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

Martijn Dietvorst^{1*}, Stéphanie Verhagen¹, M. C. (Marieke) van der Steen^{1,2}, Peter Faunø³ and Rob P. A. Janssen^{1,4,5}

Background

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 [6–8, 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 [6–8, 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

*Correspondence: martjindietvorst@gmail.com

¹ Department of Orthopaedic Surgery & Trauma, Máxima MC, Eindhoven, the Netherlands

Full list of author information is available at the end of the article

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.

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 (Fig. 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.

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 Healthcare®, 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.

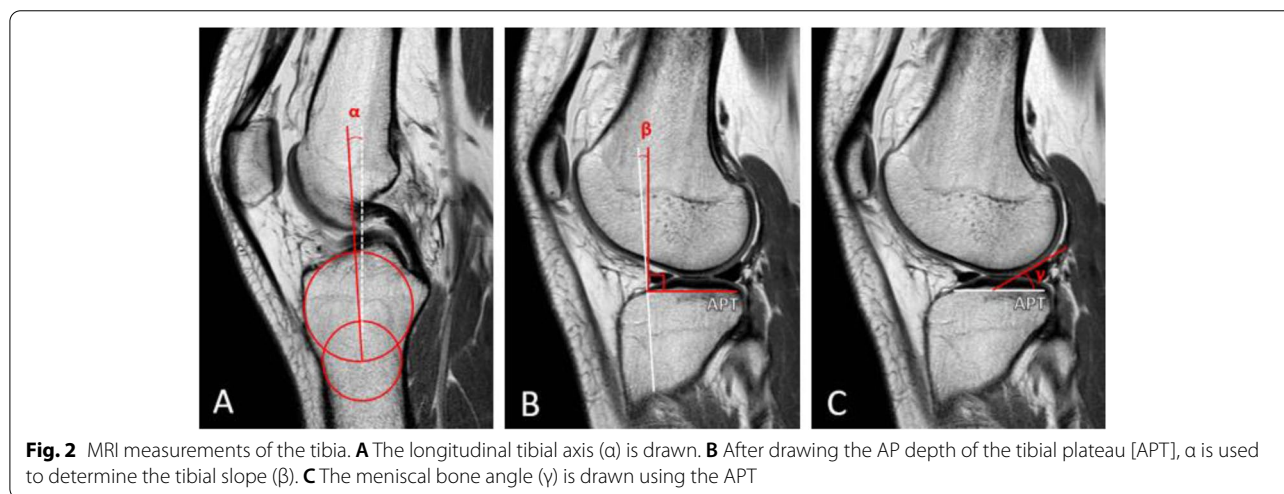
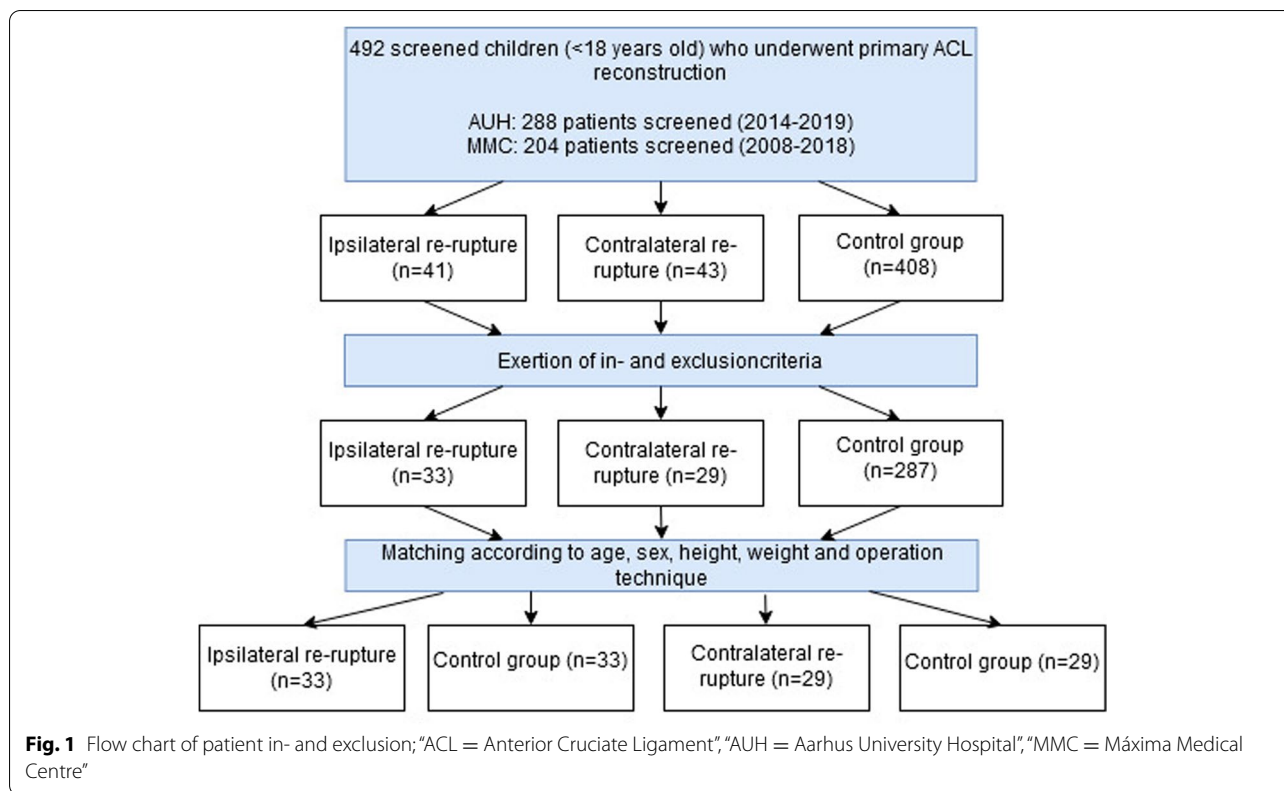
Tibia

The tibial parameters of interest were the tibial slope, the meniscal bone angle and the anterior-posterior depth of the tibial plateau (Fig. 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]

Table 1 In- and exclusion criteria for cases and controls

Inclusion criteria		Exclusion criteria
Cases	Controls	Overall
Age < 18 years ^a	Age < 18 years ^a	Absence of preoperative MRI or impossibility to perform measurements on the MRI due to 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	

^a < 18 years at time of primary ACL reconstruction



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 (Fig. 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 (Fig. 3) [14]. Second, the Porto ratio is calculated by dividing the flat femur surface (Fig. 3) by the AP depth of the tibial plateau (Fig. 2B) [31].

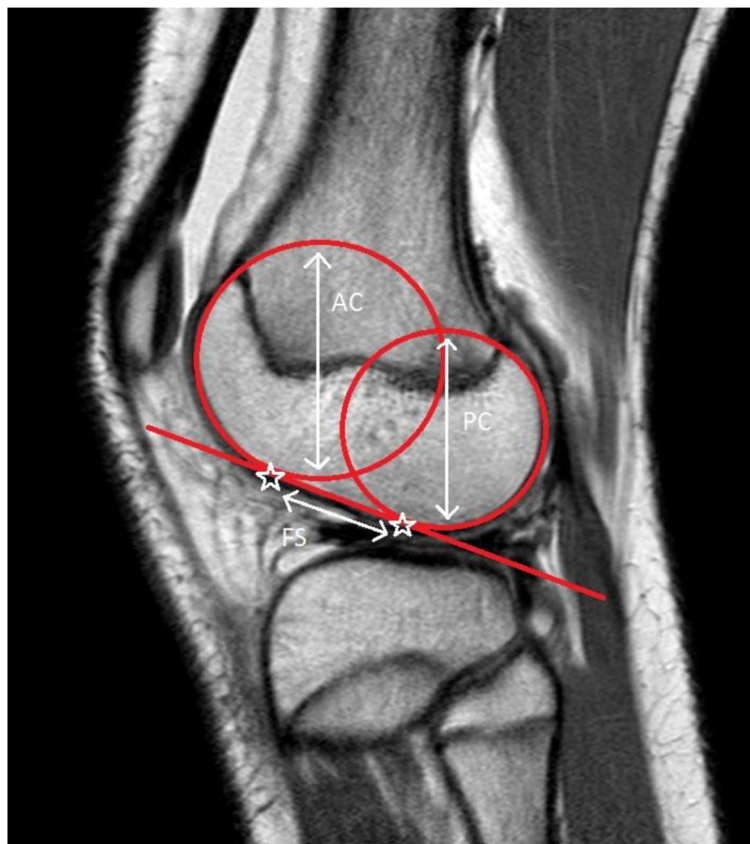


Fig. 3 MRI measurements of the femur. The anterior “extension” circle [AC] and posterior “flexion” circle [PC] are drawn [14]. A line tangent to both circles determines the flat surface [FS] [31].

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 inter-observer 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 Jaeger 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).

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

Table 2 Inter- and intra-observer reliability of morphological parameters ^a

	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)

^a Values are presented as intraclass correlation coefficient (95% CI). AP Anterior-posterior, CI Confidence interval

Table 3 Demographic characteristics ipsi- 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

and BMI between the ipsilateral and contralateral re-injured 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.

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 re-injured 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 $\geq 7^\circ$ was associated with re-injuries, as significantly more patients with a slope of $\geq 7^\circ$ had re-injuries ($p=0.023$).

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.

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 $\geq 7^\circ$ 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].

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 ($^\circ$)	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 ($^\circ$)	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

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

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., 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.

Conclusion

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 re-injured population had a significant greater lateral tibial slope compared to controls and slopes $\geq 7^\circ$ were associated with re-injuries. The lateral tibial slope was however not a discriminative factor for identifying risk of re-ruptures.

Abbreviations

ACL: Anterior Cruciate Ligament; ALL: AnteroLateral Ligament; AP: Anterior-Posterior; AUC: Area Under the Curve; AUH: Aarhus University Hospital; BPTB: Bone Patella Tendon Bone; CI: Confidence Interval; HS: Hamstrings; ICC: Intra-class Correlation Coefficient; IQR: Interquartile Range; LCL: Lateral Collateral Ligament; LFCI: Lateral Femoral Condyle Index; LFCR: Lateral Femoral Condyle Ratio; MCL: Medial Collateral Ligament; Máxima MC: Máxima Medical Centre; MRI: Magnetic Resonance Imaging; n.a.: Not applicable; PAMI: Paediatric ACL Monitoring Initiative; PCL: Posterior Cruciate Ligament; QT: Quadriceps Tendon; ROC: Receiving Operating Characteristics; SD: Standard Deviation.

Informed consent

Not applicable.

Authors' contributions

MD was the corresponding author, initiated the project, performed measurements and statistical analyses, SV performed measurements and statistical analyses and co-wrote the manuscript, MvdS initiated the project, performed statistical analyses, co-wrote the manuscript and was critical reviewer, PF initiated the project, provided patient database and was critical reviewer, RJ initiated the project, provided patient database and was critical reviewer. The author(s) read and approved the final manuscript.

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Declarations

Ethics approval and consent to participate

The study is approved by both the local ethical committee of Aarhus University Hospital and Máxima Medical Centre [L19.047].

Competing interests

The authors declare that they have no competing interests.

Author details

¹Department of Orthopaedic Surgery & Trauma, Máxima MC, Eindhoven, the Netherlands. ²Department of Orthopaedic Surgery & Trauma, Catharina Hospital Eindhoven, Eindhoven, the Netherlands. ³Department of Orthopaedic Surgery, Aarhus University Hospital, Aarhus, Denmark. ⁴Orthopaedic Biomechanics, Department of Biomedical Engineering, Eindhoven University of Technology, Eindhoven, the Netherlands. ⁵Chair Value-Based Health Care, Department of Paramedical Sciences, Fontys University of Applied Sciences, Eindhoven, the Netherlands.

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