The items that were most often regarded as complex or vague were cutting and pivoting. Sometimes, participants struggled with the difference between endurance and duration. Furthermore, a few participants had difficulty estimating the frequency of the requested item. It should however be noted that some codes were applied multiple times on the same item in the same interview, due to persistent problems in comprehensibility and questions for further explanation in some of the interviews. This added to the high frequency of applied codes in the comprehension and communication category. The problem codes for each category of comprehension and communication are shown in Supplementary file 1.

Table 2. Problem codes found in the interviews.

Problem codes	**Frequency**
Classification Coding Scheme	73
1. Comprehension and Communication	45
2. Memory Retrieval	8
3. Judgment and Evaluation	10
4. Response Selection	6
5. Other	4
Relevance	54
1. Highly relevant	37
2. Somewhat relevant	13
3. Not relevant	1
4. Unclear	3
Total	127

Professionals

The 30 professionals consisted of 9 orthopaedic surgeons, 2 trauma surgeons, 1 sports physician, 13 residents and 5 physiotherapists. Figure 2 shows the relevance according to the professionals for each item with regard to the target population and construct. Item 5 and 6 were considered relevant by less than 85% of the professionals for both the target population and construct. Item 4, 7 and 8 also achieved a relevance score of less than 85% for the construct. The recall period of 1 month was considered "good" by 67% of the professionals, 20% found that the recall period was too long and 13% that it was too short. Almost half of all professionals suggested that additional items were necessary to measure physical activity. The most frequently suggested additional items were cycling to school (n = 4), other physical activities such as playing outside or physical education (n = 4) and injuries (n = 3).

Overall, content validity among the target population was considered good and among professionals acceptable for relevance of the target population but insufficient for relevance of the construct.

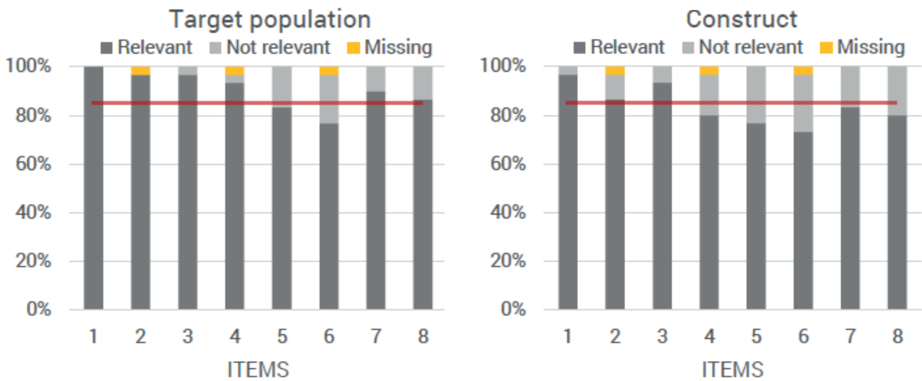

Figure 2. Relevance for the target population (left) and the construct (right) rated by professionals (n = 30).

Interpretability

Mean scores of the questionnaires assessed at baseline, together with floor and ceiling effects are presented in Table 3. HSS Pedi-FABS scores (mean score: 17.6 ± 6.2) were not normally distributed. The HSS Pedi-FABS, PAQ-C, PAQ-A and Tegner activity scale showed no floor or ceiling effect. The interpretability of the HSS Pedi-FABS was considered as good.

Table 3. Scores for each scale, floor and ceiling effects.

	Mean score ± SD	Range	Lowest score	Highest score
HSS Pedi-FABS (n=110)	17.6 ± 6.3	0 – 29	1%	0%
PAQ-C (n=42)	3.0 ± 0.5	1.8 – 4.3	0%	0%
PAQ-A (n=67)	2.6 ± 0.5	1.5 – 3.5	0%	0%
Tegner (n=108)	6.5 ± 2.3	1 – 10	3%	2%

"HSS Pedi-FABS = Hospital for Special Surgery Paediatric Functional Activity Brief scale"; PAQ-A/C = Physical Activity Questionnaire – Adolescents/Children"; "SD = standard deviation".

Construct validity

Spearman rank correlations were calculated to evaluate the predefined hypotheses for the construct validity, as shown in Table 4. Except for the PAQ-C and weekly participation in sports, the hypotheses regarding convergent validity were confirmed. Both hypotheses on discriminative validity were also confirmed. Furthermore, all correlations evaluating convergent validity were at least 0.1 higher than the correlation of age or BMI with the HSS Pedi-FABS. Eight out of the ten (80%) hypotheses were confirmed, indicating a good construct validity.

Reliability

Analysis of the internal consistency of the HSS Pedi-FABS in 110 children, resulted in a Cronbach's alpha of 0.82, indicating a good internal consistency. Of the 110 children that were included at baseline, 89 children responded at follow-up. For analysis, 14 children were excluded because of altered activity patterns and six children due to technical errors at T1. The mean interval between baseline and follow-up was 19 days ±7.2. The mean HSS Pedi-FABS score at follow-up (n = 69) was 17.7 ± 5.8. Test-retest reliability of the Dutch HSS Pedi-FABS was sufficient with ICC = 0.76 ($p < .001$). The SEM was calculated at 2.8 points and the SDC at 7.9 points, on a scale from 0 to 30.

Comparisons between the HSS Pedi-FABS versions

Several differences in psychometric properties were found between the original English, Italian and Dutch versions (Table 5). Compared to the English and Italian version, the Dutch HSS Pedi-FABS showed a lower, but acceptable, test-retest reliability [8,18]. Compared to the English and Italian HSS Pedi-FABS, the percentage of children scoring the lowest and highest possible scores, indicating floor- or ceiling effect, was lower [8,18].

Table 4. Spearman rank correlations for construct validity.

	HSS Pedi-FABS	Hypothesis confirmed?
Convergent validity (r ≥ 0.50)		
PAQ (n=109)	**0.500**	Yes
PAQ-C (n = 42)	0.105	No
PAQ-A (n = 67)	**0.588**	Yes
Tegner (n=108)	**0.666**	Yes
Weekly participation in sports	0.409	No
Competition level	**0.649**	Yes
Discriminative validity (r < 0.30)		
Age	**-0.017**	Yes
BMI	**-0.233**	Yes
Differences in correlations between convergent and discriminative validity (r>0.1)		
PAQ-C/A; Tegner; Weekly participation; Competition level *versus* Age	**All > 0.1**	Yes
PAQ-C/A; Tegner; Weekly participation; Competition level *versus* BMI	**All > 0.1**	Yes

"BMI = body mass index"; "HSS Pedi-FABS = Hospital for Special Surgery Paediatric Functional Activity Scale"; PAQ-A/C = Physical Activity Questionnaire – Adolescent/Children".

Table 5. Comparison between the original, Italian and Dutch HSS Pedi-FABS on psychometric properties, adapted from Macchiarola et al [18].

Psychometric property	Original English HSS Pedi-FABS [8]	Italian HSS Pedi-FABS [18]	Dutch HSS Pedi-FABS	Quality score*
Population	10-18 years Athletically active	8-16 years Affected by knee pathologies or deformities	10-18 years Healthy	N/A
Readability	13 years	-	11-12 years	N/A
Content validity	-	-	Target population: 92% of items considered as relevant Professionals: •Construct: <85% relevance •Target population: >85% relevance	Positive
Interpretability	Lowest score 0% Highest score 3.9%	Lowest score 19% Highest score 0%	Lowest score 1% Highest score 0%	Positive
Construct validity	Significant positive correlation with •Tegner •Marx •Noyes Sport/Functional •PAQ •Competition level •Current athletic activity •Athletic activity during peak season	Moderate-to-low correlation with Pedi-IKDC	Significant positive correlation with •PAQ (total) •PAQ-A •Tegner •Competition level	Positive
Reliability: Internal consistency	α = 0.91	α = 0.93	α = 0.82	Positive
Reliability: Test-retest reliability	ICC = 0.91	ICC = 0.94	ICC = 0.76	Positive
Reliability: SEM	-	SEM 2.1 SDC 5.8	SEM 2.8 SDC 7.9	N/A

*quality scores for the Dutch HSS Pedi-FABS according to Terwee et al [21].

"HSS Pedi-FABS = Hospital for Special Surgery Paediatric Functional Activity Scale"; "ICC = Intraclass Correlation Coefficient"; "N/A = Not Applicable"; "PAQ-A/C = Physical Activity Questionnaire – Adolescent/Children"; "SDC = Smallest Detectable Change"; "SEM = Standard Error of Measurement"; "-" stands for not assessed.

Discussion

The most important findings of this study are that the Dutch HSS Pedi-FABS has a good internal consistency, acceptable test-retest reliability, good construct validity and a positive interpretability rating in a Dutch population of healthy paediatric and adolescent participants.

Although the overall interpretation of the psychometric properties was similar, certain differences were found among the HSS Pedi-FABS versions, of which the test-retest reliability and floor and ceiling effects were the most important [8,18]. These differences may be caused by the differences in interval between T0 and T1, the inclusion criteria and population characteristics. For example, the differences in floor and ceiling effect could be caused by the differences in inclusion criteria [8,18]. The English HSS Pedi-FABS study included athletically active adolescents, the current study healthy children and adolescents and the Italian study children with knee pathologies [8,18]. Therefore, it might be expected that the mean score of the English HSS Pedi-FABS study is higher than the Dutch and the Italian, but also that the scores are distributed in the higher score ranges [8,18]. As the Italian study included children with knee pathologies, the mean score was lower and had a significant floor effect [18]. The mean score of the Dutch HSS Pedi-FABS was more similar to the mean score of the HSS Pedi-FABS in a study on normative data, although a higher floor effect was found in that study [16].

In contrast to the positive ratings on the outcomes of construct validity, interpretability and reliability, content validity showed different results. Content validity among the target population was considered to be good. However, content validity reported by professionals was acceptable for the relevance for the target population, but insufficient for the construct. The questionnaire did not reach 85% relevance on most items for the construct. Besides, 47% of the professionals suggested an additional item to measure physical activity. As multiple issues appeared already in the pre-final version during the pilot study among professionals, several transcultural adaptations were made to solve these issues and the original author was consulted. It was decided to maintain the original form and content of the HSS Pedi-FABS. No additional items were therefore added nor was the content changed.

Compared to other paediatric activity scales, the HSS Pedi-FABS has multiple advantages [8]. The HSS Pedi-FABS is a short and simple scale compared to other questionnaires, that potentially minimizes questionnaire fatigue and increases compliance [8]. Also, the HSS Pedi-FABS is a general measurement of physical activity and not specified on sports or joints, which provides a potential for broader application in clinical outcomes research [8,16]. In previous studies, the HSS Pedi-FABS has shown to capture changes in physical activity due to recent injury more likely than the Marx Activity Scale, to have more correlations with an athlete's participation in sports than the Tegner activity scale and to be reliable as patient reported outcome measure (PROM) captured electronically as on paper [33,34,35].

This study had certain limitations. Criterion validity could not be assessed, as there was no "gold standard" for questionnaires on physical activity [21]. Furthermore, a potential source of bias is the "proxy problem", as 39% of the children received help from parents in completing the questionnaire [36,37]. Self-reports of children are not equal to reports by proxy-respondents and a parents' report can therefore not be substituted for the child's report [36,37]. The readability level, however, was estimated to correspond to a readability level of 11- to 12-year-old children [25]. As children and adolescents aged 10 to 18 years were included, it seemed to be a rather high percentage of children receiving help from parents in completing the questionnaire. However, 73% of the children who received assistance were aged between 10 to 12 years and 20% were aged 13 and 14 years. The reasons and type of assistance received was not evaluated. For children who experienced problems in the comprehensibility and who were not able to complete the questionnaire properly, parental assistance might be desirable. This was also advised on the instruction form of the questionnaire. However, whether comprehensibility is the main cause is unknown. It is doubtful whether parental help was necessary for comprehensibility and whether this "proxy problem" might be a source of bias leading to limitations for future use [36,37]. Besides, most other psychometric properties are good. The current study however, included healthy children and adolescents without a condition or injury limiting their normal physical activity. As the PAMI (Paediatric Anterior cruciate ligament Monitoring Initiative) project focusses on anterior cruciate ligament injuries in children, the current Dutch version is not explicitly validated in that specific population and future research in that specific population is desirable to establish the psychometric properties of the HSS Pedi-FABS. However, previous studies have been conducted in children with knee complaints or pathologies for the English and Italian HSS Pedi-FABS and showed acceptable psychometric properties [18,33,35].

Conclusions

The Dutch HSS Pedi-FABS showed good psychometric properties in a healthy Dutch paediatric and adolescent population. Limitations of the current Dutch HSS Pedi-FABS are content validity on construct of items reported by professionals.

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Supplementary file 1 – Interviews

Problem codes found in the interviews.w
Frequency of codes that were applied to the transcribed interviews

Problem codes	Frequency	
6. Comprehension and Communication	45	
Interviewer Difficulties	*9*	
5. Inaccurate instruction		4
6. Complicated instruction		2
7. Difficult to administer		3
Question Content	*22*	
8. Vague topic/term		10
9. Complex topic		9
10. Topic carried over from earlier question		0
11. Undefined term(s)		3
Question Structure	*14*	
12. Transition needed		0
13. Unclear respondent instruction		8
14. Question too long		0
15. Complex, awkward syntax		0
16. Erroneous assumption		6
17. Several questions		0
Reference Period	*0*	
18. Carried over from earlier question		0
19. Undefined		0
20. Unanchored or rolling		0
7. Memory Retrieval	*8*	
21. Shortage of cues		8
22. High detail required or information unavailable		0
23. Long recall period		0
8. Judgment and Evaluation	*10*	
24. Complex estimation		10
25. Potentially sensitive or desirability bias		0

Problem codes	**Frequency**
9. Response Selection	6
Response Terminology	1
26. Undefined term(s)	1
27. Vague term(s)	0
Response Units	*0*
28. Responses use wrong units	0
29. Unclear what response options are	0
Response Structure	*5*
30. Overlapping categories	5
31. Missing categories	0
10. Other	4
32. Something else	4
11. Relevance	54
33. Highly relevant	37
34. Somewhat relevant	13
35. Not relevant	1
36. Unclear	3
Total	**127**

Chapter 8

Outcomes measures and (p)rehabilitation

Limited evidence for return to sport testing after ACL reconstruction in children and adolescents under 16 years: a scoping review

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Abstract

Purpose: Specific return to sport criteria for children and adolescents after anterior cruciate ligament injury and reconstruction are unknown. The aim of this scoping review is to provide an overview of current tests regarding return to sport for children and adolescents.

Methods: This scoping review was performed according to the PRISMA statement. A systematic search was performed on PubMed and EMBASE. The inclusion criteria were diagnostic and prognostic studies evaluating tests regarding return to sport after ACL injury and reconstruction in children/adolescents (age < 18 years).

Results: Twenty-six studies were included, of which 22 studies evaluated tests in the age category of 16 to 18 years. All studies evaluated tests after ACL reconstruction, no studies have been conducted in non-operative patients. Strength tests, movement quality and patient reported outcomes measures (PROMs) are investigated most frequently.

Conclusions: Clearance for return to sport should be based on a test battery including strength tests, movement quality during sport-specific tasks and (paediatric) patient reported outcome measures. There are no recommendations on which specific tests regarding quantity and quality of movement should be used. Future research should aim at developing and validating a test battery including movement quality and neuromotor control in a sport-specific context for both younger children and adolescents after both operative and non-operative treatment.

Introduction

Anterior cruciate ligament (ACL) ruptures in children and adolescents are considered to be a severe injury of the knee in a vulnerable population with high rates of secondary ruptures after ACL reconstruction [1]. There are two possible treatment options for children with an ACL rupture according to the International Olympic Committee (IOC): conservative high quality rehabilitation or surgical ACL reconstruction plus high quality rehabilitation [1,25]. The goal of either treatment regimen is to restore a stable, well-functioning knee, to reduce the risk of further meniscal or chondral injury and to successfully return to sport [1]. Successful return to sport can be defined as returning to the desired level of sport without sustaining a second ACL injury.

The IOC statement recommends using functional performance tests and return to sport criteria during rehabilitation [1]. The specific clinical and functional milestones described in the four-phased rehabilitation are based on the outcomes of a systematic review and practice guideline by Van Melick et al [40]. This systematic review, however, excluded skeletally immature children and it is therefore unknown if these milestones can be applied in the younger population [40].

The aim of this scoping review is to provide an overview of the current evidence of tests evaluating readiness for return to sport after ACL injury or ACL reconstruction in children and adolescents (age < 18 years). Based on the outcomes of this scoping review, the hiatus in the current evidence is shown and advice is given for future research.

Methods

This scoping review was performed following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement extension for scoping reviews [37]. The general purpose for inducting a scoping review is to identify and map the available evidence and not to produce a critically appraised and synthesised answer to a specific question [26].

Selection criteria

Articles included in the current scoping review had to meet the inclusion and exclusion criteria listed in Table 1.

Table 1. Overview of inclusion and exclusion criteria for this scoping review

	Inclusion criteria	Exclusion criteria
Participants	Children (average age < 18 years)	Average age ≥ 18 years
Injury	ACL rupture or reconstruction	ACL revision surgery
		Multi-ligament injury of the knee
		Fractures
Tests	Any test concerning return to sport, including:	
	• Strength tests	
	• Hop tests	
	• Movement quality tests	
	• Physical examination	
	• PROMs	
Outcomes	Diagnostic values (e.g.,sensitivity, specificity)	
	Prognostic information (e.g.,correlation coefficients, regression)	
Study design	Cross-sectional studies	
	Longitudinal studies	

Search strategy

At the 30th of March 2020, an information specialist (ED) performed a systematic literature search in PubMed (Medline) and EMBASE databases, as shown in Additional file 1. All published articles up to the 30th of March of 2020 were considered eligible. The following terms, including synonyms and closely related words, were used as index terms or free-text words: “anterior cruciate ligament injury”, “paediatric”, “adolescent” and “return to sport”. Studies written in other languages than English, Dutch and German were excluded. Duplicate articles were removed.

Study selection

Two researchers (MD, MB) independently screened the abstracts for eligibility by using the Rayyan QCRI app (rayyan.qrci.org) [28]. A full-text version of all eligible studies was reviewed. All references of these studies were screened for additional eligible articles. Any disagreements between the reviewers were resolved by discussion. Cohen’s kappa was calculated to measure inter-reviewer agreement in the selection process.

Data collection process

Two authors (MD, MB) extracted all relevant data. The data included specific details of the tests, population characteristics, interventions, study methods, follow-up period and outcomes of interest to the review question and research objectives. Any disagreements about the interpretation of the results were resolved by discussion. Due to the heterogeneity of the study designs and data and the aim of this scoping review, no risk of bias assessment was performed on the included studies.

Results

Search results

Twenty six studies were included in this scoping review (Figure 1). The inter-reviewer agreement was almost perfect with a Cohen's Kappa of 0.94. The 3 studies of conflict were resolved by discussion. All 26 studies are published in the last 10 years and 22 in the last 5 years.

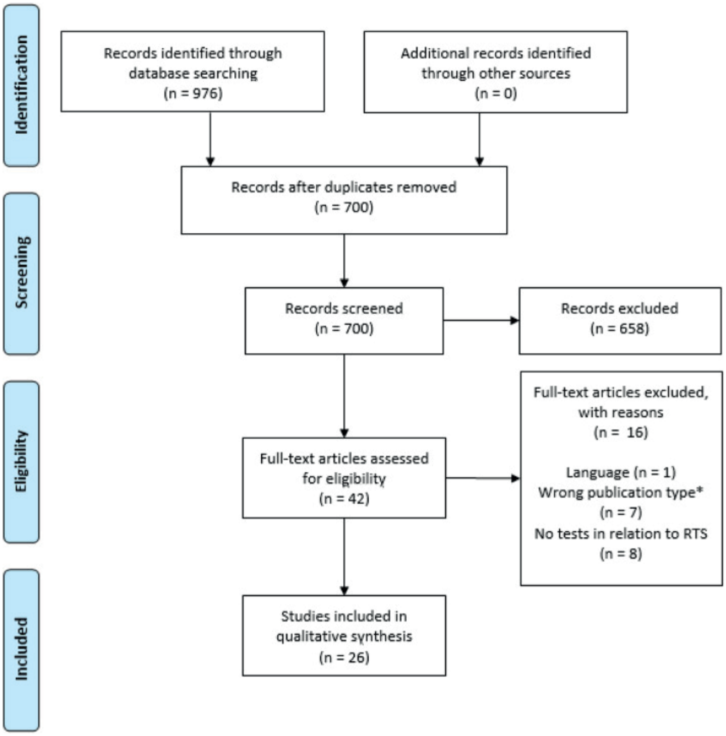

Figure 1. PRISMA flow diagram of inclusion process. *including abstracts of presentations

Study characteristics

Fifteen studies had a cross-sectional design [4,7,9,11,14,16,18,21,27,29,32, 34,35,43,44]. Eleven studies had a longitudinal design [3,10,12,19,20,22,23,30, 31,33,36]. Sixteen of the 26 included studies were from the same research group from Cincinnati Children's Hospital Medical Centre [11,14,18–22,27,30–33,35,36,44]. Ten of those sixteen studies reported to be part of a larger, prospective study on ACL reconstruction outcomes (ACL-RELAY study) [11,18–20,22,30,34–36,44].

Demographic characteristics

The exact number of included patients in this scoping review is difficult to estimate due to that some studies include participants from the same prospective study [11,18–20,22,30,34–36,44]. The range of included patients are 14 to 384 [10,29]. The number of patients for each study are shown in Additional file 2. The majority of the studies included participants of 16 to 18 years of age [4,7,10,11,14,16,18–23,27,29–36,44]. Six studies included children younger than 16 years of age [3,7,12,18,31,33]. Figure 2 shows the number of studies for each age category.

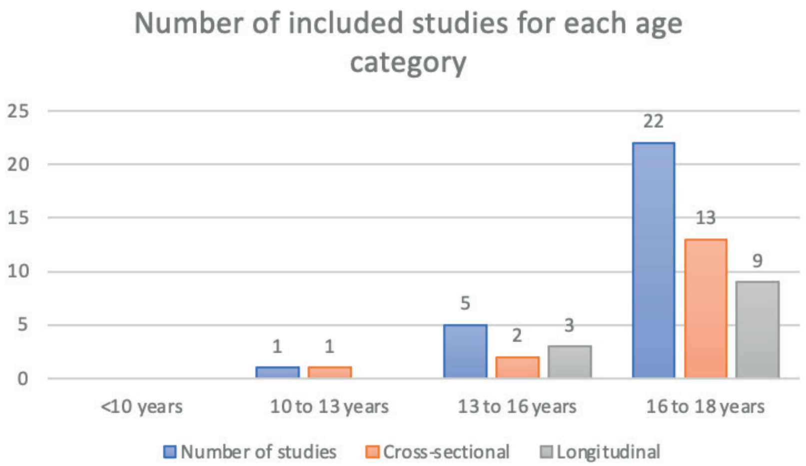

Figure 2. Number (n=26) of included studies for each mean age divided in categories. Two studies investigated two age categories which were presented seperately [7,18].

Surgical procedures

All studies investigated patients after ACL reconstruction (ACLR). No study regarding return to sport testing after non-operative treatment were available for inclusion. Four studies evaluated tests in children who had undergone a physeal sparing or transphyseal procedure, as is shown in Table 2 [3,7,12,18]. To reconstruct the ACL, a hamstring tendon autograft was used most frequently (n = 18), followed by patella tendon autograft (n = 16).

Table 2. Overview of studies providing data on modifications of ACLR due to open physes.

Studies	Procedure type
Astur [3]	Transphyseal
Boyle [7]	Transphyseal
Dekker [12]	Transphyseal, all-epiphyseal and partial-transphyseal
Ithurburn [18]	All-epiphyseal

Tests regarding return to sport

Muscle strength tests

Thirteen of the 26 studies investigated the outcomes of muscle strength tests in relation to outcomes regarding return to sport [4,9,11,14,16,18,19,21,22,29,34–36]. In Additional file 2, the different muscle strength tests are shown for each study in Table 1. In all 13 studies quadriceps strength was evaluated. Isometric quadriceps strength was evaluated in 8 studies [4,9,14,19,21,22,34,35]. Eight studies included isokinetic quadriceps strength tests [4,9,11,16,18,22,29,36]. Hamstring strength was also tested in 8 studies, of which 2 studies evaluated isometric hamstring strength [4,9] and 8 studies isokinetic hamstring strength [4,9,11,16,18,22,29,36]. Hip abduction strength was tested in 4 studies [11,14,16,22] and hip external rotation strength in one study [16]. Most studies evaluated the strength tests at return to sport (RTS) around 8 months post-ACLR. Six studies evaluated strength tests as a prognostic value for a variety of outcomes, such as movement quality outcomes, PROMs, re-ruptures and achieving RTS at follow up [9,19,21,22,29,36]. One study evaluated the prognostic value of strength tests for achieving RTS and one study for sustaining an ipsilateral re-rupture [9,29].

Hop tests

Four studies [4,18,36,43] evaluated hop tests in regard to RTS, of which two studies [18,36] tested Noyes' hop test battery -single hop for distance, triple hop for distance, crossover hop and 6-m timed hop. One study tested a single hop for distance [43]. One study analysed the hop test for distance, a vertical hop test and side hop test (see Additional file 2, Table 2) [4]. Testing occurred in two studies at RTS (around 8 months) and in one study before RTS (7 months). Toole et al. evaluated Noyes' hop test battery as a prognostic value for achieving combined test criterion cut-offs after 1 year follow-up post-RTS [36].

Movement quality

In 14 studies movement quality in relation to RTS was evaluated with a great variety of different parameters, as is shown in Additional file 2, Table 3 [7,10,11,14,16,20,21,27,29,31–34,43]. Eight studies tested different biomechanical variables during a landing task [14,16,20,21,27,33,34,43]. In 11 of the 14 studies, testing was done at RTS (approximately 7 months post-ACLR) [7,11,14,16,20,21,29,31–34]. Five studies evaluated movement quality as a prognostic factor after follow-up [10,20,29,31,33], of which four studies [10,29,31,33] investigated movement quality as a prognostic value for sustaining re-ruptures and one study [20] as prognostic factor for outcomes of PROMs and hop tests.

Patient reported outcome measures

PROMs in relation to RTS were evaluated in 10 studies, as is shown in Additional file 2, Table 4 [3,4,9,12,18,21,23,30,36,44]. The IKDC Subjective Knee Evaluation Form [21,36,44] and the ACL-RSI [4,9,23] are evaluated most frequently, followed by the Tegner Activity Scale [3,4]. Of the paediatric PROMs, the Pedi-IKDC is tested in one study [9]. Seven studies evaluated PROMs at the moment of RTS (approximately 8 months post-ACLR) [3,18,21,23,30,36,44]. Prognostic values of PROMs were investigated in 7 studies [3,9,12,21,23,30,36], of which 4 studies [3,12,23,30] tested the prognostic value of PROMs for developing a re-rupture, 2 studies [9,12] for achieving RTS and one study for meeting combined test criterion cut-offs [36].

Physical examination

Outcomes of joint laxity tests and range of motion of joints in regard to RTS were investigated in respectively three [7,22,33] and two studies [16,22], as shown in Additional file 2, Table 5. Laxity tests were performed with the KT-1000 arthrometer [7,22,33]. Two studies evaluated the prognostic values of laxity tests at the moment of RTS in relation to PROMs [22] and re-ruptures [33].

Test battery

Two studies tested the same test battery in relation to RTS, consisting of a combination of test criterion cut-off values of the IKDC, muscle strength LSI and hop tests LSI at RTS (see Additional file 2, Table 6) [18,36]. Ithurburn et al [18] analysed the proportions of participants meeting all RTS criterion cut-offs at RTS for each age category, while Toole et al [36] analysed whether those proportions maintained the same level of sport participation after 1 year follow-up post-RTS.

Return to sport clearance criteria

Seven studies included a definition of their RTS clearance criteria, including objective and subjective criteria [3,7,9,10,16,23,29]. All 7 studies used a combination of different tests to assess readiness for RTS. Table 3 provides an overview of tests for each study.

Table 3. Overview of tests used as RTS criteria. * including PROMs; ** including range of motion, effusion, laxity tests

Studies	Strength tests	Hop tests	Movement quality	Subjective outcomes*	Physical examination**	Time based
Astur [3]	X		X			
Boyle [7]	X		X	X	X	X
Burland [9]	X	X			X	
Capin [10]	X	X		X		
Hannon [16]	X		X		X	
McPherson [23]	X		X		X	
Palmieri-Smith [29]	X				X	

Discussion

The most important finding of this scoping review was that many studies have evaluated strength tests, hop tests, movement quality and PROMs regarding return to sport in adolescents after ACL reconstruction, but that only few studies have been conducted in children/adolescents under 16 years of age. There is currently sparse evidence for specific testing regarding return to sport in younger children. However, in the category of 16 to 18 years many studies have been conducted, both comparing different tests at the moment of RTS as well as evaluating prognostic values of tests with regard to ACL graft re-rupture, achieving return to pre-injury sport level or subjective outcomes [3,9,10,12,19,20,22,23,29–31,33,36].

Successful return to sport is context- and outcome-dependent and has a different meaning for different people (including the patient, clinician and coach) [2]. Criteria of clearance RTS exist in great variability and it should be noted that a true clearance is multifactorial and complex [8]. This was reflected by the variability of tests and outcomes described in the included studies, including strength tests, hop tests, movement quality, PROMs and physical examination.

The 2018 IOC consensus statement on paediatric ACL recommends return to sport clearance criteria, including a LSI > 90% for strength and single-leg hop tests for adolescents, psychological factors, knowledge and gradual increase in sport specific training without pain and effusion [1]. All of the included studies which presented their RTS clearance criteria, used a combination of tests to determine whether the child or adolescent was ready to return to sport [3,7,9,10,16,23,29]. All of those studies used strength tests as a criterium [3,7,9,10,16,23,29]. Subjective outcomes and hop tests are used in only 2 studies respectively [7,10]. One study used time as a criterium for RTS clearance, which is in contrast to the scoping review on RTS clearance after ACL reconstruction by Burgi et al [7,8]. They found that 85% of the studies used time as the primary criterion to clear athletes (no age limits defined) to RTS [8]. Children and adolescents are at a higher risk of a second ACL injury, especially in the first year after ACL reconstruction [1]. It is therefore recommended to advise the child not to return to pivoting sport within 12 months after ACL reconstruction [1]. The timing of RTS testing in the included studies was approximately 7.5 months after ACL reconstruction, which seems to be early in this population. However, it is not known whether the child was allowed to return to pivoting sport.

Thirteen of the 26 included studies evaluated the outcomes of strength tests regarding to return to sport [4,9,11,14,16,18,19,21,22,29,34–36], of which one study compared strength tests in paediatric patients (mean 12 years of age) versus adolescents (mean 16.5 years of age) [18]. Besides, one study tested muscle strength in adolescents between 12 and 16 years of age [9]. All other studies evaluated strength tests in adolescents older than 16 years of age, which may resemble adults [1]. It is recommended that in the younger patients (< 12 years) less emphasis should be on muscle strength and hypertrophy [1]. Pre-pubertal children may benefit from resistance training, but the trainability of muscle strength increases with age [6]. During puberty, boys show an accelerated increase in muscle strength and girls continue to develop in a similar rate as pre-puberty [6]. Despite these gender-related differences in trainability and outcome, only one study evaluated the differences between males and females [36].

The included studies showed a great variety of measurements regarding the quantity of movement, including isokinetic and isometric strength tests and different hop tests. However, the LSI is often used as an outcome to describe symmetry during strength tests or hop tests. Caution must be taken when interpreting an LSI in absence of an accurate baseline measurement, which includes muscle strength LSI as well as hop tests LSI [5,8,38,42,43]. A normal LSI does not exclude postoperative deterioration of the uninvolved leg [8]. The IOC therefore recommends to focus on the quality of the movements during a single-leg hop test, instead of LSI [1]. Movement quality is the most frequently evaluated test category in the included studies, but also with a great variety of tests and outcomes [7,10,11,14,16,20,21,27,29,31–34,43]. Landing variables are evaluated most frequently and are advised to use as movement quality measurement. As ACL injuries are common in pivoting sport, stricter cut-offs for strength tests are recommended in case of a return to pivoting sport [40]. Furthermore, specific movement quality tests and outcomes might be relevant in return to pivoting sport because of the loss of normal knee proprioception, such as single leg movement including cutting mechanics. Based on a recent systematic review, RTS testing should include asymmetry in loading experienced by each limb rather than the movement patterns alone, as asymmetries between the limbs were more commonly identified in kinetic variables than in kinematic variables [17].

Besides strength tests, hop tests and movement quality, subjective outcomes such as PROMs might have an important role in determining readiness for return to sport. They offer a more complete picture of the patient's perception on the actual recovery after ACL surgery [9]. Caution must be taken when interpreting PROMs scores in children and adolescents when adult PROMs are used in children instead of the specific paediatric PROMS due to problems in comprehensibility [13]. The Pedi-IKDC was described in one study, while the other studies used the (adult) IKDC and/or the KOOS [9,18,21,36,44]. Besides the IKDC and the KOOS, other PROMs are used and are not validated in children [9,13,30,39]. This in accordance with the infrequent use of paediatric-specific instruments as outcomes measures in paediatric ACL literature [15]. The ACL-RSI is validated from the age of 16 years [41]. Specific paediatric versions of adult PROMS have been developed and should be used in evaluating children with knee injuries [13,39]. One must note however, that in most of the included studies, the mean age is 17 years and that comprehensibility in that age category might not be a significant issue.

Limitations

The most important limitation of this review is that data from sixteen of the 26 included studies are from the same research group and ten of those sixteen are from the same prospective cohort study (ACL RELAY) [11,18–20,22,30,34–36,44]. It is therefore difficult to determine whether the same patients are evaluated in more than one study. It is important to note however, that these studies are published from a well-known high-quality American ACL research group and the use of measurements is based on their professional opinions and experiences. This adds to the value of the described tests in relation to return to sport.

Another important limitation of this study is that the majority of the included participants were older than 16 years of age and it may therefore be difficult to draw conclusions about return to sport criteria for younger children. This emphasizes the necessity to aim further research at younger children. Especially since the incidence of ACL injuries in this vulnerable group of is increasing [1].

Recommendations for day-to-day practice

Clearance for RTS is a complex and multifactorial issue. The following recommendations for measurements in relation to RTS are made based on the results of this scoping review and expert opinions of the authors. It is important that rehabilitation must be guided by clinical and functional milestones as described in the IOC statement and to advise the child not to return to pivoting sports within 12 months after ACL reconstruction [1]. Tests regarding RTS clearance for adolescents (16–18 years old) should include quadriceps and hamstrings strength tests, hop tests, movement quality assessment during sport specific tasks and PROMs, which might in this age category be disputable whether paediatric of adult PROMs can be used. In the age category 12–16 years, testing should include hop tests, movement quality and paediatric PROMs [24]. Strength tests in this age category are debatable as there is only sparse evidence of muscle strength tests and outcomes in this age category. In children younger than 12 years, there is currently very limited evidence and based on the physiological characteristics of this group, less emphasize should be on muscle strength and more on movement quality [1,24]. In this age category, only paediatric PROMs are recommended to evaluate subjective outcomes [13]. Furthermore, it is important in all age categories to compare the postoperative values with preoperative test outcomes and/or reference values to assess postoperative deterioration of muscle strength of the uninvolved limb. Normalized strength for body weight, compared to reference values, may also provide information about muscle strength [10].

Recommendations for further research

Future research should aim at validating specific tests in children after ACL injury and after ACL reconstruction. Validation includes measuring reliability, validity and responsiveness, as these variables are unknown of many RTS tests [8]. There should be more focus on the movement quality as a test for RTS clearance, as altered neuromuscular function and biomechanics could be a risk factor for a second ACL rupture [40]. Besides, there are individual differences in neuromotor learning capacity and flexibility, this underlines the importance of the shift from time-based rehabilitation to a patient-specific goal-based rehabilitation [40]. The aim should be to develop a test battery measuring clinical outcomes, strength tests, hop tests, movement quality and PROMs based on a goal-based rehabilitation in a sport-specific context [8,40]. As most of the studies evaluated tests in an adolescent population, we also recommend to aim future research at younger children (< 16 years of age) and to evaluate differences between the sexes. Since no studies have been conducted in non-operative patients, future research should also aim at this population. Tests regarding RTS after non-operative treatment may especially be relevant for skeletally immature children, as these children are often treated non-operatively [1].

Conclusions

Many studies on tests regarding RTS have been conducted among adolescents after ACL reconstruction, while there are only few studies evaluating tests among younger children. Strength tests, movement quality and PROMs are most frequently evaluated and are useful to determine readiness for return to sport. Further research should aim at younger children and at developing and validating a test battery including movement quality and neuromotor control in a sport-specific context in both operative and non-operative patients.

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Appendix 1 – search strategies

Search date: 30-3-2020

Databases: Pubmed and EMBASE

Results

	PUBMED	EMBASE	Total
	547	429	976
After removing duplicates	285	415	700

Search 30-03-2020

Database

Pubmed

- AND in builder
- OR in builder
- NOT in builder
- Delete from history
- Show search results
- Show search details

- AND in builder
- OR in builder
- NOT in builder
- Delete from history
- Show search results
- Show search details
- Save in My NCBI

- AND in builder
- OR in builder
- NOT in builder
- Show search results
- Save as a My NCBI Collection

Search	Query	Items found
#6	Search (#2 AND #3 AND #5)	547
#5	Search Return to Sport[Mesh] OR Return to Sport*[tiab] OR return to play[tiab] OR Return to Sporting Activit*[tiab] OR Resumption of Sporting Activit*[tiab] OR Sporting Activity Resumption*[tiab] OR Resumption of Recreational Activit*[tiab] OR recreational activities resumption*[tiab] OR Return to Recreational Activit*[tiab] OR timing of return[tiab] OR return to activ*[tiab] OR (time AND return)	39385
#3	Search child*[tw] OR schoolchild*[tw] OR infan*[tw] OR adolescen*[tw] OR pediatri*[tw] OR paediatr*[tw] OR neonat*[tw] OR boy[tw] OR boys[tw] OR boyhood[tw] OR girl[tw] OR girls[tw] OR girlhood[tw] OR youth[tw] OR youths[tw] OR baby[tw] OR babies[tw] OR toddler*[tw] OR teen[tw] OR teens[tw] OR teenager*[tw] OR newborn*[tw] OR postneonat*[tw] OR postnat*[tw] OR perinat*[tw] OR puberty[tw] OR preschool*[tw] OR suckling*[tw] OR picu[tw] OR nicu[tw] OR "Arthritis, Juvenile"[Mesh] OR "Myoclonic Epilepsy, Juvenile"[Mesh] OR "Leukemia, Myelomonocytic, Juvenile"[Mesh] OR "Xanthogranuloma, Juvenile"[Mesh] OR "Juvenile Delinquency"[Mesh] OR "Corneal Dystrophy, Juvenile Epithelial of Meesmann"[Mesh] OR "Young Adult"[Mesh] OR young adult*[tiab]	4722787

#2	Search Anterior Cruciate Ligament[Mesh] OR Anterior Cruciate Ligament Reconstruction[Mesh] OR Anterior Cruciate Ligament Injuries[Mesh] OR Anterior cruciate ligament*[tiab] OR anterior cranial cruciate ligament*[tiab] OR cranial cruciate ligament*[tiab] OR cruciate cranial ligament*[tiab] OR Bone-Patellar Tendon-Bone Grafting[tiab] OR ACL[tiab]	25383
	• AND in builder • OR in builder • NOT in builder • Delete from history • Show search results • Show search details • AND in builder • OR in builder • NOT in builder • Delete from history • Show search results • Show search details • Save in My NCBI • AND in builder • OR in builder • NOT in builder • Show search results • Save as a My NCBI Collection	
Embase	Database(s): **Embase** 1974 to 2020 Week 13 Search Strategy:	

#	Searches	Results
1	exp anterior cruciate ligament/ or exp anterior cruciate ligament reconstruction/ or exp anterior cruciate ligament injury/ or (anterior cruciate knee ligament* or anterior cruciate ligament* or anterior cranial cruciate ligament* or cranial cruciate ligament* or Bone-Patellar Tendon-Bone Grafting or ACL).ab,ti.	33171
2	exp *adolescence/ or exp *adolescent/ or exp *child/ or exp *childhood disease/ or exp *infant disease/ or exp young adult/ or (adolescen* or babies or baby or boy? or boyfriend or boyhood or girlfriend or girlhood or child or child* or child*3 or children* or girl? or infan* or juvenil* or juvenile* or kid? or minors or minors* or neonat* or neo-nat* or newborn* or new-born* or paediatric* or peadiatric* or pediatric* or perinat* or preschool* or puber* or pubescen* or school* or teen* or toddler? or underage? or under-age? or youth* or young adult*).ab,ti.	3988974
3	exp return to sport/ or (return to sport* or resumption to sport* or return to play* or return to sporting* or (tim* and return) or return to activ*). ab,ti.	54409
4	1 and 2 and 3	429

Appendix 2 – Overview of studies for each test category

Table 1. Overview of studies analysing muscle strength.

Muscle strength tests			**Beischer [4]**	**Burland [9]**	**Clagg [11]**	**Fryer [14]**	**Hannon [16]**
Quadriceps	Isometric		X	X		X	
	Isokinetic	60^0/s		X			X
		90^0/s	X				
		180^0/s		X	X		
		300^0/s		X			
Hamstrings	Isometric		X	X			
	Isokinetic	60^0/s		X			X
		90^0/s	X				
		180^0/s		X	X		
		300^0/s		X			
Hip abduction	Not specified						X
	Isokinetic	120^0/s			X	X	
Hip external rotation							X
Study data							
Number of patients (for each group as defined within the study)			384 8m 271 12m	34 RTS 16 not RTS	66 ACLR 47 C	130 ACLR 56 C	44 pass 4 fail
Timing tests (months after ACLR)			8-12	3-6	7 At RTS	8 At RTS	7 At RTS
As prognostic value for*			-	6	-	-	-
Follow-up			N/A	7m	N/A	N/A	N/A

ACLR = anterior cruciate ligament reconstruction; ACLx1 = single ACL injury; ACLx2 = double ACL injury; adol = adolescents; c = controls; m = months; HQ = high quadriceps; LQ = low quadriceps; N/A = not applicable; ped = pediatric; RTS = return to sport; y = years; y.a. = young adults.

* 1. Movement quality; 2. PROMs; 3. Hop tests; 4. Combined test criterion cut-offs; 5. Re-ruptures (only ipsilateral); 6. Achieving RTS.

	Ithurburn [18]	**Ithurburn [19]**	**Ithurburn [21]**	**Ithurburn [22]**	**Palmieri-Sm. [29]**	**Schmitt [34]**	**Schmitt [35]**	**Toole [36]**
		X	X	X		X	X	
					X			
	X			X				X
				X				
					X			
	X			X				X
				X				
				X				
	16 ped 113 adol 15 y.a.	36 HQ 36 LQ	52 HQ 41 LQ 47 C	67	7 ACLx1 7 ACLx2 7 C	37 HQ 31 LQ 47 C	55 ACLR 35 C	88 ♀ 27 ♂
	8.5 At RTS	8 At RTS	7-8 At RTS	8 At RTS	6-8 At RTS	8 At RTS	7 At RTS	8 At RTS
	-	2 & 3	1	2	5	-	-	4
	N/A	1y	N/A	2y	>3y	N/A	N/A	1y

Table 2. Overview of studies analysing hop tests.

Hop tests	Beischer [4]	Ithurburn [18]	Toole [36]	Wren [43]
Noyes' hop tests battery		X	X	
Single leg hop for maximal distance	X			X
Unilateral vertical hop	X			
Side hop	X			
Study data				
Number of patients (for each group as defined within the study)	384 (8m) 271 (12m)	16 (ped) 113 (adol) 15 (y.a.)	88 (♀) 27 (♂)	29 (SYM) 17 (ASYM) 24 (c)
Timing tests (months after ACLR)	8-12	8.5 At RTS	8 At RTS	7 Before RTS
As prognostic value for*	-	-	Test criterion cut-offs	-
Follow-up	N/A	N/A	1y	N/A

ACLR = anterior cruciate ligament reconstruction; adol = adolescent; ASYM = asymmetric; c = control; m = months; ped = pediatric; N/A = not applicable; RTS = return to sport; SYM = symmetric; y = years; y.a. = young adult.

Table 3. Overview of studies analysing movement quality.

Movement quality	**Boyle [7]**	**Capin 10]**	**Clagg [11]**	**Fryer [14]**	**Hannon [16]**	**Ithurburn [20]**	**Ithurburn [21]**	**Myer [27]**	**Palmieri-Smith [29]**	**Paterno [31]**	**Paterno [32]**	**Paterno [33]**	**Schmitt [34]**	**Wren [43]**
Landing variables														
General														
Peak vertical ground reaction force							X	X				X	X	X
Peak loading rate							X						X	
Postural														
Frontal Plane Trunk Excursion				X	X	X	X							
Pelvic tilt														X
Pelvic obliquity														X
Hip														
Flexion angle												X		X
Average flexion moment														X
Adduction angle												X		X
Rotation angle												X		X
Energy absorption														X
Knee														
Valgus angle					X									
Extension angle												X		
Peak internal extension moment						X	X						X	
Flexion angle														X
Flexion excursion					X	X	X						X	
Peak flexion													X	
Peak flexion moment													X	
Average flexion moment														X
Adduction angle												X		X

Table 3. Continued

Movement quality	**Boyle [7]**	**Capin 10]**	**Clagg [11]**	**Fryer [14]**	**Hannon [16]**	**Ithurburn [20]**	**Ithurburn [21]**	**Myer [27]**	**Palmieri-Smith [29]**	**Paterno [31]**	**Paterno [32]**	**Paterno [33]**	**Schmitt [34]**	**Wren [43]**
Average adduction moment														X
Internal rotation angle												X		
Energy absorption														X
Ankle														
Dorsiflexion angle														X
Average dorsiflexion moment														X
Energy absorption														X
Muscle (p) reactivity (EMG)														
Vastus lateralis									X					
Biceps femoris									X					
Lateral gastrocnemeus									X					
Gait pattern variables		X												
Peak knee flexion angle		X												
Peak knee adduction angle		X												
Peak internal knee extension moment		X												
Peak internal knee adduction moment		X												
Peak knee extensor muscle forces		X												
Knee flexor muscle forces at peak internal knee extension moment		X												
Peak knee flexor muscle forces		X												

Table 3. Continued

Movement quality	Boyle [7]	Capin 10]	Clagg [11]	Fryer [14]	Hannon [16]	Ithurburn [20]	Ithurburn [21]	Myer [27]	Palmieri-Smith [29]	Paterno [31]	Paterno [32]	Paterno [33]	Schmitt [34]	Wren [43]
Peak medial compartment tibiofemoral contact forces		X												
Balance tests and postural stability										X	X	X		
Star excursion balance test, distance reached			X											
Variability in ankle motion										X				
Variability in hip motion										X				
Postural coordination patterns between hip and ankle										X				
Postural sway in degrees											X	X		
Other														
FMS	X													
LQYB test	X													
Study data														
Number of patients (for each group as defined within the study)	17 SI 22 SM 16 ad	7 ACLx1 7 ACLx2	66 ACLR 47 C	130 ACLR 56 C	44 pass 4 fail	41†	52 HQ 41 LQ 47 C	33 ACLR 67 C	7 ACLx1 7 ACLx2 7 C	14 ACLx1 14 ACLX2	56 ACLR 42 C	43 ACLx1 13 ACLx2	37 HQ 31 LQ 47 C	29 SYM 17 ASYM 24 C
Timing tests (months after ACLR)	9 At RTS	5 Be-fore RTS	7 At RTS	8 At RTS	7 At RTS	7-8 At RTS	7-8 At RTS	10 Af-ter RTS	6 At RTS	8 At RTS	7 At RTS	? At RTS	8 At RTS	7 Be-fore RTS
As prognostic value for*	-	3	-	-	-	1 & 2	-	-	3	3	-	3	-	-
Follow-up	N/A	2y	N/A	N/A	N/A	2y	N/A	N/A	>3y	1y	N/A	1y	N/A	N/A

ACLR = ACL reconstruction; ACLx1 = single ACL injury; ACLx2 = double ACL injury; ASYM = asymmetric; c = control; EMG = electromyography; FMS = Functional Movement Competency; HQ = high quadriceps; LQ = low quadriceps; LQYB = Lower Quarter Y-balance; m = months; N/A = not applicable; RTS = return to sport; SI = skeletally immature; SM = skeletally mature; SYM = symmetric; y= years. †divided in SYM and ASYM for each landing variable.

* 1. PROMs; 2. Hop tests; 3. Re-ruptures (only ipsilateral [29], ipsi- and contralateral [10, 31, 33])

Table 4. Overview of studies analysing patient reported outcome measures (PROMs)

PROMs	Astur [3]	Beischer [4]	Burland [9]	Dekker [12]	Ithurburn [18]	Ithurburn [21]	McPherson [23]	Paterno [30]	Toole [36]	Zwolski [44]
IKDC					X				X	X
KOOS						X				
Pedi-IKDC			X							
Lysholm	X									
K-SES		X								
ACL-RSI		X	X				X			
Tegner	X	X								
Marx Activity Scale				X						
TSK								X		
Study data										
Number of patients (for each group as defined within the study)	34 ACLx1 18 ACLx2	384 8m 271 12m	34 RTS 16 not RTS	58 ACLx1 27 ACLx2	16 ped 113 adol 15 y.a.	52 HQ 41 LQ 47 C	103 ACLx1† 29 ACLx2†	19 high fear 21 low fear	88 ♀ 27 ♂	68 high IKDC 71 low IKDC
Timing tests (months after ACLR)	7.5 At RTS	8-12	3-6	? At latest follow-up	8.5 At RTS	7-8 At RTS	12 At RTS	8 At RTS	8 At RTS	8 At RTS
As prognostic value for*	3	-	4	3 & 4	-	1	3	3	2	-
Follow-up	2y	N/A	7m	2y	N/A	N/A	2-4y	2y	1y	N/A

ACLR = anterior cruciate ligament reconstruction; ACL-RSI = ACL Return to Sport after Injury; ACLx1 = single ACL injury; ACLx2 = double ACL injury; adol = adolescent; c = control; HQ = high quadriceps; (Pedi-) IKDC = (Pediatric) International Knee Documentation Committee; K-SES = Knee Self Efficacy Scale; KOOS = Knee injury and Osteo-arthritis Outcome Score; LQ = low quadriceps; m = months; N/A = not applicable; ped = pediatric; RTS = return to sport; TSK = Tampa Scale for Kinesiophobia; y = years; y.a. = young adult.

† within population < 20 years of age

* 1. Movement Quality; 2. Combined test criterion cut-offs; 3. Re-ruptures (only ipsilateral [3], ipsi- and contralateral [12, 23, 30]); 4. Achieving RTS.

Table 5. Overview of studies analysing physical examination.

Physical examination	Boyle [7]	Hannon [16]	Ithurburn [22]	Paterno [33]
Laxity tests				
KT-1000	X		X	X
Range of motion				
Knee		X	X	
Hip		X		
Ankle		X		
Other				
Knee joint effusion			X	
Study data				
Number of patients (for each group as defined within the study)	17 SI 22 SM 16 adult	44 pass 4 fail	67	43 ACLx1 13 ACLx2
Timing tests (months after ACLR)	9 At RTS	7 At RTS	8 At RTS	? At RTS
As prognostic value for*	-	-	1	2
Follow-up	N/A	N/A	2y	1y

ACLR = anterior cruciate ligament reconstruction; ACLx1 = single ACL injury; ACLx2 = double ACL injury; KT-1000 = Knee laxity Testing device; m = months; N/A = not applicable; RTS = return to sport; SI = skeletally immature; SM = skeletally mature; y = years.

* 1. PROMs; 2. Re-ruptures (ipsi- and contralateral).

Table 6. Overview of studies analysing test batteries.

Test battery	Ithurburn [18]	Toole [36]
Combination test criterion cut-offs	X	X
Muscle strength LSI ≥90%	X	X
IKDC score ≥90	X	X
Hop tests LSI ≥90%	X	X
Study data		
Number of patients (for each group as defined within the study)	16 ped 113 adol 15 y.a.	88 ♀ 27 ♂
Timing tests (months after ACLR)	8.5 At RTS	8 At RTS
As prognostic value for	-	Maintaining sport level
Follow-up	N/A	1y

ACLR = anterior cruciate ligament reconstruction; adol = adolescent; IKDC = International Knee Documentation Committee; LSI = limb symmetry index; m = months; N/A = not applicable; ped = pediatric; RTS = return to sport; y = years; y.a. = young adult.

Chapter 9

Outcomes measures and (p)rehabilitation

Anterior cruciate ligament rehabilitation for the 10 to 18 year old adolescent athlete: practice guidelines based on International Delphi Consensus

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In review at JOSM

Abstract

Background: For adolescent athletes with anterior cruciate ligament (ACL) injury, there are two treatment options: high-quality rehabilitation alone (non-surgical treatment) or ACL reconstruction plus high-quality rehabilitation. However, there is no clear content description of this high-quality rehabilitation for adolescent ACL athletes. Using an International Delphi consensus, we aimed to develop a practice guideline for adolescent ACL rehabilitation which can be used in day-to-day practice.

Methods: A three-round online International Delphi consensus study was conducted. A mix of open and closed literature-based statements were formulated and sent out to twenty International ACL rehabilitation experts. Consensus was reached at 70% agreement between experts. Statements were divided into three domains: non-surgical rehabilitation, prehabilitation, and postoperative rehabilitation.

Results: Experts reached consensus on rehabilitation being different for 10 to 16-year-olds compared to 17 and 18-year-olds with a need to distinguish between prepubertal athletes and mid-postpubertal athletes.

Experts reached consensus on the following topics: educational topics during rehabilitation, psychological interventions during rehabilitation, additional consultation of the orthopaedic surgeon, duration of postoperative rehabilitation, exercises during phase 1 of non-surgical and postoperative rehabilitation, criteria to progress from phase 1 to phase 2, resistance training during phase 2, jumping exercises during phase 2, criteria to progress from phase 2 to phase 3, and criteria to return to sport. The most notable differences between prepubertal and mid-postpubertal athletes are described for resistance training and return to sport criteria.

Conclusions: A rigorous consensus method led to key recommendations for adolescent ACL rehabilitation. Together with available evidence this formed a practice guideline for non-surgical rehabilitation, prehabilitation and postoperative rehabilitation. This is an important step toward reducing practice inconsistencies, closing the evidence-practice gap, and improving quality of rehabilitation after adolescent ACL injury.

Introduction

Anterior cruciate ligament (ACL) ruptures are one of the most severe knee injuries in children and adolescents [1]. Unfortunately, the incidence of primary rupture rates is increasing. Between 2004 and 2014, the annual incidence of ACL ruptures increased twofold to 31.5 per 100,000 person years in 13 to 17 year old Finnish girls and boys [1,16]. Also, secondary rupture rates are up to 2.7 times higher than in adults [1,5]. According to the International Olympic Committee (IOC) there are two possible treatment options for children and adolescents with ACL rupture: high quality rehabilitation alone (non-surgical treatment) or surgical ACL reconstruction (ACLR) plus high quality rehabilitation [1,10]. The goals of either treatment regimen are to restore a stable, well-functioning knee, to reduce the impact of existing or the risk of further meniscal or chondral injury and to minimize the risk of growth disturbances [1].

The IOC statement recommends the use of a multi stage criteria-based rehabilitation: three supervised rehabilitation phases plus a fourth phase being ongoing injury prevention [1]. In a supplement to the IOC statement some specific exercises to perform during all three rehabilitation phases are described, but a clear description of the content of this high-quality rehabilitation is lacking [1]. In addition, the specific functional performance tests used as criteria to progress from one phase to another or to return to sport (RTS) are extracted from a systematic review and practice guideline which described rehabilitation for athletes aged 16 years or older [15]. A recent scoping review on RTS criteria after ACL injury or reconstruction for children and adolescents concluded that many studies used “adult” RTS tests in the adolescent population, while it is unknown if these tests are valid in this younger population [6]. As a result, the day-to-day practitioner will still be uncertain how to rehabilitate and when to allow RTS for adolescent athletes following ACL injury or ACLR.

Due to the lack of strong evidence concerning adolescent ACL rehabilitation, we decided to create an International expert panel and use a Delphi consensus to fill in the gaps in the currently available rehabilitation protocols. Therefore, the main aim of this study is to create a practice guideline for adolescent ACL rehabilitation, which can be used in day-to-day practice.

Consensus methods

Terminology

During the Delphi process we chose to use the term “adolescent” instead of “paediatric” or “child”. This is because the World Health Organisation states the following: children are 2 to 9 years old, adolescents are 10 to 18 years old, and (young) adults are aged 19 years and older [17]. “Paediatric” is a collective term for children and adolescents and should therefore, in our opinion, be avoided when referring to specific age groups [17].

We were aware of the fact that the adolescent age group considers athletes at different physical developmental stages. Instead of using the definitions “skeletally immature” and “skeletally mature”, which are terms based on radiological findings that could be important when deciding to operate or not, we chose to use prepubertal (Tanner stage 1), midpubertal (Tanner stage 2-3) and postpubertal (Tanner 4-5) to differentiate between stages of physical development [8,9]. Self-rated Tanner staging (both by the adolescents or their parents) has been shown to have a good association with the onset of puberty (Tanner stage 1 versus Tanner stage 2-5). In this way, self-rated Tanner staging is easy to use in day-to-day practice for every physical therapist [2].

Delphi consensus topics

Based on recent literature covering rehabilitation of adults and adolescents following ACL injury or ACLR, we defined three rehabilitation domains: non-surgical rehabilitation, prehabilitation, and postoperative rehabilitation [1,6,15].

Although sport level and concomitant injuries could also influence these domains (in terms of minimum duration and specific exercises), our goal was to develop a rehabilitation framework for the recreational adolescent ACL patient, active in cutting or pivoting sports before injury, with no concomitant injuries or procedures which could influence rehabilitation protocol duration. Elite athletes and athletes with concomitant injuries which influence rehabilitation duration fall out of this framework and probably need a more experienced clinician to guide rehabilitation.

International Delphi expert panel

Experts could only participate in this Delphi consensus study if they were rehabilitating adolescent ACL athletes on a regular basis. Experts were contacted by e-mail in January 2021 and invited to participate in a three-round online Delphi consensus. Twenty International experts agreed to participate. Experts’ characteristics are listed in Table 1.

Table 1. Characteristics of International Delphi expert panel (n=20).

Profession, *n*	
(sports) physical therapist	9
(sports) physical therapist and junior researcher	6
(sports) physical therapist and post-doc researcher	5
Work location, *n*	
Africa	0
Asia	1
Europe	6
North America	8
Oceania	3
South America	0
Years of work experience with adolescent ACL athletes, *median (range)*	15 (7-30)
Average annual number of adolescent ACL athletes, *median (range)*	20 (3-150)

Delphi procedure

A mix of open and closed literature-based questions regarding rehabilitation and return to sport in adolescent ACL athletes were formulated and sent out to the international ACL rehabilitation experts. The first Delphi round aimed at developing a rehabilitation framework. Second and third Delphi rounds were used to ask more in-depth questions about training parameters in different rehabilitation phases. Consensus was reached at 70% agreement [14].

Results

Rehabilitation dependent on age and physical development

All experts agreed to use the 2018 IOC statement [1] and the 2016 ACL practice guideline [15] as the starting point for this Delphi consensus process.

Regarding patient age and stage of physical developmental, adolescent ACL patients could be divided into different groups, which differ in rehabilitation protocol and RTS criteria (Figure 1). Two age groups were used when describing high quality rehabilitation in detail: 10 to 16-year-olds versus 17 and 18-year-olds.

Within the 10 to 16-year-olds, it is important to distinguish between pre-, mid- and postpubertal athletes. These phases are directly related to hormonal production and their influence on the ability to adapt to resistance training. Changes in blood concentrations of sex hormones might play a key role in the observed differences in strength gains between immature and mature individuals. If so, one would expect trainability to increase significantly with the onset of puberty due to the sudden increases in sex hormones during that time [4]. The increase in hormones will give boys a boost through strengthening, while girls may add fat mass during puberty, which reduces strength relative to body weight. Strength gains in prepubertal athletes will be slower and mainly due to an increase in the number of motor neurons that are recruited with each contraction, while in mid/postpubertal athletes strength gains are more likely associated with muscle hypertrophy [12]. Therefore, the experts reached consensus (80%) about midpubertal athletes being treated similar to postpubertal athletes regarding resistance training. Only prepubertal athletes need to be treated differently. These differences will be outlined below when describing rehabilitation in detail.

The experts reached consensus (95%) regarding 17 and 18-year-old adolescents being treated according to an "adult" rehabilitation protocol as defined in the 2016 ACL practice guideline [15]. However, some details differ between 17 and 18-years-olds and adults.

Firstly, it would be ideal to consider the biological age of 17 and 18-year-old athletes, since hormonal response to training could be limited if they are not mid- or postpubertal (85% consensus). In day-to-day practice, this would only be considered if the adolescent is not responding to resistance training as expected.

Secondly, additional attention needs to be paid to social support from parents and/ or coaches (90% consensus).

Thirdly, concerning postoperative ACL rehabilitation, consensus was reached (95%) for RTS progression in two steps. ACL patients aged 17 to 18 years are allowed to return to sport (full training) after nine months, but only when they are able to meet (adult) RTS criteria. From 9 to 12 months postoperatively, patients will progress their independence towards preinjury sport. These guidelines and treatment recommendations always need to be individualized to the patient.

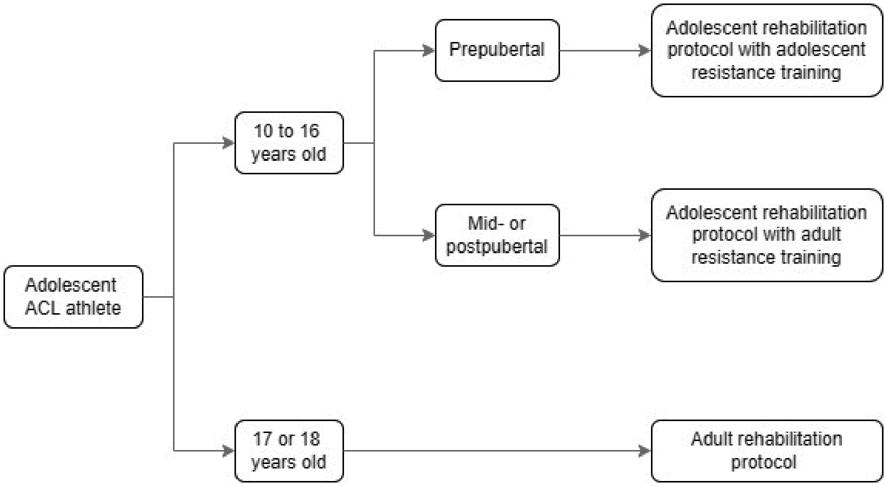

Figure 1. Age and physical development-dependent rehabilitation for adolescent ACL athletes.

Educational topics during rehabilitation

Education of both patients and parents is important during every rehabilitation domain, both for 10 to 16-year-olds and 17 and 18-year-olds. All topics that reached consensus are listed in Table 2.

Table 2. Educational topics during non-surgical rehabilitation, prehabilitation or postoperative rehabilitation with >70% consensus.

Educational topic	Domains
Patient and parent expectations	NON, PRE, POST
Key stakeholders during the rehabilitation process	NON, PRE, POST
School requirements and social activity expectations within the first several weeks of rehabilitation	NON, PRE, POST
A short overview of the rehabilitation period	NON, PRE, POST
Variability in recovery between athletes	NON, PRE, POST
Knee symptoms and when to visit a physiotherapist or surgeon	NON, POST
Long-term knee health and appropriate activities safe for current level of function	NON, POST
Injury prevention	NON, POST
Realistic minimum RTS targets	NON, POST
Realistic minimum RTS times	NON, POST
Risks and benefits of non-surgical rehabilitation	NON
Details of surgery	PRE
Details of first postoperative week, including use of crutches, transfers and home management, and first postoperative exercises	PRE
Details of further postoperative rehabilitation	PRE

NON=non-surgical rehabilitation; POST=postoperative rehabilitation; PRE=prehabilitation

Psychological interventions during rehabilitation

For all adolescent ACL athletes, psychological interventions are also an important part of rehabilitation. Short-term goal setting (100%) and graded exposure (75%) reached consensus. Other psychological treatment regimens were used by less than 70% of experts.

Additional consultation of the orthopaedic surgeon

Besides pre-arranged outpatient appointments with the orthopaedic surgeon, there could be a few important reasons to schedule an additional consultation during the rehabilitation process. These reasons are divided into four main topics: concern for serious medical complications, concern for motion complications, concern for re-injuries, and concern for failure to progress. All reasons that reached consensus are mentioned in Table 3.

Table 3. Reasons (with >70% consensus) to schedule additional outpatient consultations with the orthopaedic surgeon during the rehabilitation process.

Topic	Reason	Domain
Concern for serious medical complications	Issues with wound healing or potential infection	POST
	Suspicion of deep vein thrombosis	POST
Concern for motion complications	Persistent passive knee extension deficit beyond 6 weeks (indicative of arthrofibrosis)	POST
	Worsening passive knee extension deficit with anterior knee pain if forced (indicative of cyclops lesion)	POST
Concern for re-injuries	New trauma, recurrence of giving way and/or positive Lachman or pivot shift test (indicative of graft failure)	POST
	Knee locking (indicative of meniscal or chondral defects)	POST
Concern for failure to progress	Persistent effusion, despite appropriate rehabilitation	NON, PRE, POST
	Prolonged (postoperative) pain interfering with rehabilitation	NON, POST

NON=non-surgical rehabilitation; POST=postoperative rehabilitation; PRE=prehabilitation

In-depth description of rehabilitation domains for 10 to 16-year-olds

Both non-surgical and postoperative rehabilitation are similar in many ways. Therefore, we decided to describe these domains together. It will be explicitly stated if specific exercises are different between those domains. Prehabilitation is described separately. However, depending on time spent in prehabilitation, phases and exercises from non-surgical rehabilitation could be copied to this domain. An overview of treatment domains with important moments of decision is illustrated in Figure 2 at the end of this paragraph.

Prehabilitation

Duration of prehabilitation

The experts did not reach consensus on the duration of prehabilitation. Twelve experts (60%) stated that time is not important, but only meeting criteria is. The other eight experts argued that meeting criteria is important as well, but aimed for a minimum duration of 3-6 weeks (25%), 6-8 weeks (10%) and 12 weeks (5%).

Criteria for surgery

A minimum set of criteria an athlete should meet before undergoing ACLR are described in Table 4.

Table 4. Minimum set of criteria an adolescent ACL athlete should meet before undergoing surgery (percentage of consensus in parentheses).

Clinical signs	Neuromuscular control	Psychology
Trace to no effusion (95%)	Ability to control lower limb alignment during functional tasks (90%)	Emotional readiness for surgery and postoperative rehabilitation (80%)
Full range of motion, particularly extension, minor flexion loss (>95% compared to non-injured knee or 120° at minimum) is acceptable (100%)	Good quadriceps function, defined as straight leg raise (SLR) without lag and ability to control the knee during gait and single-leg stance (90%)	
Minimal to no pain (NPRS 2 at most) (80%)	Normal gait without crutches (90%)	

Non-surgical and postoperative rehabilitation

When describing non-surgical rehabilitation, two groups of athletes emerge. Firstly, those who try to avoid surgery completely and want to manage their ACL injury non-surgically. Their main goal is to return to their desired activities without any episodes of functional instability or additional knee injuries.

Secondly, those who are skeletally immature and would like to avoid surgery until they have reached skeletal maturity. This latter group would benefit from additional education regarding activity modification to avoid functional instability or recommendations for wearing a knee brace during pivoting activities [1]. This period of non-surgical rehabilitation would be comparable to an extended version of preoperative rehabilitation, as some will eventually undergo surgery.

Non-surgical rehabilitation should – like postoperative rehabilitation – consist of three criterion-based phases (85% consensus) with a fourth phase being continued injury prevention (95% consensus). The "11+ Kids" program is advised as a secondary prevention program with 75% consensus [3,11].

Duration of non-surgical and postoperative rehabilitation

The experts did not reach consensus regarding the duration of non-surgical rehabilitation. Eleven experts (55%) stated that time is not important, but only meeting criteria is. The other nine experts argued that meeting criteria is important as well, but aimed for a minimum duration of 3-4 months (10%), 6 months (25%) and 9 months (10%).

Postoperative adolescent ACL patients should only return to full group training when RTS criteria are met. At least four to six weeks of full group training are needed before returning to competition (85% consensus). Patients should not return to pivoting sport competition before 12 months after ACLR (75% consensus).

Phase 1 of non-surgical and postoperative rehabilitation

General principles of phase 1

The experts agreed (70% consensus) that prepubertal and mid-postpubertal athletes could be treated the same way in phase 1.

Exercises during phase 1

The IOC statement [1] already recommends the following exercises to be performed in phase 1: stationary bike, active extension (unloaded), quads setting, squat variations with and without support, single limb standing (with control of isometric terminal knee extension) and closed chain hip and pelvic control exercises. The experts reached consensus on additional exercises:

- Heel props or prone hangs when needed to reach full extension (95%)
- Straight leg raises (without extension lag) (85%)
- Prone hip extensions (75%)
- Side lying abductions (75%)
- Standing position pulley/theraband-resisted terminal knee extensions (70%)
- Heel raises (75%)
- Gait re-training (85%)

Prescribing any exercise depends on individual limitations in function.

Criteria to progress from phase 1 to phase 2

Table 5 lists all criteria that should be met before progressing from phase 1 to phase 2 during non-surgical or postoperative rehabilitation. The experts added two criteria to the pre-existing list of three criteria from the IOC statement [1]. These criteria to progress are the same for prepubertal or mid-postpubertal athletes.

Table 5. Minimum set of criteria a 10 to 16-year-old adolescent ACL athlete should meet before progressing from phase 1 to phase 2 during non-surgical or postoperative rehabilitation. (Percentage of consensus of two additional criteria in parentheses; the other three were in the IOC statement already).

Clinical signs	Neuromuscular control	Psychology
Trace to no effusion [1]	Ability to hold terminal knee extension during single-leg standing [1]	Emotionally ready to start phase 2 resistance training exercises (70%)
Full active extension and 120° of flexion [1]	Correct gait pattern without crutches (85%)	

Phase 2 of non-surgical and postoperative rehabilitation

General principles of phase 2

The experts reached consensus regarding the rehabilitation of adolescent athletes focusing more on neuromuscular training and movement quality (75%) compared to adult rehabilitation. Additionally, more parental involvement is needed in adolescents (80% consensus).

Resistance training during phase 2

All resistance exercises for both prepubertal and mid/postpubertal athletes recommended by the experts are listed Table 6.

Table 6. Resistance exercises recommended for both prepubertal and mid/postpubertal athletes (percentage of consensus in parentheses).

Quadriceps dominant exercises	Hamstring dominant exercises	Other
Double or single-leg knee extension variations (isometrics, isometrics against powerball, resistance from elastic bands or machine) (100%)	Double or single-leg bridge variations (isometrics, bent or straight knee, with powerball) (80%)	Hip abduction variations (side lying or standing, resistance from elastic band or pulley) (70%)
Double or single-leg leg press (80%)	Double or single-leg hamstring curl variations (prone lying or standing, with powerball, resistance from elastic bands or machine) (75%)	Double or single-leg straight knee calf raise variations (standing, jumping rope) (85%)
Double or single-leg squat variations (isometrics, mini squat, TRX assisted squat, Spanish squat, Bulgarian split squat, pistol squat) (95%)	Double or single-leg dead lift variations (Romanian, stiff-legged, hip hinge) (75%)	Double or single-leg bent knee calf raise variations (seated or standing) (80%)
Lunges in all directions (75%)		Trunk exercises (70%)
Hip thrust variations (75%)		
Combined exercises (e.g. squat to lunge, Romanian dead lift to step up) (85%)		

As stated earlier in this Delphi consensus, phase 2 is different for prepubertal athletes compared with mid-postpubertal athletes, especially due to the differences in hormonal response to resistance training.

The main focus during resistance training for prepubertal athletes is maintaining correct movement quality. Resistance training for prepubertal athletes could be progressed according to the following steps (95% consensus):

- Start with functional movements and an emphasis on technical development with correct movement quality (low load, 15-25 repetitions);
- Progress to resistance training (increase load, decrease repetitions to less than 12, rate of perceived exertion 7-9): combine body weight exercises (from double to single-leg, or combined exercises) and plyometric type exercises with fun and game-like elements (manipulating tempo, use ball throws or unstable surfaces).

Mid- postpubertal athletes are able to follow resistance training programs designed for adults (95% consensus). Such an adult program could be designed as follows:

- One or two exercises (quadriceps dominant, e.g. squat) with progression according to the size principle and reversed size principle.
- Other exercises with progression to 3-4 sets of 8-12 repetition maximum (RM), and only increases in weights thereafter.

Jumping exercises during phase 2

The experts reached consensus (80%) that hopping and jumping should be part of phase 2. To start jumping and running in phase 2, athletes should have equal ROM, no effusion and sufficient leg strength (Limb Symmetry Index (LSI) >70%) (85% consensus). There should always be a focus on correct movement quality during jumping. Progression for both prepubertal and mid-postpubertal athletes is recommended as follows (85% consensus):

- Partial weight bearing jumps or pre-jumping tasks as mini tramp marching (focus on neuromuscular control, gain confidence);
- Double-leg drop downs from a small height (to gain confidence in landing and encourage symmetrical loading);
- Double-leg vertical jumps (counter movement jumps, squat jumps, box jumps, tuck jumps, rope jumps);
- Double-leg horizontal jumps (broad jumps);

- Double-leg plyometric work;
- Change direction from forward and upward to backward, lateral, diagonal and rotational;
- Progress as above for double-to-single-leg jumps;
- Progress as above for single-leg jumps;
- Add variations and external challenges in terms of height (e.g. boxes, hurdles), pacing (athlete controlled timing to externally paced activities), speed, surface, sensory input (eyes open/eyes closed), perturbation (push by physical therapist or unanticipated location and direction), and cognitive load (external demands of attention, double tasks).

Criteria to progress from phase 2 to phase 3

Table 7 lists all criteria that should be met before progressing from phase 2 to phase 3 during non-surgical or postoperative rehabilitation. These were already prescribed by the IOC statement [1]. These criteria are the same for prepubertal or mid-postpubertal athletes.

Table 7. Minimum set of criteria a 10-16 year-old adolescent ACL athlete should meet before progressing from phase 2 to phase 3 during non-surgical or postoperative rehabilitation [1].

Clinical signs	Neuromuscular control
No effusion	Ability to jog for 10 minutes with good form and no subsequent effusion
Full range of motion	LSI >80% on single-leg sit-to-stand test (*prepubertal athletes only*) or isokinetic quadriceps and hamstrings strength (*mid-postpubertal athletes only*)
	LSI >80% on hop tests (*mid-postpubertal athletes only*)

LSI=Limb Symmetry Index

Phase 3 of non-surgical and postoperative rehabilitation

General principles of phase 3

The emphasis in phase 3 should be on return to training in a gradual progression from highly controlled to highly chaotic activity related tasks. This could be under supervision of a skilled physiotherapist or physical trainer, in consultation with a club trainer (85% consensus).

Prepubertal athletes should have more restrictions and supervision on the field than mid-postpubertal athletes, because they have limited capacity to appraise risk and differentiate between safe and unsafe situations (90% consensus). Also, progression of resistance training exercises remains different between prepubertal and mid-postpubertal athletes.

Criteria to return to sport

According to the experts (85% consensus) clearance for RTS should always be a shared-decision making process between patient, parents, physical therapist and orthopaedic surgeon. Table 8 highlights all RTS criteria.

Table 8. Minimum set of criteria a 10-16 year-old adolescent ACL athlete should meet before RTS clearance (percentage of consensus in parentheses).

Clinical signs	Neuromuscular control	Psychology
No functional instability episodes (95%)	LSI >95% on single-leg sit-to-stand test (*prepubertal athletes only*) (70%)	Confident in tasks that mimic their goal (75%)
No effusion (100%)	LSI >95% isokinetic quadriceps and hamstrings strength (*mid-postpubertal athletes only*) (85%)	Psychological readiness measured with ACL-RSI (*mid-postpubertal athletes only*) (85%)
Full range of motion (100%)	LSI >95% on hop test battery (*mid-postpubertal athletes only*) (80%)	
Pain-free in tasks that mimic their goal (95%)		
	Movement quality during video-taped single-leg hopping and jumping variations (70%)	
	Movement quality during video-taped field training (jumping, landing, accelerating, decelerating, cutting) (70%)	

ACL-RSI=Anterior Cruciate Ligament Return to Sport after Injury scale; LSI=Limb Symmetry Index

How to use this adolescent ACL rehabilitation practice guideline in day-to-day practice?

When an adolescent ACL athlete has their first appointment, it is important to know how to apply this practice guideline to that specific athlete. Most 17 and 18-year-old ACL athletes could be treated according to adult ACL practice guidelines [15], as seen in Figure 1. Consider a prolonged rehabilitation until 12 months for this age group. The treatment algorithm for 10 to 16-year old ACL athletes in Figure 2 could help in translating Delphi study results to day-to-day practice.

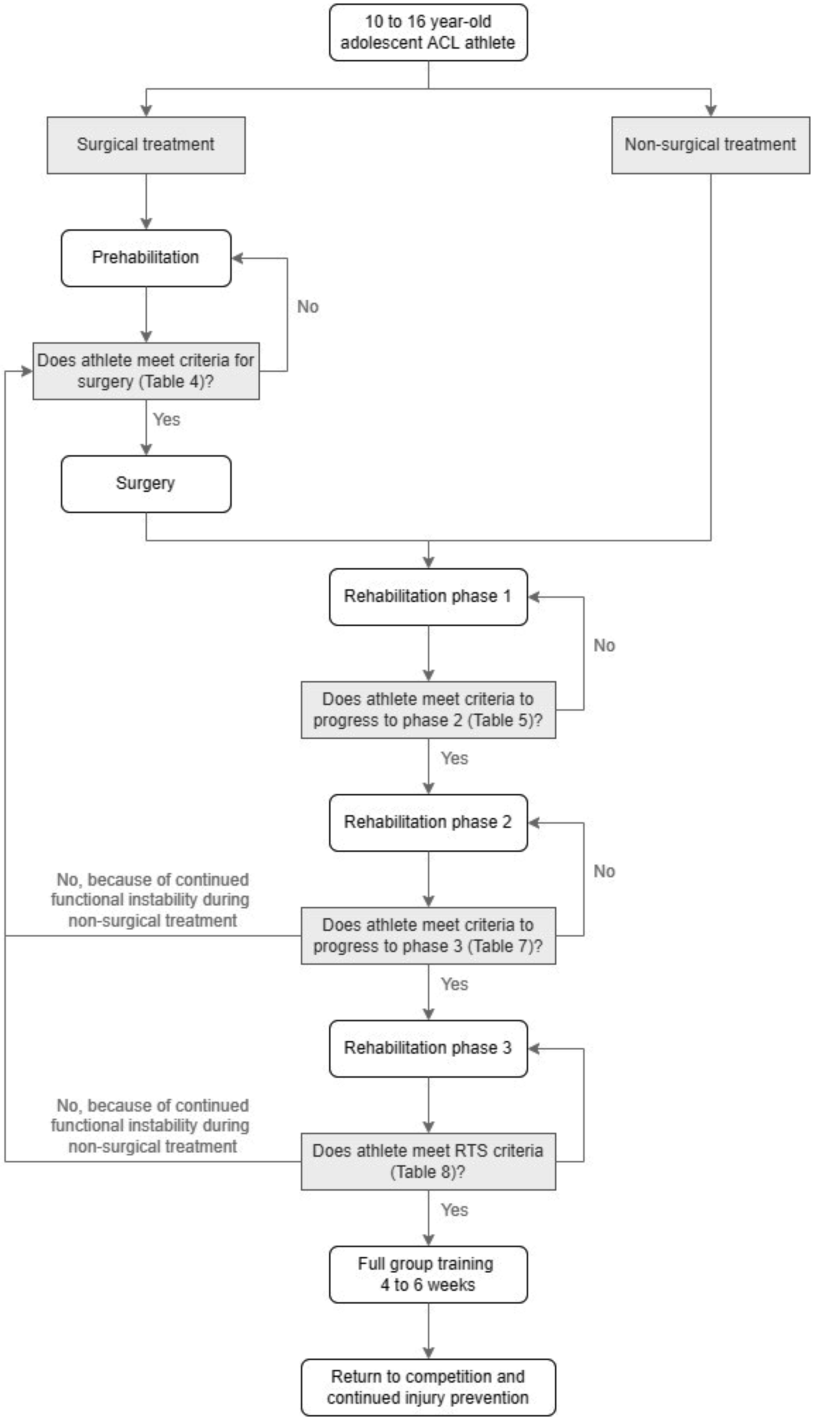

Figure 2. Treatment algorithm for 10 to 16 year-old adolescent ACL athletes.

Firstly, it is important to know if a treatment decision has already been made. Will the adolescent athlete have surgical treatment as soon as possible, opt for non-surgical treatment, or start with non-surgical treatment and proceed to surgical treatment when skeletally mature? If the treatment decision has not yet been made, physical therapists play an important role in objectively educating the patient and parents (see Table 2).

Secondly, as discussed with the expert panel a distinction should be made between 10 to 16-year-old and 17 and 18-year-old athletes. The latter could be treated according to adult rehabilitation guidelines [15], while 10 to 16-year-old athletes need an adapted adolescent rehabilitation protocol, which is described in this Delphi consensus practice guideline. The most important differences between adult and adolescent (10 to 16-year-old) rehabilitation are: more emphasis on neuromuscular training and movement quality for adolescents, more parental involvement for adolescents, and longer postoperative rehabilitation for adolescents (minimum of 12 months versus minimum of 9 months).

Thirdly, physical therapists should distinguish between prepubertal athletes and mid-postpubertal athletes, which can easily be done using the self-rated Tanner staging [2]. This is important since resistance training principles are dependent on these physical development stages. Also, criteria to progress during rehabilitation or criteria for RTS clearance differ between those groups. Prepubertal athletes should preferably not be measured with isokinetic strength tests or hop tests alone, as these tests require a change above 16-25% to represent a true change, thus possibly less useful in day-to-day practice [7]. Therefore, the expert panel chose to add a single-leg sit-to-stand test for these prepubertal athletes. This test has a high intertester reliability (ICC 0.960) and has a good negative correlation with hip and knee extensor strength (r=-0.72 and r=-0.711 respectively) in healthy young adults [13]. This single-leg sit-to-stand test is performed as follows:

- Use a chair (or treatment table) without arms and back rest, that could be adjusted in height to have 90 degrees of flexion at both the hip and knee;
- The test is performed barefooted, with the arms folded across the chest;
- The opposing limb has to be lifted just above the floor throughout the whole test. If this leg touches the floor, the test is invalid;
- Instruction: "Rise from the chair five times as fast as possible. Fully extend your hip and knee when standing and make firm contact with the chair when sitting." Start timing when the physical therapist says "go" and stop when the athlete sits on the chair for the fifth time;
- Perform two valid trials and register the fastest one for calculating an LSI.

Finally, the experts decided to use an LSI of above 95% on isokinetic strength tests, hop tests and the single-leg sit-to-stand test. A more strict criterion than applied to adults, where an LSI of above 90% is common. Predictive validity of both this LSI criterion and all RTS criteria has not been examined in adolescents yet, so we challenge the day-to-day practitioner to be critical and perform sound clinical reasoning when deciding to clear an adolescent ACL athlete to return to sports.

Conclusions

Rehabilitation of adolescent ACL athletes remains challenging due to lack of evidence-based guidance for treatment decisions. This International Delphi study fills in some of these gaps with expert consensus and describes a practice guideline for adolescent ACL rehabilitation, which can be used in day-to-day practice. This is an important step toward reducing practice inconsistencies, closing the evidence-practice gap, and improving quality of rehabilitation after adolescent ACL injury.

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Chapter 10

General discussion and valorisation

General discussion

This thesis aimed to enhance the evidence-based day-to-day clinical practice related to paediatric and adolescent ACL injuries. In my research I focussed on three main themes: (1) current state of care in the Netherlands, (2) diagnostics and predictors, and (3) outcome measures and rehabilitation. In this final chapter I provide practical conclusions and recommendations for daily practice based on this thesis. Furthermore, a discussion is added related to the following topics in the care pathway: diagnostic work-up, considerations for treatment decision-making and outcome measures during follow-up. At the end, future perspectives for research are given.

Practical conclusions and recommendations

Based on this thesis, several conclusions can be drawn and recommendations can be provided for daily practice in paediatric and adolescent ACL injuries in the Netherlands:

1. There is a great variability in treatment of ACL injured children and adolescents with open physes in the Netherlands. Many surgeons are consulted but only treat a few of these patients each year. In the Netherlands, physeal status is key in treatment decision making: skeletally immature patients are primarily treated non-operatively, while skeletally mature patients are treated operatively.

2. During history taking, the question whether the patient had a "popping sensation" during trauma is highly specific. It can therefore be used in primary care settings as well as an emergency department for screening ACL injuries and early referral to a specialised orthopaedic surgeon. Absence of a popping sensation does, however, not exclude an ACL injury and thorough examination of the knee is always essential. KT-1000 arthrometer is the most accurate diagnostic tool, but has to be interpreted with caution as age, gender and physiological development influence laxity of the knee.

3. Hamstring tendon lengths and closed-socket ACL reconstruction hamstring autografts types can be predicted based on preoperative body height. Based on body height and predictions of hamstring tendon lengths, preoperative graft planning for ligament reconstruction surgery is possible. ST tendon autograft was in 75% of the ACL reconstruction sufficient to create a graft with a diameter of 8mm or more. For the remaining 25%, which were mainly girls with shorter body height, STG tendon autograft was also sufficient to create a graft with a diameter of 8mm or more.

4. Morphometry of the lateral compartment of the knee did not identify diagnostic risk factors for re-injuries after ACL reconstruction. Steeper lateral tibial slopes (≥7°) are associated with re-injuries after ACL reconstruction. A steep tibial slope should therefore be taken into consideration before ACL reconstruction and in case of re-injuries after ACL reconstruction.

5. Many knee specific PROMs are available. For children and adolescents however, paediatric PROMs should be used due to potential problems of comprehensibility when using adult PROMs. For children and adolescents with ACL injuries, the Pedi-IKDC or KOOS-Child is recommended as knee specific PROM.

6. The HSS Pedi-FABS is available in Dutch as short and simple physical activity scale for children and adolescents. The questionnaire has good psychometric properties and can be used for daily practice and for (international) scientific research.

7. There is currently limited evidence for return to sport testing after ACL reconstruction in children and adolescents under 16 years. Based on the Delphi consensus statement, key recommendations were given for adolescent athletes with ACL injury. Together with available evidence, this Delphi consensus statement forms practical guidelines for non-surgical rehabilitation, prehabilitation and postoperative rehabilitation. This is an important step toward reducing practice variation, closing the evidence-practice gap, and improving the quality of rehabilitation after ACL injury.

In the following paragraphs, the diagnostic work-up, considerations for treatment decision-making and outcome measures during follow-up will be discussed.

Diagnostic work-up

Missed or delayed diagnosis and treatment of ACL injuries in children and adolescents increase the risk of -irreparable- meniscal lesion or chondral lesions [1-4]. Diagnosing ACL injuries in children is more difficult compared to adults [5, 6]. In order to timely and accurately diagnose an ACL injury in children and adolescents, history taking, physical examination and imaging are important [7]. Evidence on history taking and physical examination within ACL diagnostics in children and adolescents was low and limited to retrospective studies [6, 8-11].

History taking

History taking in children is different to history taking in adults and is age dependent [12]. In younger children, caregivers often provide information during history taking [12]. Older children and adolescents are more verbally proficient to discuss their complaints. But the specific details on the onset, location, duration and evolution of symptoms as well as previous treatment, might be difficult to elaborate upon for the paediatric patient [12]. History taking in ACL injured children and adolescents had not yet been studied. Do children and adolescents report the same symptoms as adults? Are they able to report a "popping sensation", posttraumatic effusion or instability of the knee? These questions and the lack of evidence of the diagnostic values of physical examination tests in this population, led to the initiation of the "Paediatric ACL Diagnostics (PAD)" study (**Chapter 3**) in which the diagnostic values of history taking, physical examination and KT-1000 arthrometer were evaluated [13]. The most important finding was that report of a popping sensation during trauma had a specificity and PPV of 100% [13]. This question may therefore be a valuable question for (early) referral of children and adolescents with posttraumatic knee complaints to an orthopaedic surgeon.

Absence of a popping sensation did not rule out an ACL injury [13]. Other factors, such as posttraumatic effusion of the knee and complaints of instability are factors to take into consideration as well [13]. The diagnostic values of these history taking items indicate that children and adolescents (sometimes with help of their caregivers) are able to discuss relevant details of complaints in ACL injured knees [13]. This might especially be helpful for primary health care professionals who rely more on history taking than on physical examination of the knee for diagnosis. For primary health care professionals, diagnosing ACL injuries in adults is challenging due to difficulty in performing and interpreting stability tests of the knee [14]. In children and adolescents, physical examination might be even more demanding, because of a greater physiological laxity, a lack of cooperation and relaxation during physical examination [5, 6].

Physical examination

Diagnostic values of clinical stability tests, such as Lachman, anterior drawer and pivot shift test, have extensively been studied in adults [7, 15]. Stability tests are important to assess the anterior-posterior stability, valgus and varus stability and rotational stability of the knee. The tests provide information on which ligaments are injured and whether the ligament is completely or partially injured [16, 17]. The diagnostic value of physical examination in ACL injured children and adolescents was limited to retrospective studies and not specified for stability tests [6, 8-11]. In the PAD study, the

Lachman test, anterior drawer test and pivot shift test were accurate when performed by an experienced orthopaedic surgeon [13]. The diagnostic values of the stability tests performed by less experienced orthopaedic surgeons or other health care professionals in this population are currently not known. Experience level is a factor that might affect the reproducibility of the physical examination tests [7, 14].

Instrumented tests, such as the KT-1000 arthrometer, were developed in order to have a less observer dependent and a more objective method to measure laxity of the knee as diagnostic tool [18-20]. Translations within the healthy knee in the KT-1000 arthrometer in children are different to healthy adults due to differences of physiological laxity [19]. The absolute translation of the tibia in the KT-1000 arthrometer should therefore be interpreted with the physiological joint laxity and age in mind [19]. The absolute translation in the KT-1000 arthrometer had the highest diagnostic values of all tests in diagnosing ACL injuries in children and adolescents however [13]. KT-1000 arthrometers are often used to measure leg-to-leg (relative) differences, which showed lower diagnostic values compared to the absolute translations in children [13]. For daily practice, both absolute and relative translations should be measured to gain more information on the physiological laxity of the knee in children and adolescents.

Imaging

Diagnosis of ACL injury is confirmed and concomitant injuries are diagnosed or excluded with a radiograph and an MRI of the knee, which are part of the standard diagnostic work-up [5]. This work-up should not be limited to injury diagnosis in case of skeletally immaturity. Skeletal age assessment is part of the diagnostic work-up and is essential for the choice of treatment, timing of surgery and the ACL reconstruction technique [5, 21, 22, 23]. An understanding and documentation of remaining growth and pre-existent deformities is crucial for postoperative analysis of angular deformities or leg length discrepancies [5]. In the NVA survey (**Chapter 2**), skeletal age assessment was not evaluated [23]. It is therefore unknown how many surgeons perform skeletal age analysis and which methods are used in the Netherlands. In the ESSKA survey, 53% of the respondents performed a systematic analysis (radiograph of the hand) of the skeletal age before deciding on surgical treatment [24]. The percentage of 53% is relatively low, as skeletal maturity is a relevant factor when deciding whether to operate or not [23].

Considerations for treatment decision-making

Non-operative treatment

Non-operative treatment, often referred to as high quality rehabilitation, is regarded to be a safe and viable treatment option in case of absent concomitant injuries and limited knee instability in children [5, 25] A prospective cohort study by Moksnes et al.[25] showed that ACL injured skeletally immature children remained physically active following a non-operative treatment algorithm and that even the majority of the non-operated children continued sports participation in level 1 (frequent pivoting and contact) sports [25]. After a two year follow-up, symmetrical knee function and low number (4%) of surgical procedures for new meniscal injuries were seen [25]. Based on this study, clinicians could more confidently be able to recommend a non-operative treatment algorithm to skeletally immature children with an ACL injury and their families [25].

In contrast, a recent systematic review showed that non-operative treatment resulted in high rates of residual knee instability, increased risk of meniscal tears and low rates of return to sports [26]. The authors also concluded that delaying an ACL reconstruction (ACLR) in children or adolescents for more than 12 weeks increased the risk of meniscal injuries and irreparable meniscal tears [26]. Patients with delayed ACLR had a higher numbers of secondary meniscal injuries compared to early ACLR patients [5, 27, 28]. Persistent instability also increases the risk of secondary meniscal injury [5, 29]. For whom is non-operative treatment then a safe treatment option as protecting knee integrity is the most important treatment goal?

The main problem in answering this question is that the level of evidence of studies is low, the heterogeneity among studies and rehabilitation protocols is high and outcomes are often not paediatric-specific or not assessed in detail [26, 30]. Based on the current literature, it is difficult to predict which child will respond to non-operative treatment and has low risks of developing secondary meniscal damage. Sports participation might be a factor to take into consideration. It is known that when young patients return to level 1 sports (frequent pivoting and contact sports, for example football and basketball) after ACLR, there is a relatively high risk of re-injury and additional damage [21, 31, 32]. Changing to level 2 sports (less pivoting and non-contact sports, for example tennis) might be a safer option for children to protect the integrity of the knee [31, 32]. This often occurs in non-operative treatment, as less patients return to level 1 sports compared to patients after ACLR [32]. This results in an obvious downside for the child: what does it mean for the child to not be able to participate in their favourite sports anymore, in which their friends participate? The consequences on quality of life, social interactions, general health and sports participation are depending on the individual patient, especially in children and adolescents who are developing through different life phases. It is known that ACL injured patients in general can suffer from symptoms of depression [33] and have a lower quality of life [34, 35]. Therefore, the IOC statement by Ardern et al. [5] recommended unacceptable restrictions in sports activities as an indication for ACLR in children and adolescents [5].

A knee brace is one of the solutions to provide stability, protect the knee and allow sports participation in non-operative treatment. The ESSKA and NVA surveys showed that many surgeons prescribe a brace in case of non-operative treatment [5, 23, 34]. The protective effect of a brace is currently not known for children and adolescent who are treated non-operatively. After ACLR in adolescents, one study showed that postoperative functional bracing can result in reduced risk of graft failure and no change in contralateral injury rates [37]. Additional studies on the effects of bracing on kinematics and kinetics after ACL reconstruction and on hamstring reflex times in ACL deficient knees, showed that limb asymmetries persisted when adolescent patients were wearing a functional knee brace [38] and that ACL deficient knees (in general) should not rely on knee braces to facilitate hamstring reflex for joint protection [39]. The question then remains whether the theoretically protective effect of a brace during non-operative treatment outweighs the potential differences in kinetics, kinematics and muscle reflexes compared to the uninjured leg on the long term. The effect of bracing in non-operative treatment is therefore an important subject for future research, in which both the positive and negative effects should be evaluated on the short and long term and in sport-specific contexts. Preliminary and unpublished data of the PAMI registry show promising results of children who are able to participate in level 1 pivoting sports (football) with a brace in non-operative treatment.

ACL reconstruction (ACLR)

ACLR in children and adolescents have higher rates of ipsilateral graft failure and contralateral ACL injuries compared to adults [5, 32, 40, 41]. Correct diagnostic work-up, risk assessment and ACLR technique planning and graft planning are necessary to optimise ACLR outcomes and prevent complications (Figure 1).

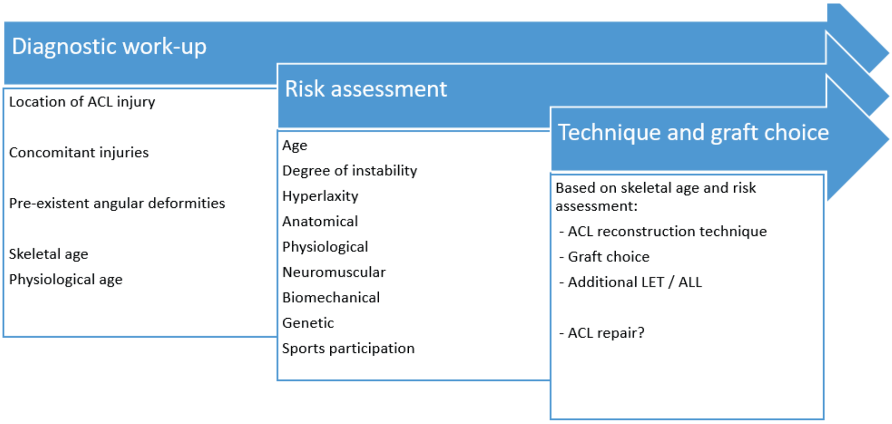

Figure 1. Overview of diagnostic work-up, risk assessment and ACL reconstruction planning. ACL = Anterior Cruciate Ligament; ALL = AnteroLateral Ligament; LET = Lateral Extra-articular Tenodesis

Risk assessment

Multiple risk factors for primary ACL injuries have been studied, which can be divided in extrinsic and intrinsic factors [42]. Examples of extrinsic factors are the type of sports and weather conditions during specific sports [42]. Intrinsic factors include anatomical, physiological, biomechanical, neuromuscular and genetic risk factors [42-48].

Graft failures after are likely to have a multifactorial cause [49, 50, 51]. It is known that graft failure is most often caused by a new trauma or by malposition of the femoral tunnel [50]. Some intrinsic risk factors for graft failure are non-modifiable, such as age, female sex and ligament hyperlaxity [51]. Other risk factors for re-injuries are modifiable, such as concomitant ligament injuries, graft diameter and type of sports participation [51]. Current evidence shows that several risk factors and patient characteristics should be taken into consideration prior to planning an ACLR: (skeletal) age, sports participation, anatomical morphology, degree of knee instability, general hyperlaxity, knee hyperextension and graft planning [5, 49, 52, 53, 54].

In children and adolescents, a few studies have been conducted on morphological risk factors for re-injuries after ACLR, mainly focusing on the lateral and medial tibial slope [55, 56, 57]. In adults, a broader perspective on anatomical tibiofemoral relations and morphometrics in relation to re-injuries have been proposed [58-62]. In **Chapter 5**, morphological, tibiofemoral parameters regarding the lateral compartment were evaluated as risk factor for graft failure and contralateral ACL injury after primary ACLR [63]. The parameters of interest were the tibial slope, meniscal bone angle, lateral femoral condyle index [59], length of the flat surface of the femur and the Porto ndex [58]. None of the parameters were identified as diagnostic valuable risk factor for graft failure or contralateral ACL injuries after ACLR [63]. The total re-injured population had a slightly steeper lateral tibial slope (5° versus 4°). Although the tibial slope was not a discriminative risk factor for re-injuries as a diagnostic value, a slope of ≥ 7° was associated with re-injuries [63]. That finding was in accordance with the study by Cooper et al. [55], who found that more extreme tibial slopes were associated with re-injuries in children and adolescents [55].

This raises the question whether more extreme tibial slopes should be corrected to prevent ACL re-injuries prior, during or after ACLR. In skeletally mature patients, this would require a proximal tibia osteotomy to correct the tibial slope [64, 65, 66]. In children with remaining growth, it might be possible to perform guided growth to correct tibial slope [67, 68]. Guided growth, or temporary partial epiphysiodesis, is a relatively minimal invasive treatment, compared to an osteotomy. To date, no studies have been published on this topic in humans. In dogs, proximal tibial epiphysiodesis was performed in cranial ligament deficient stifles [68]. This study showed that the partial proximal tibial fusion in dogs with ACL injuries was effective in reducing the tibial slope during the residual growing time leading to joint stabilisation [68]. Guided growth slope correction in patients with steep tibial slopes might therefore be effective in preventing re-injuries after ACLR or during ACL revision surgery.

In the preoperative risk assessment, risk factors for re-injury have to be evaluated in order to plan an operative procedure: the bony morphology, the degree of knee instability, general hyperlaxity and knee hyperextension [49, 52, 53, 54, 69, 70]. High degrees of pivot shift (rotational instability), for example, are associated with higher re-injury rates after ACLR. If the preoperative risk assessment shows a combination of risk factors - for example young age, steep tibial slope, high grade pivot shift and hyperlaxity– this may influence the operation plan, including ACLR technique and graft planning [49, 52, 53, 71, 72].

ACLR technique and graft planning

In the past, ACL injuries in skeletally immature patients were often treated non-operatively [27]. Suture repair of the ACL resulted too frequently in unsuccessful outcomes [27]. ACL repair has regained interest in recent ACL literature [73-77]. According to the PhD thesis by Van der List [73], ACL repair might be a good option in adult patients with a proximal ACL tear and good tissue quality who can be operated in a timely setting [73]. ACL repair seems to have several advantages over ACLR: maintaining proprioception [74, 78], less invasive surgery without donor site morbidity [74, 74], restoring native knee kinematics [74, 79] and prevention of osteoarthritis [74, 80]. The primary problem is however that ACL's fail to heal, because there is a premature loss of the provisional scaffold in the wound site [27, 81]. When the ACL tears, the ends bleed, but the fibrinolytic system in the synovial fluid prevents a clot from forming, and thus there is no scaffold to support repair of the ligament [27, 82].

Recent studies showed that by bringing the ruptured ends tight to each other or by placing a bioactive scaffold to bridge between the torn ends, synovial fluid does not prevent the formation of scar tissue anymore [83-89]. A recent randomized controlled trial showed non-inferior patient-reported outcomes, AP knee laxity and superior hamstring muscle strength when compared with autograft ACLR at 2-year follow-up in a young and active cohort [84]. But similar to ACL reconstruction in children and adolescents, ACL repair seems also to have higher re-rupture rates compared to adults and there is far less evidence in this population [83, 90]. As ACL repair showed best results in proximal ACL tears, which are more often found in patients of 25 years of age and older [83, 91]. Question therefore remains what the exact role of ACL repair in children and adolescents will be.

Nowadays, it has been established that paediatric ACL reconstruction is a safe procedure [27]. Diagnostic work-up and risk assessment may provide more insights on the risks of re-injuries. But skeletal maturity was shown to be the most important factor to take in consideration when performing an ACLR [23]. Seventy-eight percent of the respondents in the NVA survey treated children with open physes non-operatively, while 65% treated children with closed physes operatively [23]. Different ACLR techniques have been developed in order to prevent postoperative growth disturbances (**Chapter 1**). Current evidence does not show differences in postoperative growth disturbances or graft survival among these different techniques [92, 93].

Tendon autograft is commonly used during ACLR techniques in skeletally immature and mature children and adolescents. Hamstring tendon, quadriceps tendon and bone patellar tendon bone (BPTB) autografts are being used most frequently. Allograft is less commonly used as results of allograft show higher graft failure rates compared to autograft [5, 94-97]. In case of skeletally mature patients, there is ample research on graft choice [98, 99]. In skeletally immature patients however, it is currently not known which autograft has lowest re-injury and growth disturbance rates, as there are no large prospective randomized studies [100]. Previous studies showed that hamstring tendon autograft is most often used as graft for ACL reconstruction in children and adolescents with open growth plates [5, 24, 100, 101].

Quadriceps tendon autograft seems to be a good alternative for hamstring tendon autograft [5, 100]. It is hypothesized that BPTB should not be harvested as damage to the tibial tubercle apophysis may result in a recurvatum deformity [5].

Graft type is a factor to take in consideration to reduce graft failure rates in skeletally mature patients, but not (yet) in skeletally immature patients [100]. Graft diameter has been shown to be a factor that influences risk of graft failure, as a diameter of <8mm is associated with higher re-injury rates in skeletally immature and mature adolescents [102-108]. Preoperative knowledge of autograft tendon characteristics may therefore help to plan graft choice for ACLR [109]. In **Chapter 4**, the predictive values of anthropometrics on hamstring tendon lengths and graft characteristics were analysed [110]. Previous studies showed that anthropometric data and cross-sectional area (CSA) measurements of hamstring tendon on MRI are correlated to the diameter of hamstring grafts [111-114]. Based on the current study and other available literature on hamstring tendon CSA, prediction of hamstring characteristics can be made for preoperative graft planning in ligament reconstruction surgery [110-114].

In this thesis, the hypothesis that hamstring tendons in an adolescent population may be too small to create a graft with adequate dimensions, was rejected [110]. Due to the age distribution in that study, conclusions cannot be drawn about hamstring tendons in younger children and adolescents (<12 years). One might question if younger and smaller children and adolescents also require a graft of 8mm in diameter. The graft will not increase in diameter during growth, but may actually become thinner and longer [5, 115, 116]. Does the decrease of diameter influence the stability and risk of graft failure? Is the decrease also graft dependent? The answers to these questions are currently not known.

Despite of different graft options, modern ACLR techniques have improved rotational instability [117]. There are however still patients with high grade pivot shift after ACLR [117]. Persistent anterolateral rotatory instability has been shown to correlate with poor clinical outcomes, graft failure, and the subsequent need for revision surgery [118, 119]. Anterolateral augmentation procedures (anterolateral ligament (ALL) reconstruction or lateral extra-articular tenodesis (LET)) have recently generated increased focus regarding their ability to limit rotational instability, which decreases tension on the ACL reconstruction graft [119-126].

LET and ALL reconstruction are more frequently used in younger (skeletal mature) patients with hyperlaxity, grade 2 pivot shift or higher and ACL revision cases [52, 117, 127]. Literature on LET or ALL reconstruction in skeletally immature patients is scarce and long-term outcomes are not available for all techniques [127, 128, 129]. Several techniques for skeletally immature patients have been developed [120, 127, 129, 130]. Current LET techniques include modified Lemaire [120], modified Ellison [131] and modified MacIntosh [132, 133] techniques, which are adjusted to the open growth plates [129]. Current ALL reconstruction technique includes iliotibial tract autograft and is also adjusted to the open growth plates [127]. Long term outcomes of combined ACLR with anterolateral augmentation (over-the-top) in skeletally immature patients showed promising results with low graft failure rates and minimal growth disturbances [133].

In conclusion, an accurate diagnostic work-up, risk assessment, graft planning and ACLR technique are necessary to prevent complications and to optimise outcomes after ACLR. There are currently many different surgical techniques, graft options and anterolateral augmentation procedures that have to be evaluated in future studies to discover which have the lowest risk of graft failure and growth disturbance rates. In order to evaluate outcomes of these techniques and graft, paediatric and adolescent specific outcome measurements are important to use in daily practice and for scientific research.

Outcome measures during follow-up

Outcome measures can be differentiated in objective outcomes and subjective outcomes [134]. Objective outcomes include clinical examination tests, strength tests, movement quality and complications and adverse events [134, 135]. As discussed in **Chapter 8**, many tests and outcomes are age dependent. Outcome measures developed for adults are often not appropriate for children and adolescents [134, 136]. A structured outcome set is necessary to gather relevant data for future research, covering all domains of the International Classification of Functioning, Disability and Health (ICF), which is also available for children (ICF-CY) [134, 137, 138]. These ICF domains are: (1) body structure and function, (2) activities and (3) participation [134, 137].

Body structure and function

This domain covers problems with the anatomic feature of the body and with the function of the body system [134, 137]. Examples of outcomes in this domain are clinical examination tests and strength tests [134]. The body structure and function of children and adolescents is not always comparable to adults due to growth and physiological development. It is therefore important that these tests are also evaluated and validated in children and adolescents, hence the initiation of the PAD study (**Chapter 3**) and scoping review on tests evaluating return to sports (**Chapter 8**) [13, 135].

Regarding outcomes within the body structure and function domain, certain complications, such as growth disturbances, should be evaluated during postoperative follow-up. Growth disturbances are an unique complication that occur only in skeletally immature patients after ACL reconstruction. The exact incidence of growth disturbances is not known and studies show a range between 2-24% of the patients after ACL reconstruction [27, 139, 140]. Timely diagnosis and identification of the growth disturbance is essential, as timely surgical intervention may be indicated (soft-tissue interposition or epiphysiodesis) [21]. After skeletal maturity, guided growth surgery is no longer an option. Severe growth disturbances can then only be corrected by more invasive procedures [21].

The NVA survey showed that only 27% followed the patients until skeletal maturity in order to detect potential growth disturbances [23]. In the ESSKA survey, 42% administered long standing radiographs to evaluate skeletal growth after ACLR, while 36% used other methods (such as clinical exams) and 21% did not perform any analysis measures of skeletal growth [24]. These seem to be a rather low percentages, as skeletal immaturity was the most important decisive factor for primary ACL reconstruction or non-operative treatment and growth disturbances seem to be underreported in literature [23, 141]. The considerations underlying the clinical practice whether or not to follow the patients until skeletal maturity were not evaluated in the surveys [23, 24]. Based on the current available evidence and in order to gather evidence on the incidence and severity of growth disturbances, it is important to regularly monitor patients until skeletal maturity, preferably with weight bearing long-leg alignment radiographs and compare to the preoperative radiographs [5].

During the follow-up of non-operative treatment in skeletally immature patients, some authors argue to perform a systematic follow-up with annual MRI's in order to evaluate meniscal status as well as the posterior cruciate ligament (PCL) angle [21]. A PCL angle <105 degrees is suggestive for a chronic anterior translation of the tibia in relation to the femur [21, 142-145] Progression of meniscal lesions and anterior translation of the tibia is an indication for a decompensation of an ACL-deficient knee [21]. In order to prevent further meniscal injury, this decompensation is considered to be an indication for ACL reconstruction [21].

Activities & participation

These domains refer to (the difficulty in) executing activities and the participation in normal daily activities respectively [134, 137]. The most commonly used outcome measures within paediatric ACL are patient reported outcome measures (PROMs) [134]. PROMs are considered to be important as outcome measures as patient's perspective on treatment and health condition is evaluated [146]. A problem is that adults PROMs are often used in children and adolescents, leading to potential problems in comprehensibility [147, 148, 149]. The Pedi-IKDC and the KOOS-Child are modified versions of the IKDC and KOOS for children based on cognitive interviews with children [147, 150]. Modifications concerning instructions, item and response format, mapping and layout were made for comprehensibility purposes based on those cognitive interviews [147, 150].

In **Chapter 6**, a systematic review was conducted to provide an overview of the validated PROMs for children and adolescents with knee ligament injuries [136]. Knee specific PROMs cover all three ICF domains [134]. The PEDI-IKDC is the most frequently studied PROM in children and adolescents with knee ligament injuries [136]. This PROM showed acceptable psychometric properties in different studies [136, 151-154]. The KOOS-Child has been evaluated in one study and appears to be valid and reliable [136, 155]. In a recent validation study of the Dutch the Pedi-IKDC and KOOS-Child, the Pedi-IKDC showed better psychometric properties in a Dutch population of adolescents with knee complaints [156]. For daily practice, the Dutch Pedi-IKDC can therefore be used as knee specific PROM [156].

The systematic review aimed at knee specific PROMs [136]. A more general PROM on physical activity is relevant to gain insight in patients' perceived treatment results and health status. Physical activity can be measured objectively (for example accelerometers) or subjectively (for example PROMs) [157]. The level of physical activity is increasingly recognized as both an important prognostic factor and outcome variable in orthopaedics [158]. In Dutch however, there was no validated, short and simple physical activity scale for children and adolescents available. The 2018 IOC consensus statement and PAMI recommended the use of the Hospital for Special Surgery Paediatric Functional Activity Brief Scale (HSS Pedi-FABS) as a physical activity scale [5, 82, 159, 160].

In **Chapter 7**, the HSS Pedi-FABS was translated and transculturally validated among healthy Dutch children and adolescents [161]. The Dutch HSS Pedi-FABS showed a good internal consistency, acceptable test-retest reliability, good construct validity and a positive interpretability rating in a Dutch population of healthy paediatric and adolescent participants [161]. Content validity of the target population was considered good and there were no major problems with comprehensibility. Based on **Chapters 6 and 7**, a knee specific and physical activity PROM can be used for children and adolescents in daily practice in the Netherlands to evaluate the all three ICF domains [134, 137]. The Pedi-IKDC, KOOS-Child and HSS Pedi-FABS are available and validated in different languages and can therefore also be used for (international) scientific research [147, 152, 155, 156, 159-163].

Return to sport is often used as follow-up outcome measure to measure the success of the treatment [134]. What is "successful return to sport"? Successful return to sport is context- and outcome-dependent and has a different meaning for different people (including the patient, clinician and coach) [5]. Criteria of clearance RTS exist in great variability and it should be noted that a true clearance is multifactorial and complex [164, 165]. This was reflected by the variability of tests and outcomes described in the included studies of the scoping review presented in **Chapter 8**, including strength tests, hop tests, movement quality, PROMs and physical examination [135].

In this scoping review, strength tests, hop tests and movement quality were analysed most frequently [135]. Various tests in different set-ups were evaluated, mainly in patients older than 16 years of age [135]. In younger patients, there is very limited evidence on postoperative strength tests, hop tests or movement quality [135]. There were no tests analysed in non-operative treatment [135]. One of the purposes of the Delphi consensus based ACL rehabilitation guideline (**Chapter 9**) was to create a minimum set of criteria which the patient should meet before return to sport [165]. This Delphi consensus study included both non-operative and operative treatment rehabilitation programs including test protocols, education and criteria for return to sport [165]. As children and adolescents are not small adults, it seemed important to create specific rehabilitation programs and testing based on physiological age [165].

The Delphi consensus included consensus statements on ACL injured adolescents (10 to 18 years of age) [165, 166]. There was consensus to divide adolescents in two age groups, namely 10 to 16-year-olds and 17 to 18-year-olds [165]. The 17 to 18-year-olds could be treated according to the adults rehabilitation protocols, except when the physiological age is lower [165]. Within the adolescents between 10 to 16-year-olds, pre-, mid- and post-pubertal phases can be distinguished based on Tanner staging [167, 168]. These phases are directly related to hormonal production and their influence on the ability to adapt to resistance training [169]. Changes in blood concentrations of sex hormones might play a key role in the observed differences in strength gains between immature and mature individuals [169]. If so, one would expect trainability to increase significantly with the onset of puberty due to the sudden increases in sex hormones during that time [169].

In the Delphi study, there was consensus that pre-pubertal adolescents should have different rehabilitation programs and testing compared to mid- and post-pubertal adolescents, who also have different protocols than adults [165]. Differences in criteria were between pre-pubertal and mid-/post-pubertal, as pre-pubertal criteria were not muscle strength or hop test based [165]. The expert panel chose to add a single-leg sit-to-stand test for these pre-pubertal athletes, which has a high inter-tester reliability and has a good negative correlation with hip and knee extensor strength in healthy young adults [165, 170].

The aim of RTS batteries is to decrease the risk of re-injuries. RTS criteria must also be feasible. A systematic review by Webster et al. [171] showed that only 28% of the patients pass RTS test batteries after ACL reconstruction [171]. The good news is, that younger patients (< 21 years) have higher rates in passing RTS test batteries than older patients [172]. When passing RTS test batteries, there is a significantly reduced risk for graft failure, but an increased risk (235%) in contralateral ACL injury in the general population [171]. This might be due to an increased load on the contralateral leg [171]. In the younger ACL population, the return to sport rates are higher compared to adults and the total re-injury rates are also higher [41, 173, 174]. It has been speculated that high return to sport rates resulting in continued exposure from playing high-risk sports, may be an important factor contributing to the high re-injury rates after ACL reconstruction [173]. This leads to a conflicting situation in which it is important for young patients to return to sport for physical, social, and emotional development, but there is a high risk for re-injury [173]. The participation of large proportions of younger patients in level 1 pivoting sports, poses a risk for re-injury and should be a consideration when planning and making return-to-sport decisions [173]. There was no current consensus on what RTS criteria should be used to "clear" a younger patient to return to sport [165, 173]. In the Delphi consensus study (**Chapter 9**), RTS criteria were established based on international expert opinions [165]. The feasibility and validity of the RTS criteria in the test battery from the Delphi consensus statement should be evaluated in future studies in order to assess its effects on return to sport participation and the risk for re-injuries.

Future perspectives: towards an individualised approach

Establishing consensus and creating registries

Although the incidence of ACL injuries in children and adolescents is increasing [175-178], ACL injuries in skeletally immature children remain relatively rare [27]. Growth and physiological development make treatment plans more complex in this specific population. Re-injury rates are relatively high compared to adults and there is currently a lack of high level evidence to guide decision-making for treatment [30, 40]. The combination of these factors led to the IOC-ESSKA consensus statement on paediatric ACL in 2018 [5]. This statement provided consensus among world leading specialists on six fundamental clinical questions regarding the prevention, diagnosis and management of paediatric ACL injuries [5]. The consensus statement gave an evidence-informed summary to support the clinician, and help children with ACL injury and their parents/guardians make the best possible decisions [5]. The most recent Dutch National ACL Guidelines (2018) added a chapter on paediatric ACL injuries [179]. There is consensus on several topics within paediatric ACL, such as treatment indications and necessity to treat concomitant meniscal and cartilage injuries [5, 23, 179]. There is, however, still a lack of high quality evidence on paediatric ACL injuries with more questions than answers.

Current evidence within paediatric and adolescent ACL injuries is mainly based on retrospective cohort studies or case series with small populations, high risks of bias and short follow-up periods [5]. Long term knee health and quality of life remain therefore unknown [5]. In order to gain more practical evidence for daily practice, several topics need to be addressed in future research: non-operative treatment and knee bracing, risk assessment for ACL reconstruction on re-injuries and growth disturbances, evaluation of different ACL reconstruction techniques and grafts (including anterolateral augmentation and ACL repair techniques), postoperative rehabilitation and outcome measurements [5, 27]. Important aspects that should be considered in future studies are more detailed description of received treatment (including rehabilitation protocols), assessment of skeletal age and remaining growth, inclusion of homogenous population of skeletally immature patients and knowledge of preinjury and post-treatment activity levels [5].

As described in **Chapter 2**, ACL injuries in patients with open physes are rare in orthopaedic practice [23]. Multicentre and registry studies should be prioritised including larger numbers of skeletally immature patients [5]. For this purpose, two paediatric ACL registries were created, the Paediatric ACL Monitoring Initiative (PAMI) in Europa (organised by the European Society of Sports Traumatology, Knee Surgery & Arthroscopy (ESSKA)) and Pediatric ACL Understanding Treatment Options (PLUTO)) in the United States of America. These registries will provide large scale databases that go beyond local case studies [5, 82, 180, 181]. Both registries focus on treatment options and short-, medium- and long-term outcomes, which will provide stronger scientific evidence on treatment of children and adolescents with ACL injuries [180, 181].

From each patient a great amount of data will be gathered. This is currently done by the individual centres participating in the PAMI registry in Europe [82, 180]. ACL injuries in skeletally immature patients remain rare however in the Netherlands, which leads to limited numbers of consultations and surgeries for the individual orthopaedic surgeon in this population [23]. It is therefore important to centralise care for these patients to improve the quality of care [182] and to gain as much experience and evidence as possible in order to do more scientific research in this population. The data of these specialised centres can then be used for local research and for future registry (PAMI) research.

Description of phenotypes

Based on future research, the clinician would, ideally, be able to create an individual-based treatment that aims to protect the integrity of the knee, restores a stable and well-functioning knee for a healthy and active life style, and minimises the risk of growth disturbances in case of an ACL reconstruction [5]. Identification of risk factors for primary ACL injuries, failed non-operative treatment, graft failure and growth disturbances after ACL reconstruction should be a priority for future research. For personalised care, it is essential to understand risk factors for failure and potential benefits from each treatment option in order to predict outcomes [183, 184]. When the clinician is able to predict outcomes of a disease and treatment, care changes from a reactive state to a proactive state [183, 184, 185].

In order to predict outcomes of treatments in this vulnerable population, more patient-specific information is necessary. For example, which child will be a coper in non-operative treatment and will not sustain further meniscal injury? What is the best surgical technique in this specific patient in order to reduce risks of graft failure, growth disturbances and joint degeneration? It is currently not known whether the risk assessment, as described earlier, will provide sufficient information to predict outcomes in the current situation, as the underlying evidence is low. Based on future evidence of risk factors and outcomes of treatments, one could hypothesize that specific phenotypes of patients could be described that predict outcomes of treatment.

As more biological and biomechanical evidence on the prediction of outcomes will be available in the future, psychological and social factors must not be overlooked. Adolescence is a phase of psychological and social development, as it is the time for identity development, social skill acquisition, and developing independence [186, 187]. Knee injuries, including ACL injuries, result in lower quality of life [187-190] and adolescent patients may experience emotional reactions such as loss, denial, frustration, and anger [187, 191, 192, 193] decreased academic performance [187, 194], and loss of identity and loneliness [187, 192, 195, 196]. There is also evidence that ACL injuries should not only be viewed as a musculoskeletal but also as a neural lesion with neurocognitive and neurophysiological aspects [197]. Rehabilitation and RTS paradigms should take these neurocognitive and neurophysiological changes for assessment and interventions after injury in consideration [165, 196]. Although psychological and social factors might be somewhat unfamiliar (in research and clinical practice) to us as orthopaedic surgeons, these factors are important predictors of graft failure, return to sports and self-reported outcomes [198-201]. It is therefore important to take psychological and social factors in consideration in current treatment protocols and future scientific research, including screening for kinesiophobia and consulting a psychotherapist when necessary.

Different subspecialties are involved in the diagnosis and treatment of paediatric and adolescent patients. Collaboration between knee surgeons, paediatric orthopaedic surgeons, specialised physiotherapists and psychotherapists is necessary to gain further insights in risk assessment, rehabilitation protocols, surgical techniques, complications, long-term knee health and quality of life. But the different specialists can also learn from each other. It is therefore that the collaboration between different (sub)specialties and internationally specialised centres should be emphasised in order to share, to discuss and to study these complex topics within ACL injuries in children and adolescents.

Creation of prediction models

Experience and evidence of all different specialties will be necessary to create specific phenotypes of patients for risk prediction and treatment planning. Detailed data registration of all previously mentioned factors will provide evidence on these topics. Based on this thesis and the current literature, the following data of patients as shown in Figure 2 should ideally be gathered to serve as input for clinically relevant prediction models.

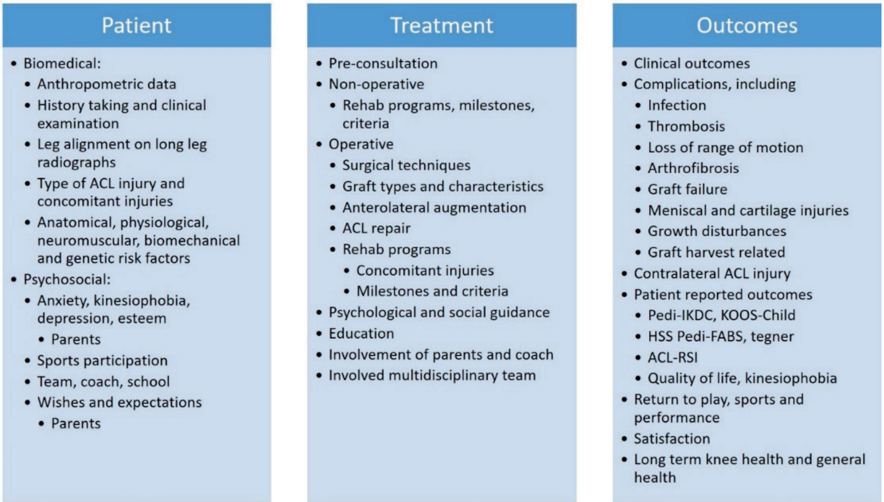

Figure 2. Suggestion of current input of data for clinical practice and scientific research.

Predictive modelling will be a major part of our future clinical practice [202]. Prediction models can be based on classical statistical analyses of regression models, but also newer technics such as data mining and machine learning should be considered [203, 204, 205]. The integrated algorithms of machine learning and artificial intelligence have rapidly been accepted in "everyday life" around us, for example with "Google Search" or Apple's "Siri" [206]. While within the orthopaedic practice, surgeons stood behind craftsmanship of their clinical trade and remained, somewhat, ignorant to the global forward creep of technology [206]. But as orthopaedic surgeons seek to further improve the quality of care and as an exponentially-expanding volume of information is collected, computer-driven applications such as artificial intelligence show increasingly apparent opportunities for integration in everyday practice [206].

Orthopaedic surgeons have to adapt to machine learning and artificial intelligence in future practice, as integration in daily practice will be an inevitable future step [202, 206]. But like any new technology for clinical use, these applications must be based on evidence-based rationales and prove accuracy before adoption in daily practice [206]. It is important to notice that we, as humans, program machines to analyse and recognise patterns that may serve as a basis for medical diagnosis or treatment [202]. Therefore, the outputs of machine learning and other artificial intelligence analyses are limited by the accuracy of the available input data [202, 207].

Prediction models, algorithms, shared decision programs and apps have already been developed to improve prediction of outcomes after ACLR [53, 184, 208]. A state-of-the-art example is the Digital Twin (DT), which is a digital replica of an object, process or system, that is used to better understand how a system will behave over its lifecycle [184, 185, 209]. A DT combines a mechanical model and statistical models and can provide a connection between a physical object and a digital object [184, 210, 211]. For a complex structure as the knee, a DT of the injured knee might serve to select the best type of treatment for each patient. The DT knee should contain mechanical and statistical data with personal input from the patient [184]. DT's have the potential to revolutionise surgical care, as DT personalises treatments and may provide future clinicians to use artificial intelligence to help as decision support [185, 209].

To conclude the future perspectives, large amounts of data will be gathered of paediatric and adolescents ACL injuries within the coming years in (inter)national registries. This may lead to a better understanding of the ACL injury, risk factors and treatment options within this population. Future care may involve a detailed description of phenotypes of patients based on risk factors, which may predict treatment outcomes. As machine learning and artificial intelligence technology advances, future ACL diagnostics and treatment will involve more computer-driven technology to predict and improve outcomes in children and adolescents.

There remain more questions than answers in the treatment of ACL injuries in children and adolescents. With this dissertation, I hope to add knowledge to improve care and outcomes for these children and adolescents.

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Valorisation

The incidence of ACL injuries in adolescents is increasing [1]. Compared to adults, the risk of graft failure or a contralateral ACL injury is higher after ACL reconstruction [2]. An ACL injury can be considered as a permanent injury to the knee. On the long term, there is an increased risk of posttraumatic osteoarthritis of the knee [3]. In case of concomitant meniscus or cartilage injury, posttraumatic osteoarthritis can even be manifest at 30 or 40 years of age [3]. The importance of primary prevention for ACL injuries and secondary prevention for meniscus and cartilage injuries after ACL injury is therefore clear.

Primary prevention is of uttermost importance, as the incidence of ACL injuries among girls aged 13 to 15 years is increasing rapidly [1]. Girl's football (soccer) has the highest ACL injury rate of all sports [4]. In the Netherlands, the participation of girls in football is increasing in recent years [5]. Although no epidemiological data on ACL injuries in children and adolescents are available in the Netherlands, it seems obvious that there should be more attention on the primary prevention of ACL injuries in this vulnerable population. Biomechanical movement patterns are a key modifiable risk factor for injury and injury prevention programs target at movement patterns [6,7]. Injury prevention programs have shown the be effective in reducing the number of primary ACL injuries in skeletally mature patients and secondary ACL injuries after ACL reconstruction. Those injury programs are straightforward to implement as they require little to no equipment and can be performed as regular team training or during physical education programs [6,7]. Given the low costs and ease of implementation, neuromuscular training of all young athletes represents a cost-effective strategy for reducing costs and morbidity from ACL injuries [6,7]. Although primary prevention was not one of the aims of this thesis, I believe that it is important to highlight this topic in this thesis at the impact paragraph. If we are able to prevent ACL injuries among children and adolescent by drawing more attention to this topic and create awareness for the role of primary prevention programs, the impact of this thesis is more relevant.

When a child or adolescent sustains an ACL injury, timely diagnosis is essential to prevent secondary damage to the menisci or cartilage. In **Chapter 3**, the diagnostic values of history taking were evaluated in order to help clinicians to screen for ACL injuries in this population. Timely suspicion may lead to timely referral and timely diagnosis. Timely diagnosis is the start point for management planning and shared decision making [6]. An adequate, physiological age based rehabilitation is furthermore important to prevent damage to the knee. As discussed in **the General discussion**, a more individualised approach seems to be necessary, because children and adolescents with an ACL injury present in different physiological and developmental stages. Those children and adolescents may also have different underlying risk factors for ACL injuries and may present with concomitant injuries which have to be addressed. This individualised approach makes diagnosis and treating children and adolescents, especially in case of open growth plates, rather complex. Hence, we aimed to develop a practice guideline for adolescent ACL rehabilitation which can be used in day-to-day practice in **Chapter 9**. We believe that this is an important step toward reducing practice inconsistencies, closing the evidence-practice gap, and improving quality of rehabilitation after adolescent ACL injury.

Should any specialised knee (sports) surgeon and physiotherapist treat children and adolescents with open growth plates? As discussed in **Chapter 2**, in the survey among NVA members, it was found that many surgeons are consulted by only a few skeletally immature patients and perform ACL reconstructions on even less patients. These numbers do not specifically include paediatric orthopaedic surgeons, as the survey was conducted among members of the NVA and not among the Werkgroep Kinderorthopedie (WKO). These numbers do also not include the experience of the physiotherapists who are guiding the rehabilitation process. Given the complexity of growth and physiological development, specific expertise in rehabilitation of children and adolescents and the potential complications of ACL reconstruction, should children and adolescents with open growth plates be treated in a rather multidisciplinary, specialised team of knee (sports) surgeons, paediatric orthopaedic surgeons and paediatric sports physiotherapists? ACL reconstructions are often performed by knee (sports) surgeons, however can also be performed by paediatric orthopaedic surgeons [8]. A study among American orthopaedic surgeons showed no significant differences in outcomes between knee sports orthopaedic surgeons or paediatric orthopaedic surgeons [8]. Paediatric orthopaedic surgeons have specific knowledge of musculoskeletal growth and are able to diagnose and treat growth disturbances. In case of growth disturbances, it is essential that a paediatric orthopaedic surgeons can be consulted as knee sports orthopaedic surgeons do not often treat growth disturbances.

Rehabilitation of children and adolescents is depending on the physiological age and specific treatment regimens and criteria should be used, as discussed in **Chapter 9**. In case of severe kinesiophobia or post-traumatic stress disorder symptoms, I argue that a paediatric psychotherapist also be included in a multidisciplinary team [9]. Psychological factors have to be taken in consideration and to be treated when necessary. In order to improve the re-injury outcomes, reduce secondary meniscal and chondral injuries and to prevent and treat growth disturbances, this multidisciplinary approach might be a valuable step in increasing the quality of care for this vulnerable population. One might consider, regarding the (relatively) low incidence of ACL injuries in skeletally immature patients, to organise several centres of expertise including a multidisciplinary and dedicational team, which also participates in (internationally) scientific research programs. This expertise and data, gathered for example in the PAMI registry, is important to gain more evidence on this topic and to improve care for these patients [10].

With this thesis, I want to draw attention to ACL injuries in children and adolescents in the Netherlands and hopefully to start multidisciplinary collaborations and dicussions, in order to centralise and optimise care. At this point, the incidence of ACL injuries in adolescents is increasing, treatment protocols and surgical techniques are becoming more complex and there are high risks of re-injuries with – probably – poor long term knee health. As the evidence in general is still low however, this takes us back to the primary aim of this thesis: to gain insight in the current state of care in the Netherlands, to gain evidence on basic topics within diagnostics and predictors and to create outcome measures and rehabilitation protocols for future clinical and scientific use. The impact of this thesis can be summarised:

- The current state of care for children and adolescents with ACL injuries in the Netherlands are known, which is necessary for organising, and centralising, care for these patients
- Diagnostic values of history taking, physical examination and KT-1000 arthrometer are studied and questions for early referral for ACL injuries are formulated
- Hamstring tendon lengths and graft characteristics can be predicted preoperatively and in case of a closed socket technique, hamstring tendons are sufficient to create a graft of ≥8mm
- Lateral tibial slope is a morphological factor to take in consideration before and after ACL reconstruction as a risk factor for re-injuries
- There is an evidence based overview knee specific, paediatric patient reported outcome measures
- A short and simple paediatric activity scale is translated and transculturally validated in Dutch for clinical and scientific use
- There is an evidence based overview of current tests and outcomes regarding return to sports after ACL reconstruction in children and adolescents
- Based on an international expert panel, new (p)rehabilitation guidelines are created for children and adolescents based on physiological age

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Chapter 11

Summary & samenvatting

Summary

ACL injuries are a severe injury of the paediatric and adolescent knee, which increase the risk of further damage and early onset osteoarthritis. ACL reconstructions in this population are associated with high risks of re-injuries. Current evidence on treatment is still low. The aim of this thesis was therefore to gain evidence for day-to-day practice for children and adolescents with ACL injuries. This thesis can be divided in three topics related to paediatric ACL injuries: (1) current state of care , (2) diagnostics and predictors and (3) outcome measures and rehabilitation.

Current state of care

Treatment of ACL injuries in children and adolescents with open growth plates is a matter of debate within paediatric orthopaedic and sports medicine community. There are many different treatment algorithms, although the underlying evidence is still low. In order to gain insight in the current state of care for paediatric ACL injuries in the Netherlands, in **Chapter 2** a survey was conducted among members of the NVA (Nederlandse Vereniging voor Arthroscopie). A total of 126 responses were analysed on treatment of skeletally immature patients. The main finding of this survey is that 78% of the respondents tend to treat children with open physes non-operatively, while 65% tend to treat children with closed physes operatively. The most frequently performed operative procedure in skeletally immature patients is the transphyseal ACL reconstruction. Many considerations, such as concomitant meniscal injury and type of sports participation, were involved in choosing operative treatment. The postoperative follow-up period varied from less than 1 year (24%) until skeletal maturity (27%). In conclusion, this survey showed that the current state of care for paediatric ACL injuries is variable and many surgeons treat skeletally immature patients with ACL injuries in the Netherlands.

Diagnostics and predictors

Diagnosing ACL injuries in children is more difficult compared to adults. This difficulty might be due to a greater physiological laxity, a lack of cooperation during physical examination and a more varied differential diagnosis in this age category. There is however limited evidence of the diagnostic values of history taking and physical examination related to paediatric ACL injuries. In **Chapter 3**, the diagnostic values of history taking, physical examination and KT-1000 arthrometer were evaluated in a prospective, diagnostic study on 66 children and adolescents with post-traumatic knee complaints. During history taking by an experienced orthopaedic surgeon, report of a 'popping sensation' had a specificity and PPV of 100% for diagnosing ACL injuries in children and adolescents. This question is therefore useful for early

referral to an orthopaedic surgeon. Physical examination tests (Lachman, anterior drawer and pivot shift tests) have a high diagnostic values when performed by an experienced orthopaedic surgeon. Absolute anterior translation of ≥7mm in the KT-1000 arthrometer has the highest diagnostic values of all tests.

Most common used autograft for ACL reconstruction in children and adolescents is hamstring tendon autograft. There are concerns however that the tendons might be too small to create a graft with adequate dimensions. In **Chapter 4**, the predictability of hamstring tendon length and graft characteristics based on anthropometric values were studied in 171 children and adolescents. It was found that height was a significant predictor of semitendinosus and gracilis tendon length in adolescents between 13 and 17 years of age. These outcomes are similar to anthropometric predictions in adults. In 75% of the closed socket ACL reconstructions, the semitendinosus tendon alone was sufficient to create an adequate graft with a minimum diameter of 8mm. Additional use of the gracilis tendon was more often necessary in females and shorter patients.

Re-injuries after ACL injury are high in adolescents compared to adults. Several morphological risk factors of the knee are known to be a risk factor for primary ACL injuries in children and adolescents and for re-injuries in adults after ACL reconstruction. However, there is limited knowledge of knee morphology as risk factor for ACL re-injuries after ACL reconstruction in children and adolescents. In **Chapter 5**, in a multi-centre, retrospective, case-control study (n=124), the morphological risk factors of the lateral compartment of the knee were evaluated as risk factors for re-injuries after ACL reconstruction. The most important finding was that the morphological measurements of the lateral compartment of the knee were not found to be statistically significant risk factors for ipsilateral graft ruptures and contralateral ACL ruptures in children and adolescents. The total re-injured population had a significant greater lateral tibial slope compared to controls. Tibial slopes of ≥7° were associated with re-injuries. Tibial slope could however not be identified as discriminative factor for identifying the risk of re-injuries.

Outcome measures and rehabilitation

Patient reported outcome measures (PROMs) are used as subjective outcome measure after ACL injury. Adults PROMs are often used for children and adolescents. Although adults PROMs are often not validated in a paediatric and adolescent population and there are problems concerning comprehensibility. In **Chapter 6**, an overview of the available (validated) PROMs for children and adolescents with knee ligament injuries was provided by performing a systematic review. Based on the review, the Pedi-IKDC is the most adequate PROM for children with knee ligament injuries. It was reported in literature to be valid, reliable and responsive. The KOOS-Child might be an alternative PROM for the Pedi-IKDC, but has only been evaluated in one study. Adult versions of PROMs are not recommended to be used in children and adolescents to measure subjective outcomes.

The HSS Pedi-FABS is advised by the Paediatric ACL Monitoring Initiative (PAMI) to assess the activity level in children and adolescent with ACL injuries. The HSS Pedi-FABS is a brief and simple scale to measure subjective physical activity. In **Chapter 7**, the HSS Pedi-FABS was translated and transculturally validated in Dutch. The Dutch HSS Pedi-FABS showed good psychometric properties in a healthy Dutch paediatric and adolescent population. Limitations of the current Dutch HSS Pedi-FABS are content validity on construct of items reported by professionals. The Dutch HSS Pedi-FABS is now available as short and simple physical activity scale for children and adolescent for clinical practice and scientific research.

Current evidence on non-operative treatment and postoperative rehabilitation after ACL reconstruction in children and adolescents is low. Rehabilitation protocols and return to sport criteria are often based on adult protocols and are therefore not developed for specific physiological age categories. In **Chapter 8**, an overview of the available tests and criteria for return to sport after ACL injury and ACL reconstruction in children was presented. All identified studies evaluated tests after ACL reconstruction. Strength tests, movement quality and PROMs were investigated most frequently as prognostic factor. There was very limited evidence of tests and return to sports criteria for children and adolescents under 16 years of age. There are no recommendations on which specific tests regarding quantity and quality of movement should be used based on this review for return to sport testing. Based on expert opinion, clearance for return to sport should be based on a physiological age specific test battery including strength tests, movement quality during sport-specific tasks and (paediatric) PROMS.

Due to limited evidence on rehabilitation and return to sport clearance in children and adolescents, in **Chapter 9**, a consensus statement was built on (p)rehabilitation and return to sport criteria testing by performing a Delphi consensus study among 20 international paediatric ACL rehabilitation experts. Based on this consensus statement, practice guidelines for paediatric and adolescent ACL rehabilitation were created which can be used in everyday practice.

Samenvatting

Voorste kruisbandletsels bij kinderen en adolescenten zijn ernstige knieletsels, die het risico op bijkomende meniscus- en kraakbeenschade en vroegtijdige artrose verhogen. Voorste kruisbandreconstructies hebben in deze leeftijdscategorie een groter risico op re-rupturen vergeleken met volwassenen. In het geval van open groeischijven bestaat na een voorste kruisbandreconstructie ook het risico op groeistoornissen. Er is weinig wetenschappelijk bewijs van hoge kwaliteit voor de behandeling van deze kinderen en adolescenten. Het doel van dit proefschrift is het verzamelen van wetenschappelijk bewijs gericht op de dagelijkse, klinische praktijk over voorste kruisbandletsels bij kinderen en adolescenten. Het proefschrift wordt opgedeeld in drie thema's: (1) huidige stand van zorg , (2) diagnose en voorspellers, (3) uitkomsten en revalidatie.

Huidige stand van zorg

De behandeling van voorste kruisbandrupturen bij kinderen en adolescenten met open groeischijven is onderwerp van debat binnen de kinder- en sportorthopedie. Hoewel er wereldwijd veel verschillende behandelalgoritmes zijn, is het onderliggende wetenschappelijke bewijs gering. In het onderzoek zoals beschreven in **Hoofdstuk 2**, is een enquête verstuurd naar de leden van de Nederlandse Vereniging voor Arthroscopie (NVA), om inzicht te krijgen in de huidige stand van zorg voor kinderen en adolescenten met voorste kruisbandletsels in Nederland. In totaal zijn de antwoorden van 126 leden geanalyseerd. De belangrijkste bevinding was dat 78% van de respondenten kinderen met open groeischijven primair conservatief behandelde, waar 65% van hen kinderen met gesloten groeischijven primair operatief behandelde. De meest uitgevoerde procedure bij kinderen met open groeischijven was transfyseale voorste kruisbandreconstructie. Er bleken verschillende overwegingen te zijn als indicatie voor een operatieve behandeling. De postoperatieve follow-up varieerde sterk: van minder dan 1 jaar (24%) tot volledig uitgegroeid (27%). Deze enquête toont aan dat in Nederland veel variatie is in de behandeling van voorste kruisbandrupturen bij kinderen met open groeischijven en dat veel orthopedisch chirurgen kinderen en adolescenten met open groeischijven aan een voorste kruisbandruptuur behandelen.

Diagnose en voorspellers

Het diagnosticeren van voorste kruisbandletsels bij kinderen is lastiger dan bij volwassenen. Kinderen hebben grotere fysiologische laxiteit, zijn bij het lichamelijk onderzoek minder coöperatief en er is in deze leeftijdscategorie een meer gevarieerde differentiaal diagnose. Er is echter weinig bewijs over de diagnostische waarden van de anamnese, het lichamelijk onderzoek en de KT-1000 arthrometer bij kinderen. In het onderzoek in **Hoofdstuk 3** zijn de diagnostische waarden van de anamnese, het lichamelijk onderzoek en de KT-1000 arthrometer bij 66 kinderen met posttraumatische knieklachten prospectief onderzocht. Een knappend gevoel ten tijde van het trauma heeft bij kinderen en adolescenten een 100% specificiteit en positief voorspellende waarde van 100% voor het diagnosticeren van een voorste kruisbandlaesie. De vraag naar een knappend gevoel is daarom voor tijdige verwijzing naar de orthopedisch chirurg als screeningsvraag in de eerste lijn uiterst zinvol. Stabiliteitstesten (Lachman, voorste schuiflade en pivot shift test) tijdens het lichamelijk onderzoek hebben hoge positief en negatief voorspellende waarden als deze worden uitgevoerd door een ervaren orthopedisch chirurg. De meest nauwkeurige test is het meten van absolute translatie van ≥7mm in de KT-1000 arthrometer.

Hamstringpees autograft is de meest gebruikte graft bij voorste kruisbandreconstructies. Of de hamstringpezen bij een kind of adolescent te klein zijn om voorste kruisbandgrafts te maken, kan een preoperatieve zorg zijn. In het onderzoek van **Hoofstuk 4** zijn de antropometrische voorspellingen van hamstringpeeslengtes en graftkarakteristieken onderzocht. Lichaamslengte bleek in de populatie van 13- tot 17-jarigen (n=171), net als bij volwassenen, een voorspeller voor semitendinosuspees- en gracilispeeslengte te zijn. In 75% van de voorste kruisbandreconstructies bleek de semitendinosuspees alleen al voldoende om een graft met de juiste afmetingen te maken. Additioneel gebruik van de gracilispees was bij meisjes en bij een kleinere lichaamslengte vaker nodig.

Bij kinderen en adolescenten komen letsels van de voorste kruisbandgraft of voorste kruisband van de andere knie na een voorste kruisbandreconstructie vaker voor dan bij volwassenen. Er zijn verschillende morfologische factoren van de knie die een risicofactor zijn voor voorste kruisbandlaesies bij kinderen en adolescenten alsook voor nieuwe letsels na voorste kruisbandreconstructie bij volwassenen. Toch is er bij kinderen en adolescenten nog beperkte kennis van deze risicofactoren voor het opnieuw optreden van voorste kruisbandletsel na een voorste kruisbandreconstructie. In het onderzoek in **Hoofdstuk 5** zijn morfologische risicofactoren voor nieuwe letsels van de voorste kruisbandgraft of contralaterale voorste kruisband na een voorste kruisbandreconstructie retrospectief onderzocht (n=124) in het Máxima Medisch Centrum en Aarhus University Hospital. Uit dit onderzoek volgde dat de morfologische metingen van de laterale zijde van de knie geen statistisch significante voorspellers waren voor nieuwe letsels na een voorste kruisband reconstructie. Een opvallende bevinding was dat kinderen en adolescenten met een nieuw letsel van de ipsi- of contralaterale voorste kruisband na een voorste kruisbandreconstructie een gemiddeld steilere tibial slope hadden en dat een tibial slope van ≥7° werd geassocieerd met voorste kruisbandlaesies. De tibial slope was echter niet een diagnostisch significante factor voor het identificeren en voorspellen van een nieuw letsel na voorste kruisband reconstructie.

Uitkomstmaten en revalidatie

Als subjectieve uitkomstmaat worden in de kliniek en voor wetenschappelijk onderzoek vaak "Patient reported outcome measures" (PROMs) gebruikt. Hoewel PROMs voor volwassenen vaak worden uitgevraagd bij kinderen en adolescenten, zijn deze PROMs vaak niet bij deze populatie niet gevalideerd. Een aandachtspunt is dan ook de begrijpbaarheid van deze PROMs voor kinderen en adolescenten. In **Hoofdstuk 6** is in een systematic review een overzicht gegeven van de huidig gevalideerde PROMs voor kinderen en adolescenten met ligamentaire knieletsels . Uitkomst is dat de Pedi-IKDC de meeste adequate PROM bij kinderen en adolescenten met ligamentaire knieletsels is. Deze PROM is valide, betrouwbaar en responsief. De KOOS-Child is een alternatieve PROM voor de Pedi-IKDC, maar is slechts in één studie onderzocht. De klinische relevante van deze systematic review is dat geadviseerd wordt PROMs voor volwassenen niet bij kinderen en adolescenten te gebruiken.

Vanuit de PAMI wordt de HSS Pedi-FABS geadviseerd als PROM voor fysieke activiteit bij kinderen en adolescenten na een voorste kruisbandlaesie. In **Hoofdstuk 7** werd de HSS Pedi-FABS vertaald naar het Nederlands en transcultureel gevalideerd in een gezonde Nederlandse populatie van kinderen en adolescenten. De Nederlandse versie van de HSS Pedi-FABS liet goede psychometrische waarden zien. Beperkingen waren de beoordelingen van professionals op de content validiteit. De Nederlandse HSS Pedi-FABS is nu beschikbaar als korte en simpele fysieke activiteitenschaal voor kinderen en adolescenten voor de dagelijkse praktijk of wetenschappelijk onderzoek.

Er is beperkte wetenschap over niet-operatieve behandeling na voorste kruisbandlaesies en revalidatie na voorste kruisbandreconstructies bij kinderen en adolescenten. Revalidatie- en behandelprotocollen zijn vaak gebaseerd op protocollen voor volwassenen, die niet zijn ontwikkeld voor andere fysiologische leeftijdscategorieën. In **Hoofdstuk 8** werd een overzicht gepresenteerd van beschikbare testen en "return to sport" (RTS) criteria na een voorste kruisbandlaesie en –reconstructie in een scoping review. Alle studies richtten zich op testen en RTS criteria na een voorste kruisbandreconstructie. Er zijn geen studies gericht op niet-operatieve behandeling. Daarnaast is er zeer weinig wetenschappelijke onderzoek verricht naar kinderen en adolescenten jonger dan 16 jaar. Als prognostische factor zijn krachttesten, kwaliteit van bewegen en PROMs de meest onderzochte testen. Over het testen van kwantiteit en kwaliteit van bewegen kunnen op basis van deze review geen aanbevelingen worden gedaan. Gebaseerd op "expert opinion" zou

“RTS clearance” gebaseerd moeten worden op een fysiologische leeftijdsspecifieke testbatterij van krachttesten, kwaliteit van bewegen en kinder-PROMs.
Vanwege de beperkte wetenschap over revalidatie en RTS clearance bij kinderen en adolescenten werd er in **Hoofdstuk 9** een consensus statement over revalidatie en RTS testen gepresenteerd. Deze consensus statement is gebaseerd op een Delphi consensus studie onder 20 internationale experts op het gebied van revalidatie na voorste kruisbandlaesie of –reconstructie bij kinderen en adolescenten. Gebaseerd op deze consensus statement zijn praktische richtlijnen voor revalidatie na voorste kruisbandlaesies en –reconstructie bij kinderen en adolescenten ontwikkeld die in de dagelijkse praktijk kunnen worden gebruikt.

Appendices

List of abbreviations

ACL: Anterior cruciate ligament
ACLR: Anterior Cruciate ligament reconstruction
ACL RELAY: Anterior Cruciate Ligament Reconstruction Long-term outcomes in Adolescents and Young adults
ACL-RSI: Anterior Cruciate Ligament - Return to Sport after Injury
AI: Artifical Intelligence
ALL: Anterolateral Ligament
AP: Anterior-Posterior
AUC: Area under curve
AUH: Aarhus University Hospital
BMI: Body mass index
BPTB: Bone Patellar Tendon Bone
CCS: Classification coding scheme
CHQ: Child Health Questionnaire
CI: Confidence Interval
CKRS: Cincinnati Knee Rating System
COSMIN: Consensus-based standards for the selection of health measurement instruments
CSA: Cross-Sectional Area
DM: Data Mining
DT: Digital Twin
ESSKA: European Society of Sports Traumatology, Knee Surgery & Arthroscopy
FN: False Negatives
FP: False Positives
FRE: Flesch reading ease
G: Gracilis
HSS Pedi-FABS: Hospital for Special Surgery Paediatric Functional Activity Brief Scale
HS: Hamstrings
ICC: Intra-class correlation
ICF: International Classification of Functioning, Disability and Health
ICF-CY: International Classification of Functioning, Disability and Health for Children and Youth
IOC: International Olympic Committee
IQR: Interquartile range
IRB: The Institutional Review Board
KOOS (-Child): Knee injury and Osteoarthritis Outcome Score (for children)
KT-1000 Arthrometer: Knee laxity Testing device 1000 Arthrometer
LCL: Lateral Collateral Ligament
LET: Lateral Extra-articular Tenodesis

LFCI: Lateral Femoral Condyle Index
LFCR: Lateral Femoral Condyle Ratio
LOA: Limits Of Agreement
LSI: Limb Symmetry Index
Máxima MC: Máxima Medical Centre/ Máxima Medisch Centrum
MCL: Medial Collateral Ligament
METC: Medical Ethics Committee
MIC: Minimal Important Changes
mm: millimeters
MRI: Magnetic Resonance Imaging
N: Newton
N.A.: Not Applicable
NOV: Nederlandse Orthopaedische Vereniging / (the Dutch Orthopaedic Association)
NPV: Negative Predictive Value
NVA: Nederlandse Vereniging voor Arthroscopie / (Dutch Arthroscopy Society)
PAMI: Paediatric Anterior Cruciate Ligament Monitoring Initiative
PAQ-A: Physical Activity Questionnaire for Adolescents
PAQ-C: Physical Activity Questionnaire for Children
PCL: Posterior cruciate ligament
(Pedi-) IKDC: (Paediatric) International Knee Documentation Committee Subjective Knee Form
PedsQL: Pediatric Quality of Life Inventory
PLUTO: Pediatric ACL Understanding Treatment Options
PPV: Positive Predictive Value
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PROMs: Patient-reported Outcome Measures
Q: Question
QT: Quadriceps Tendon
ROC: Receiving Operating Characteristics
RR: Responsiveness Ratio
RTS: Return To Sport
SANE: Single Assessment Numeric Evaluation
SD: Standard Deviation
SDC: Smallest Detectable Changes
SEM: Standard Error of Measurement
ST: Semitendinosus
STG: Semitendinosus – Gracilis gecombineerd / combined
TN: True Negatives
TP: True Positives
WKO: Werkgroep kinderorthopaedie / (Dutch Paediatric Orthopaedics Society)

List of Publications

PhD thesis

- **Dietvorst M**, van der Steen MCM, Reijman M, Janssen RPA. Diagnostic values of history taking, physical examination and KT-1000 arthrometer for suspect anterior cruciate ligament injuries in children and adolescents: a prospective diagnostic study. BMC Musculoskelet Disord. 2022;23(1):710. Published 2022 Jul 26. doi:10.1186/s12891-022-05659-1

- **Dietvorst M**, Reijman M, van Zutven R, et al. Current State of Care for Pediatric ACL Ruptures in the Netherlands: A Survey. J Knee Surg. 2021;34(5):520-525. doi:10.1055/s-0039-1697626

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Currently in review

- **Dietvorst M**, van der Steen MC, van den Besselaar M, Janssen RPA. Height is a predictor of hamstring tendons length and closed socket anterior cruciate ligament reconstruction graft characteristics in adolescents. In review at BMC Musculoskeletal disorders.

- van Melick N, **Dietvorst M**, van Oort MIAM, Claessens RLA, Janssen RPA, Bogie R, A-ACL rehabilitation group. Anterior cruciate ligament rehabilitation for the 10 to 18 year old adolescent athlete: practice guidelines based on International Delphi Consensus. In review at OJSM.

- Verhagen S**, Dietvorst M,** van der Steen MC, Delvaux E, Janssen RPA. Clinical outcomes of different autografts used for anterior cruciate ligament reconstruction in skeletally immature patients – a systematic review. In review at BMC Musculoskeletal Disorders.

Presentations

- 2023 EPOS congress oral presentation: "Anterolateral augmentation procedures during ACL reconstructions in skeletally immature patients - scoping review of surgical techniques and outcomes".
- 2023 EPOS congress poster presentation: "Anterior cruciate ligament rehabilitation for the 10 to 18 year old adolescent athlete: practice guidelines based on International Delphi Consensus".
- 2023 EPOS congress poster presentation: "Height is a predictor of hamstring tendon length and closed socket ACL reconstruction graft characteristics in adolescents".
- 2023 EPOS congress poster presentation: "Clinical outcomes of different autografts used for ACL reconstruction in skeletally immature patients - a systematic review".
- 2022 MMC PhD Event Vitaliteitscentrum oral presentation: "Voorste kruisband-rupturen bij kinderen & adolescenten".
- 2022 ESSKA congress Paris poster presentation: "Height is a predictor of hamstring tendons length and closed socket anterior cruciate ligament (ACL) reconstruction graft characteristics in adolescents".
- 2022 ESSKA congress Paris poster presentation: "Translation & Transcultural Validation Of The Dutch Hospital For Special Surgery Pediatric Functional Activity Brief Scale (HSS PEDI-FABS)".
- 2022 ESSKA congress Paris poster presentation: "Lateral tibiofemoral morphometry does not identify risk of re-ruptures after ACL reconstruction in children and adolescents".
- 2022 ESSKA congress Paris poster presentation: "Diagnostic values of history taking, physical examination and KT-1000 arthrometer for anterior cruciate ligament injuries in children and adolescents: a prospective diagnostic study".
- 2021 ROGO Zuid refereermiddag oral presentation "Falende VKB reconstructies".
- 2021 NVA lustrum congress oral presentation "Translation and transcultural validation of the Dutch hospital for special surgery paediatric functional activity brief scale (HSS Pedi-FABS)".
- 2021 NVA lustrum congress poster presentation "Lateral tibiofemoral morphometry does not identify risk of re-ruptures after ACL reconstruction in children and adolescents".
- 2021 NVA lustrum congress poster presentation "Diagnostic values of history taking, physical examination and KT-1000 arthrometer for anterior cruciate ligament injuries in children and adolescents: a prospective diagnostic study".

- 2021 NVA lustrum congress poster presentation "Height is a predictor of hamstring tendons length and closed socket anterior cruciate ligament reconstruction graft characteristics in adolescents".
- 2021 ESSKA digital congress poster presentation "Limited evidence for return to sport testing after ACL reconstruction in children and adolescents under 16 years: a scoping review".
- 2021 MMC wetenschapsavond poster presentation "Height is a predictor of hamstring tendons length and closed socket anterior cruciate ligament reconstruction graft characteristics in adolescents".
- 2021 MMC wetenschapsavond poster presentation "Diagnostic values of history taking, physical examination and KT-1000 arthrometer for anterior cruciate ligament injuries in children and adolescents: a prospective diagnostic study".
- 2021 MMC wetenschapsavond poster presentation "Lateral tibiofemoral morphometry does not identify risk of re-ruptures after ACL reconstruction in children and adolescents".
- 2021 MMC wetenschapsavond poster presentation "Translation and transcultural validation of the Dutch hospital for special surgery paediatric functional activity brief scale (HSS Pedi-FABS)".
- 2020 MMC staflunch oral presentation "Voorste kruisbandrupturen bij kinderen".
- 2019 ROGO Zuid refereermiddag oral presentation "Voorste kruisbandrupturen bij kinderen: wanneer groei in de weg zit".
- 2019 MMC wetenschapsavond poster presentation "Limited evidence for return to sport testing after ACL reconstruction in children and adolescents under 16 years: a scoping review".
- 2018 NVA congress oral presentation "Landelijke registratie kinderkruisbanden"
- 2018 MMC wetenschapsavond poster presentation "Current State of Care for Pediatric ACL Ruptures in the Netherlands: A Survey" .
- 2018 ESSKA Glasgow poster presentation "PROMs in paediatric knee ligament injury: use the Pedi-IKDC and avoid using adult PROMs".
- 2017 MMC wetenschapsavond poster presentation "PROMs in paediatric knee ligament injury: use the Pedi-IKDC and avoid using adult PROMs"

Awards and nominations

2021 NVA lustrum congress: best poster award for "Height is a predictor of hamstring tendons length and closed socket anterior cruciate ligament (ACL) reconstruction graft characteristics in adolescents"

2021 NVA lustrum congress: 2nd place oral presentation Dr Eikelaar award for "Translation and transcultural validation of the Dutch HSS Pedi-FABS"

PhD Portfolio

Courses

2022 Advanced Instructional Course on Arthroscopy of the Knee

2021 GCP-WMO

Supervision / teaching

2022 R. Voskuilen, PhD candidate "Impact of ACL injuries on children and adolescents", Máxima Medical Centre
2022 S. Tamaç, master thesis medicine, PAMI
2021 tutor course "bewegingsapparaat", Maastricht University
2020 T. van de Kerkhoff, master thesis, HSS Pedi-FABS
2019 S. Verhagen, master thesis medicine, morphology study
2019 M. Brzoskowski, bachelor thesis physiotherapy, scoping review RTS

Peer reviewing

Journal Experimental Orthopaedics

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Curriculum vitae

Martijn Dietvorst was born in Eindhoven, the Netherlands on December 10^{th}, 1991. In 2010, Martijn graduated with distinction from secondary school (Gymnasium, Lorentz Casimir Lyceum, Eindhoven) and started his medical training at Maastricht University in Maastricht, the Netherlands. During his study, Martijn developed interests in the locomotor system and orthopaedic surgery, which resulted in science projects and pre-clinical work at the department of orthopaedic surgery in Jeroen Bosch Ziekenhuis, 's-Hertogenbosch, together with Ramon Roerdink. During his master, Martijn wrote his master thesis on a project called "Digitale poli voor frozen shoulder patiënten" under supervision of Hans Hendriks and Jean-Paul van Kollenburg at Máxima Medical Centre, Eindhoven. In 2016, Martijn completed his medical degree with distinction and started working as resident not in training under supervision of Rob Janssen, Jan van Mourik and Hans Hendriks at Máxima Medical Centre, Veldhoven. During this period, Martijn developed his interest in clinical research, ligament injuries of the knee and paediatric orthopaedics, which resulted in the start of this PhD thesis under supervision of Lodewijk van Rhijn, Rob Janssen, Marieke van der Steen and Max Reijman.

In 2018, Martijn started his residency at general surgery under supervision of Heinrich Janzing and Charles van Berlo at VieCuri Hospital, Venlo. Martijn returned in 2019 to Máxima Medical Centre for his orthopaedic residency under supervision of Rob Janssen and Hans Hendriks. For the academic part, Martijn continued his residency in 2021 in Maastricht University Medical Centre (MUMC+) under supervision of Heleen Staal, Lodewijk van Rhijn and Peter Feczko. In 2022, Martijn returned to Máxima Medical Centre to complete his specialty training in 2023.

During his medical study and residency, Martijn always enjoyed organizing educational projects (FORTE traveling fellowship "Under the knee" and "7 days around the shoulder, Educational meeting on finance of Dutch health care and hospitals), performing "doelmatigheidsprojecten", co-writing hospital protocols and educating patients and students. In his spare time, Martijn likes to windsurf, surf, cycle, skate, play bass guitar and cook (and eat!) Indonesian food. He lives in 's-Hertogenbosch together with ChiChi.