Diagnostic Imaging of Patellofemoral Instability

Bildgebende Diagnostik der patellofemoralen Instabilität

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ABSTRACT

Background Throughout the literature, patellofemoral instability (PI) is defined as an increased risk of re-/luxation of the patella within the patellofemoral joint (PFJ). In most patients it is caused by traumatic patella luxation or the existence of a range of predisposing anatomic risk factors leading to an unphysiological movement sequence within the PFJ also known as patellofemoral maltracking. In order to provide an individualized therapy approach, clinical and radiological evaluation of those risk factors of variable magnitude becomes essential. Diagnostic imaging such as magnetic resonance imaging (MRI), plain radiography, and computed tomography (CT) are straightforward diagnostic tools in terms of evaluation and treatment of PI.

Method In this review we performed a precise analysis of today's literature concerning the radiological evaluation of anatomic risk factors leading to PI. The purpose of the review is to present a logical compilation of the different anatomical risk factors causing PI and provide a straight overview of valuable radiological imaging techniques.

Results and Conclusion PI is frequently based on a multifactorial disposition. The most relevant predisposing risk factors are trochlea dysplasia, rupture of the medial patellofemoral ligament (MPFL), patella alta, abnormal tibial tubercle to trochlea groove distance (TT-TG), femoral torsion deformities, and genu valgum. Although plain X-rays may provide basic diagnostic value, cross-sectional imaging (MRI, CT) is the standard radiological tool in terms of evaluation and detection of severity of predisposing anatomic variants leading to PI.

Key Points:

- Based on today's literature, PI is characterized as an increased risk of patella re-/luxation within the PFJ.
- Underlying anatomic risk factors of variable magnitude mark the pathological cause of PI.
- Modern diagnostic imaging (MRI and CT) permits straightforward diagnosis of the typical features in terms of PI.
- To provide an individualized therapy approach, precise radiological evaluation and determination of the severity of predisposing anatomic anomalies are essential.

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ZUSAMMENFASSUNG

Hintergrund Die patellofemorale Instabilität (PI) umschreibt ein erhöhtes Luxations- bzw. Reluxationsrisiko der Kniescheibe im Patellofemoralgelenk (PFG). In den meisten Fällen liegt ein adäquates Trauma mit Patellaluxation und Verletzung des Haltebandapparats oder das Vorliegen anatomischer Risikofaktoren vor, welche zu einem unphysiologischen Bewegungsablauf im Patellofemoralgelenk führen (Maltracking). Neben der Anamnese und der klinischen Untersuchung stellt die radiologische Bildgebung (Röntgen, Computertomografie und Magnetresonanztomografie) den zentralen Grundpfeiler bei der Diagnostik der PI dar, um das Vorliegen und den Ausprägungsgrad anatomischer Risikofaktoren zu evaluieren.

Methodik Im Rahmen dieser Übersichtsarbeit wird der aktuelle Stellenwert der bildgebenden Diagnostik und Therapieplanung der patellofemoralen Instabilität vorgestellt. Das Ziel dieser Arbeit besteht in der übersichtlichen Darstellung der wichtigsten anatomischen Risikofaktoren der PI sowie der Möglichkeiten der Bildgebung, diese zu detektieren und zu quantifizieren.

Ergebnisse und Schlussfolgerung Die PI basiert häufig auf einer multifaktoriellen Disposition. Bei den Risikofaktoren muss zwischen der Trochleadysplasie, strukturellen Defekten des medialen patellofemoralen Ligaments (MPFL), der Patella alta, einer erhöhten Tuberositas-Tibiae-Trochlea-Groove-Distanz (TT-TG), Torsionsdeformitäten sowie dem Genu valgum differenziert werden. Obwohl das konventionelle Röntgen häufig noch zur Basisdiagnostik der PI eingesetzt wird, ist die Schnittbilddiagnostik (MRT und CT) heutzutage die Methode der Wahl, um die PI und ihre zugrunde liegenden Risikofaktoren zu evaluieren.

Introduction

Patellofemoral instability (PI) describes an elevated risk of dislocation/redislocation of the patella. PI can occur after traumatic patellar dislocation caused by injury to the patellofemoral ligaments and is associated with an increased risk of redislocation. Alternatively, PI can be the result of unphysiological movement of the patella within the trochlear groove (known as maltracking) resulting in recurrent patellar dislocation or subluxation [1]. PI causes cartilage damage at the joint surfaces, which often ultimately results in retropatellar arthrosis [2].

The incidence rate of PI is 7–49 per 100 000 inhabitants [3]. Young, athletic, active women are most commonly affected. Typical symptoms include anterior knee pain and recurrent spontaneous patellar dislocation. Patients can remain symptom-free for a long time. Initial clinical manifestation of PI is often preceded by an acute injury to the knee [4]. An important clinical finding in PI is the “J sign”, which describes the sudden lateralization of the patella in cranial extension [5].

Knowledge of the multiple, often connected, anatomical risk factors is important for diagnosis and treatment planning in PI. Different treatment concepts are initiated depending on the presence of maltracking and the presence or combination of various risk factors [1]. In addition to clinical examination, imaging is a cornerstone of diagnosis and treatment planning in PI. Methods include conventional radiography, magnetic resonance imaging (MRI), and multidetector computed tomography (MDCT). Kinematic MRI and 4-dimensional computed tomography (4D-CT) are additional innovative examination techniques that make it possible to visualize movement of the patella in real time[6, 7]. Finally, quantitative MRI is a promising method that allows early detection of cartilage damage due to maltracking.

Anatomy and biomechanics

Anatomy

Articulation between the patella and the trochlea in the patellofemoral joint is a complex sequence of movements with the bony structures, the quadriceps tendon, the joint capsule, and the ligaments contributing greatly to stability. Deviations in this physiological anatomy are risk factors for PI. The retropatellar joint surface is comprised of a prominent lateral facet, a median ridge, and a medial facet. The trochlea has a classic concave shape. With its upper pole attached to the quadriceps tendon, the patella is surrounded by all four parts of the quadriceps femoris muscle. Muscle fibers of the quadriceps tendon extend over the anterior surface of the patella and connect as an aponeurosis to the patellar tendon which is attached to the tibial tubercle [7]. One of the most important static stabilizers of the patella is the medial patellofemoral ligament (MPFL) [8]. The MPFL runs almost horizontal to the vastus medialis oblique (VMO) between the medial femoral epicondyle and the medial edge of the patella [9], The MPFL has a close anatomical location with fibers radiating into the joint capsule, medial collateral ligament, and medial retinaculum. In addition, there are bundles of fibers between the anterior portion of the MPFL and the tendon of the VMO, the most important dynamic stabilizer against lateral patellar translation [10, 11] (▶ **Fig. 1**).

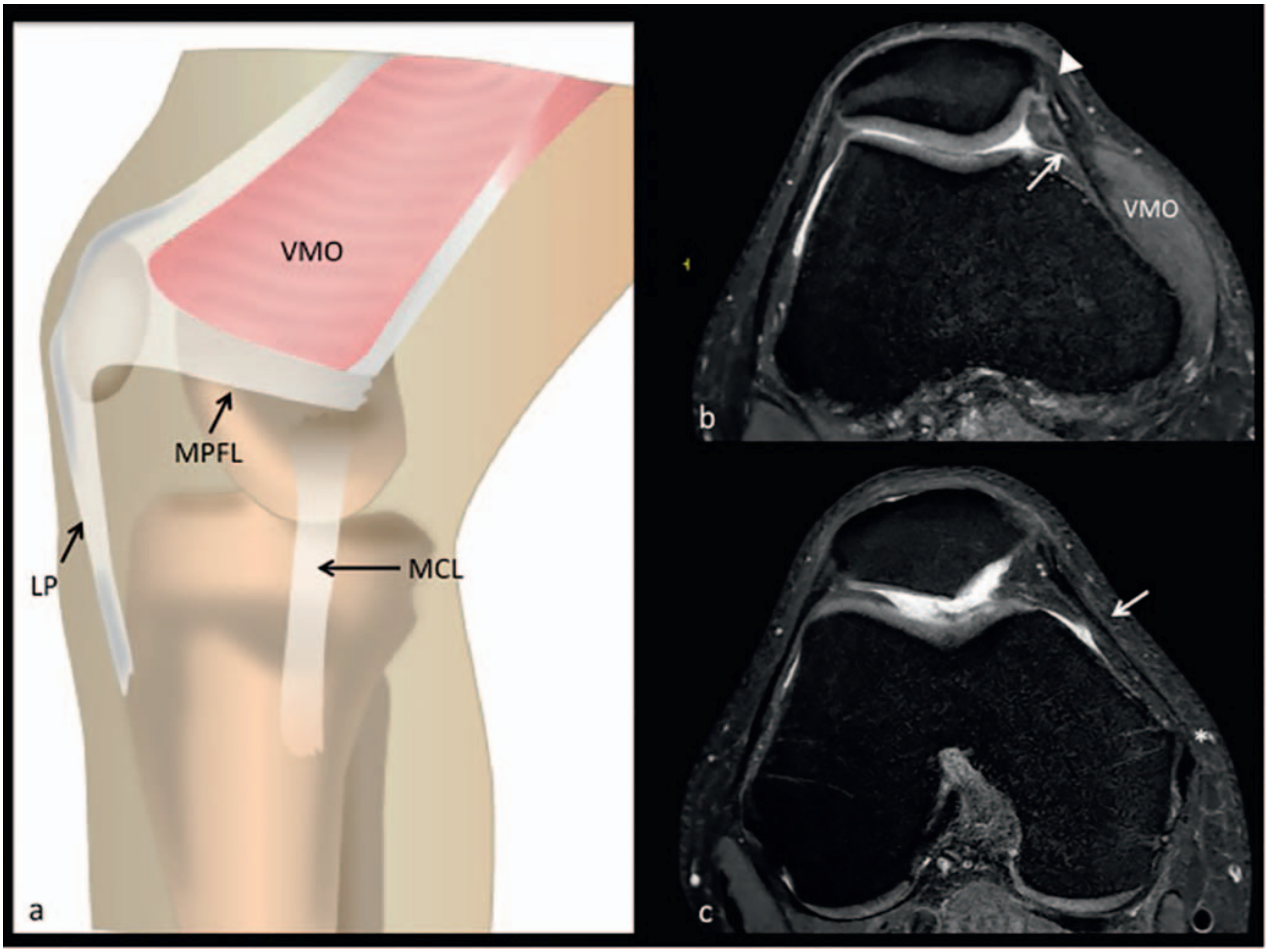
Biomechanics

During physiological flexion of the knee, the patella slides back and forth in the trochlear groove accompanied by mediolateral translation. In full extension the patella is still proximal to the trochlear groove. At the start of flexion (0–40°), only the distal portion of the patella is in contact with the proximal part of the trochlear groove. In this phase of movement, the MPFL plays a significant role in the stabilization of the patella and prevents lateral dislocation [12]. In the case of flexion > 40°, the morphology of the trochlear groove becomes increasingly important since the patella slides further into the groove.

Starting at a flexion of 60°, the muscular structures, primarily the VMO, have a stabilizing function and center the patella in the trochlear groove during flexion.

Stability and instability

Patellofemoral joint stability is described as “the patella being guided into the trochlear groove and kept engaged within the trochlear groove” by constraint by passive soft tissue tethers, bony geometry, and active muscle contraction as the knee flexes and extends. PI is defined as the deficiency of passive constraint (patholaxity) when the patella partially or completely leaves its physiological position under the influence of a displacing force. Such forces can be generated by muscular tension, movement, or external forces. An intact medial and lateral retinaculum, a physiological joint formed by the patella and trochlear groove, and the height of the patella are factors supporting patellofemoral stability. The quadriceps femoris provides important active stability. In particular, the VMO counteracts patella lateralization during flexion [9]. A conventional means of clinically evaluating the quadriceps femoris with regard to the presence of maltracking is meas-



▶ **Fig. 1** **a** Medial view of the anatomical structures and the course of the MPFL. **b, c** MPFL (arrow) with almost horizontal orientation of the ligament fibers with respect to the VMO (vastus medialis obliquus) originating at the medial femoral epicondyle (*) and with insertion at the medial edge of the patella (tip of the arrow). LP = patella ligament.

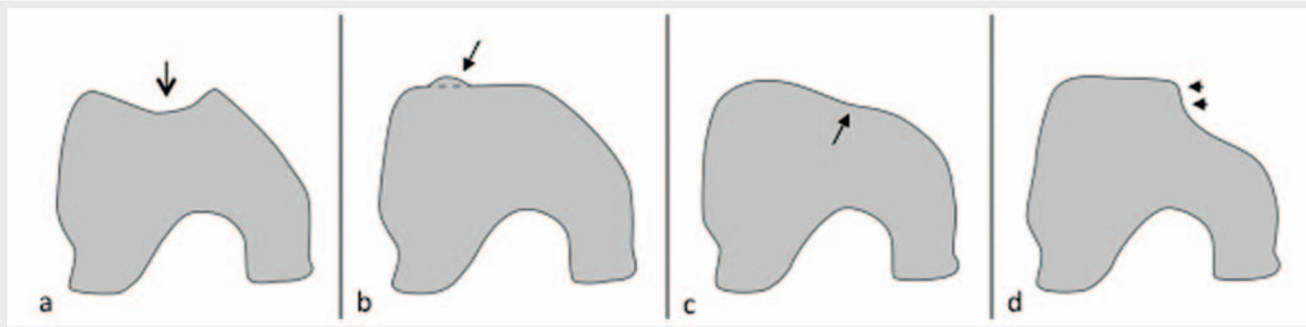
urement of the Q-angle (quadriceps angle) at 25° flexion. The angle between the two intersecting lines (anterior superior iliac spine to the center of the patella and center of the patella to the tibial tuberosity) is measured. Values > 20–25° are considered a relevant pathological factor regarding PI [13].

The MPFL is a main stabilizer in the patellofemoral joint. In the case of a knee with an insufficient MPFL, the force needed for lateral translation of the patella is reduced by 50 % in an extended position thereby greatly increasing the risk of lateral PI. Further risk factors like patella alta, femorotibial torsion deformities, increased TT-TG distance, or trochlear dysplasia also contribute to PI [3, 14]. In light of the above factors that can all influence patellofemoral joint instability, it is clear that PI usually has a multifactorial origin. The extent of the individual factors in PI can vary greatly on an individual basis [15]. Therefore, it is important to identify these anatomical parameters with the help of radiological imaging and to quantify them when possible since their presence and extent influence the selection of the optimal treatment [16]. The most important risk factors as well as their classification and importance are shown in the following (▶ **Table 1**).

Risk factors

Trochlear dysplasia

Trochlear dysplasia (TD) is considered the most important congenital risk factor for PI [17]. A characteristic of TD is a flattened medialized trochlear groove, that however does not affect the condyles at the anteroposterior level. As a result, the trochlear groove does not ensure proper tracking of the patella. In addition, there is flattening of the lateral slope of the lateral trochlear facet. The trochlear groove is then often not only slightly concave but is often flat of even convex. According to Dejour et al., there are four different types of trochlear dysplasia that are considered predisposing risk factors for PI [18]. Type A is a mild form of dysplasia with only flattening of the trochlear angle (> 145°). More severe forms of dysplasia are represented by types B-D. Type B dysplasia is characterized by a flattened trochlea with a prominent supratrochlear spur or bump on the joint surface. Type C indicates flattening of the trochlea with hypoplasia of the medial joint facet and convexity of the lateral joint facet. Finally, type D refers to complete flattening of the trochlea and an abrupt depression in



▶ **Fig. 2** Axial view of trochlear dysplasia according to Dejour. **a** Dysplasia type A with flattening of the trochlea (sulcus angle > 145°) but concavity is preserved (arrow). **b** Dysplasia type B, lateral facet is flat to convex, possibly with supratrochlear spur or bump (arrow). **c** Dysplasia type C, lateral facet is convex, and the medial facet is hypoplastic (arrow). **d** Dysplasia type D, complete flattening of the trochlea with abrupt depression in the medial facet (cliff sign; arrows).

the medial facet (cliff sign), the most severe form of trochlear dysplasia according to Dejour [18] (▶ **Fig. 2**).

In addition to the categorization according to Dejour, there are a number of geometric measurement techniques that can be used to diagnose trochlear dysplasia. Determination of the trochlear depth (or the groove angle), the trochlear facet asymmetry, and of the lateral trochlear inclination are the most useful methods [19]. To perform MRI measurements, the selection of an imaging plane approximately 3 cm above the joint line is recommended. However, this anatomical reference point varies on an individual basis due to differences in the size of the patient's knee joint. The entire trochlear facet should always be covered with cartilage. To determine the lateral trochlear inclination, the angle between the subchondral bone of the lateral trochlear facet and a tangent along the posterior edge of the femoral condyles is measured. An angle < 11° is considered pathological here. Trochlear facet asymmetry is calculated from the ratio of the width of the medial lateral facet to the lateral trochlear facet (normal value > 40 %). The trochlear depth is defined as the distance from the cartilage surface to the deepest point of the groove (normal value > 3 mm) (▶ **Fig. 3, 4**). The shape of the patella (Wiberg's classification A-C), which is based on the configuration of the lateral and medial joint facet, is considered a further cause of TD. Type A (medial and lateral facet equal length and concave) as well as type B (flattened medial slightly shortened facet) are considered non-pathological patella shapes, while a convex, shortened medial joint facet (Wiberg Type C) is considered a risk factor for the development of patellofemoral instability [20]. A pathologically increased patella tilt (angle between the posterior edge of the femoral condyles and the axis of the patella on the axial plane) is a further "patellar" risk factor for PI and a consequence of TD (▶ **Table 2**) [51].

Patella-Nail Syndrome is a rare form of congenital osseous dysplasia that is typically associated with severe patellofemoral instability. Pathognomonic changes caused by this disease include dysplasia of the patella, the fingernails, and the head of the radius, and typical iliac horns. Characteristic patellofemoral joint findings include a dysplastic and lateralized patella as well as dysplasia of the femoral trochlea, with the lateral femoral condyle often representing the patellar groove. Cartilage damage can often already be detected on MRI at the time of diagnosis (▶ **Fig. 5**).

▶ **Table 1** Overview of risk factors for patellofemoral instability.

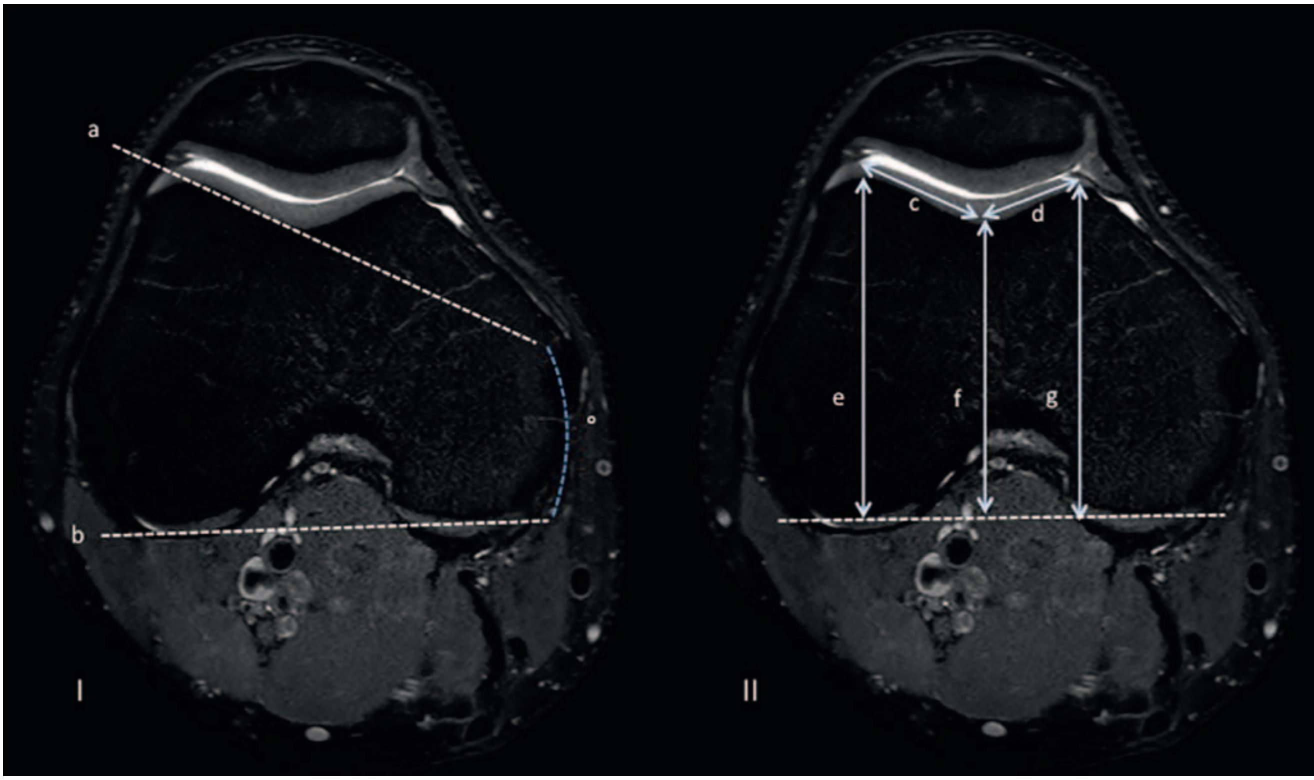
risk factors	
trochlear dysplasia	▪ Dejour classification (A–D) ▪ quantification (standard values) based on: – trochlear depth: 3–10 mm – lateral trochlear inclination angle: 11–16.9° – trochlear facet asymmetry limit value: > 40 %
increased TT-TG distance	▪ physiological range: 10–15 mm ▪ pathological > 15 with maltracking, ≥ 20 mm
structural defect of the MPFL	▪ critical stabilizer of the patellofemoral joint ▪ course in the deep portion of the medial retinaculum ▪ most commonly injured ligament after patella luxation
patella alta	▪ Insall-Salvati Index (ISI) range: 0.8–1.2 ▪ Caton-Deschamps Index (CDI) range: 0.6–1.2
genu valgum	pathological: lateral deviation from the Mikulicz line > 10 mm or leg axis turned outward by > 5°
pathological torsion angle of the axis of the leg	physiological torsion angle according to Strecker et al.: ▪ femoral internal torsion: 24.1 ± 17.4° ▪ tibial external torsion: 34.9 ± 15.9°

Medial patellofemoral ligament (MPFL)

Injury to the medial retinaculum is the most common pathomorphology after patellar dislocation. In almost all cases, the MPFL is also affected [15]. Current studies show the patellar insertion as the most common location (50–90 %) [21]. The MPFL is the most important passive stabilizer against lateral translation when the knee is almost fully extended so that a structural defect of the MPFL often results in hypermobility of the patella. As a result, MPFL injuries should be treated surgically depending on the risk of recurrent dislocation to prevent future PI [8, 12] (▶ **Fig. 6**).

Patella alta

A high-riding patella is specified as a relative anatomical risk factor for the development of PI [17, 22]. In the physiological state, the



▸ **Fig. 3** Measurement parameter regarding trochlear morphology. (I) Lateral trochlear inclination: Angle (°) measured between a line along the subchondral bone of the lateral trochlea **a** and the dorsal femoral condyle plane **b**. Limit value < 11°. (II) Trochlear facet asymmetry and trochlear depth. Trochlear facet asymmetry: Length of the medial trochlear facet **d** divided by the length of the lateral trochlear facet **c** in percentage = d/c – 100 %. Normal value > 40 %. Trochlear depth: The distance of the trochlear groove **f** is subtracted from the mean of the distances of the lateral **e** and medial **g** trochlear facet to the dorsal femoral condyle plane = (e + g)/2–f. Normal value > 3 mm.

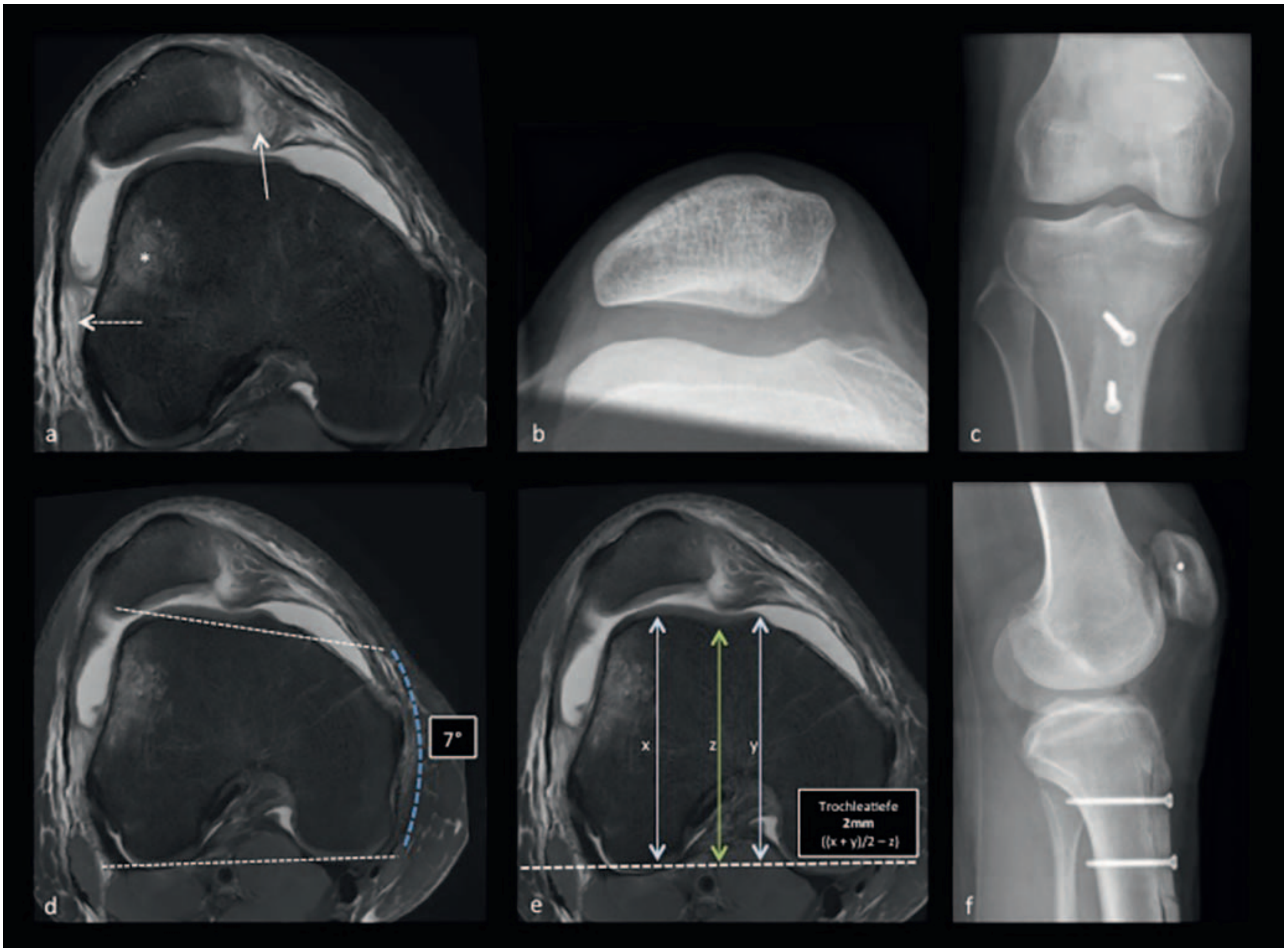
patella slides into the trochlear groove as flexion increases and is stabilized by the groove. In the case of a pathologically large distance, contact of the joint facets is delayed so that the patella has less bony stability. Lateral X-ray of the knee at approx. 30° flexion is a simple means of determining the height of the patella. The Insall-Salvati Index (ISI) and the Caton-Deschamps Index (CDI) are two established measurement methods. The ISI is the ratio of the length of the patellar tendon to the longest sagittal diameter of the patella [23]. The CDI is based on the ratio between the length of the retropatellar joint surface and the distance between the caudal pole of patella and the anterior tibial joint surface. In both measurement methods, patella alta is defined with a ratio > 1.2.

TT-TG distance

If the tibial tuberosity (TT) as the attachment point of the patellar tendon is lateralized compared to the trochlear groove (TG), the force vector is directed outward resulting in a predisposition to PI. The TT-TG distance is a simple and reproducible method for determining the valgus stress (lateralization) on the patella. The distance from the lowest point of the trochlear groove to the center of the tibial tuberosity (TT) on axial views of cross-sectional images is measured. Both anatomical measurement points are projected onto a 90° tangent with respect to the posterior edge of the femoral condyles. The distance between both lines represents the TT-TG distance. Physiological TT-TG values are

▸ **Table 2** Patella Instability Severity Score (PISS) according to Balcarek et al. 2014.

risk factors	points
age	
▪ > 16	0
▪ < 16	1
bilateral instability	
▪ no	0
▪ yes	1
trochlear dysplasia	
▪ none	0
▪ mild	1
▪ severe	2
height of the patella	
▪ < 1.2	0
▪ > 1.2	1
TT-TG distance (mm)	
▪ < 16	0
▪ > 16	1
patella tilt (°)	
▪ < 20	0
▪ > 20	1
maximum number of points	7



▶ **Fig. 4** 16-year-old female with patella instability and recurrent bilateral patellar dislocation. **a** MRI after spontaneous patellar dislocation shows lateral subluxation of the patella with postcontusional edema in the lateral femoral condyle (*). In addition, rupture of the MPFL (arrow) and the lateral retinaculum (dashed arrow). Signs of trochlear dysplasia (type B according to Dejour) on radiography **b** and MRI **d, e** with flattened lateral trochlear inclination (7°) and decreased trochlear depth (2 mm). Decision to perform trochleoplasty with medialization of the tibial tuberosity and MPFL augmentation using autologous gracilis tendon (postoperative radiological follow-up **c, f**).

< 15 mm. Values of ≥ 16 mm in connection with maltracking and distances > 20 mm are considered pathological and there is an indication for surgical tuberosity transfer [17, 24] (▶ **Fig. 7**). For several years, the TT-PCL (tibial tuberosity – posterior cruciate ligament) distance has been increasingly used in the clinical routine since it can be measured in a flexion-independent manner in contrast to the TT-TG distance [25].

Genu valgum

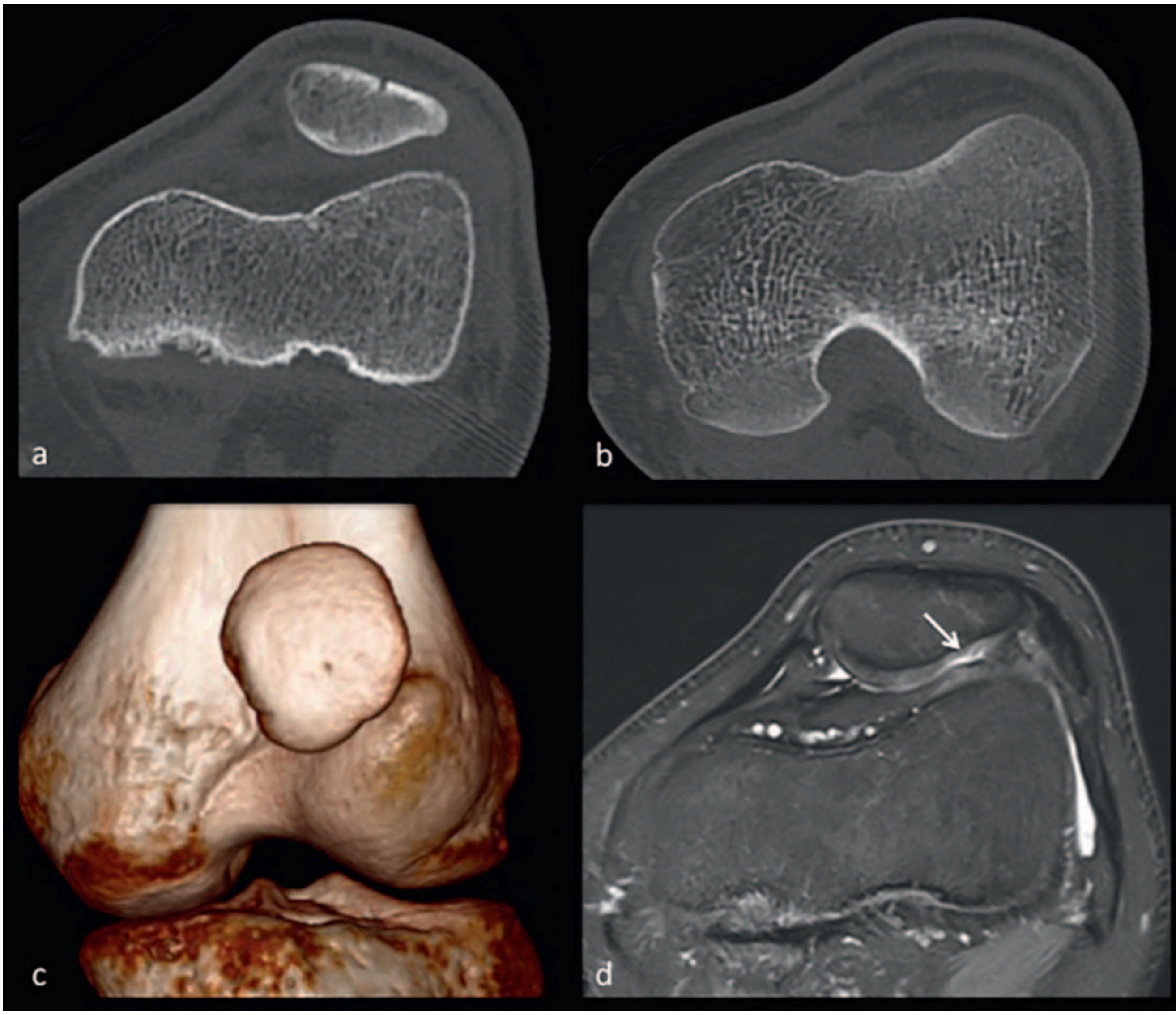
Genu valgum is considered a risk factor for patellofemoral instability [26]. Valgus alignment of the axis of the leg results in lateralization of the patella and a modified patellar tilt. Biomechanical studies were also able to show that a valgus deformity of the axis of the leg has a significant effect on patellar tracking. A leg axis that is turned outward by > 5° or lateralization of the leg axis > 10 mm from the Mikulicz line in combination with corresponding clinical symptoms is discussed here as a valgus deformity requiring surgery [27].

Torsion deformities

Torsion deformity is described as a further risk fact for PI. The term "inwardly pointing knee" was first described by Cooke et al. in 1990 [28]. In approx. 12 % of all patients with maltracking, a torsion deviation was identified as the cause. An internal torsion of 24.1° (± 17.4°) is described in the literature as the standard value for femoral torsion and an external torsion of 34.9° (± 15.9°) for the tibia [29]. Exact threshold values for surgical correction of torsional deviations have not yet been defined in the literature. Torsional deviations of 10° or more with corresponding clinical symptoms are being discussed [29] (▶ **Fig. 8**).

Patellar instability severity score (PISS)

Depending on the patient's anatomic and demographic risk factors, the risk of recurrence after initial patellar dislocation can vary significantly. Accordingly, the expected success of conserva-



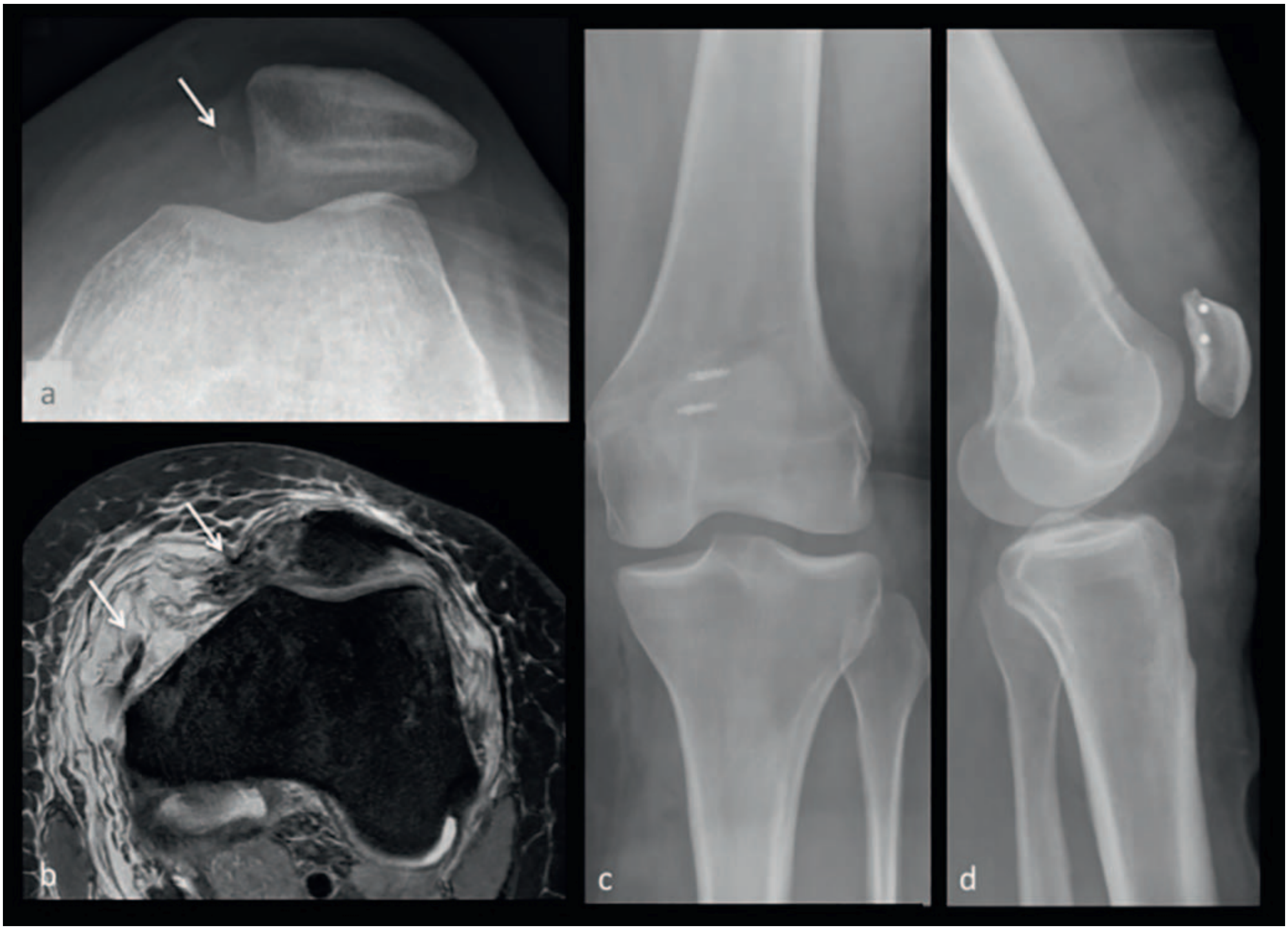
▶ **Fig. 5** 19-year-old patient with confirmed Patella-Nail Syndrome and chronic bilateral patella instability. Transverse CT images **a, b** and 3D reconstruction **c** show left-sided trochlear dysplasia (Dejour C). The trochlear groove shows marked flattening, and the articulation of the patella is highly lateralized with the lateral femoral condyle. The fat-saturated proton-weighted MRI sequence shows a loss of substance and signal changes in the cartilage at the lateral retropatellar joint facet (arrow) indicating the onset of chondropathy **d**.

tive or surgical treatment approaches depends greatly on the combination of various factors [52]. Predictive scoring systems like the patellar instability severity (PISS) score are helpful clinical tools that allow assessment of the risk of recurrent dislocation after initial patellar dislocation based on risk factors. Patient age, bilateral instabilities, trochlear dysplasia, TT-TG, patellar tilt, and patellar height are taken into consideration in the PIS score and are added up in a point system as a function of their extent. A point value of ≥ 4 points is associated with an up to 5 times greater risk of recurrent dislocation (▶ **Table 2**) [53].

Treatment options

The classification of PI and/or maltracking in individual subtypes according to Frosch et al. can be used to support a comprehensive, structured treatment approach [30]. It must be taken into consideration that PI and maltracking are different pathologies and this difference must also be taken into consideration in treatment. After initial patellar dislocation, surgical treatment of the underlying pathology is indicated due to the high risk of recurrent dislocation and the often associated subsequent chondral damage. In addition to the fixation or removal of cartilage or cartilage-bone fragments, reconstruction of the MPFL is a commonly used treatment approach. PI (but not maltracking) can be treated this way and a recurrence of patellar dislocation can be prevented.

In contrast, maltracking is usually caused by bone and requires careful analysis. In the case of a pathological TT-TG distance, tuberosity osteotomy can be used as a therapeutic option to change the TT-TG distance and the patellar height [31]. Normalization of the TT-TG is critical here. Overcorrection must be avoid-



▶ **Fig. 6** 30-year-old female with traumatic patellar dislocation. **a** Conventional radiography of the patella shows lateral subluxation of the patella. In addition, there is a small bony avulsion medial to the patella (arrow). **b** MRI (PD weighting with FS transverse) confirmed the suspicion of MPFL rupture with bony avulsion (arrow). **c, d** Normal postoperative finding in radiological follow-up after arthroscopy with removal of the loose body and MPFL reconstruction via gracilis transplant.

ed. In the case of incomplete growth and open epiphyseal plates, a transfer of the patellar tendon insertion can be performed [31]. In patients with chronic PI, trochlear dysplasia is present in up to 96 % of cases [32]. While MPFL reconstruction is usually sufficient in patients with a mild form of dysplasia (Dejour type A), trochleoplasty is often additionally necessary in the case of severe forms of dysplasia (types B-D) [31, 33].

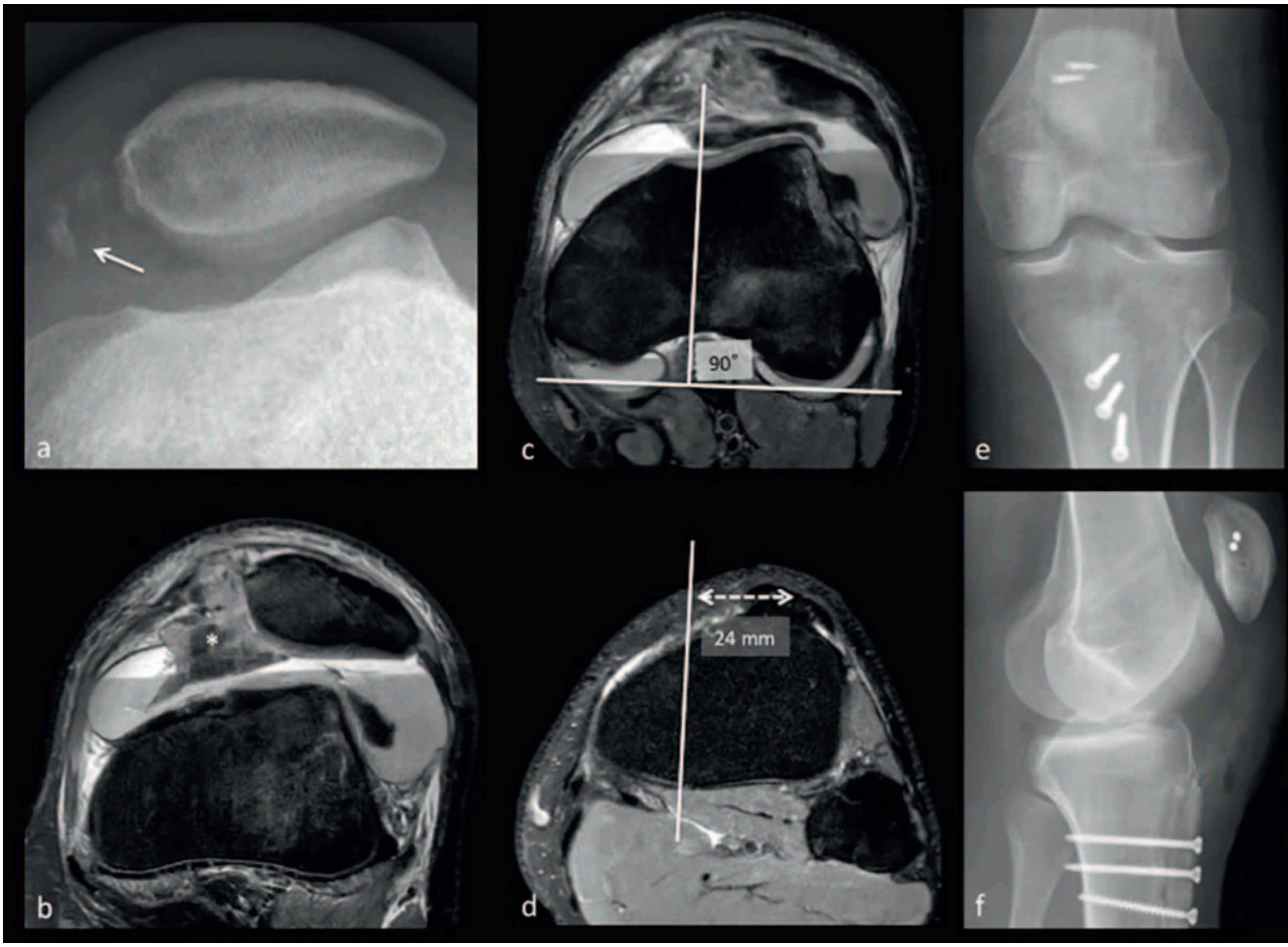
In the case of an axial deformity in the form of genu valgum or a torsional deformity as the cause of PI, adjustment osteotomy is the method of choice [31]. Distal femoral osteotomy is a validated method in the treatment of symptomatic genu valgum in fully grown patients [27] (▶ **Fig. 9**). However, it must be taken into consideration that the bone deformity is not always in the femur but is located in the tibia in up to 20 % of cases. This would then result in a correction of the tibial axis. Therefore, an exact preoperative analysis of the leg geometry is essential for planning purposes.

Diagnostic imaging

Conventional radiography

Traditionally, conventional X-ray of the knee joint on two planes (a. p. and lateral) and axial projection of the patella (in 30–45 % flexion) is the standard imaging method for ruling out fracture. However, it was able to be shown in multiple studies that the evaluation of anatomical risk factors is limited due to the use of inexact imaging settings [34]. Therefore, torsional deformities can mask or simulate trochlear dysplasia if a true lateral view is not used or in the case of flexion > 45° on the axial projection [34]. Therefore, conventional imaging is being increasingly supplemented by cross-sectional imaging methods like CT and MRI, particularly for preoperative planning.

Anterior-posterior native full leg standing radiographs are used to diagnose genu valgum. The most common indication for full leg imaging is determination of the axis of the lower extremity on the coronal plane prior to surgical correction of the leg axis [35], A



▶ **Fig. 7** 17-year-old patient after recurrent patellar dislocation while playing soccer. **a** Radiograph shows bony avulsions of the medial patella (arrow). **b–d** Detection of a rupture of the MPFL in MRI examination (PD weighting with FS, transverse) (*). The calculated TT-TG distance (24 mm) is abnormally high **c, d**. Decision to perform open surgical MPFL reconstruction (autogenous gracilis tendon) and osteotomy of the tibial tuberosity with medialization according to Elmslie (8 mm) with normal finding in the postoperative follow-up **e, f**.

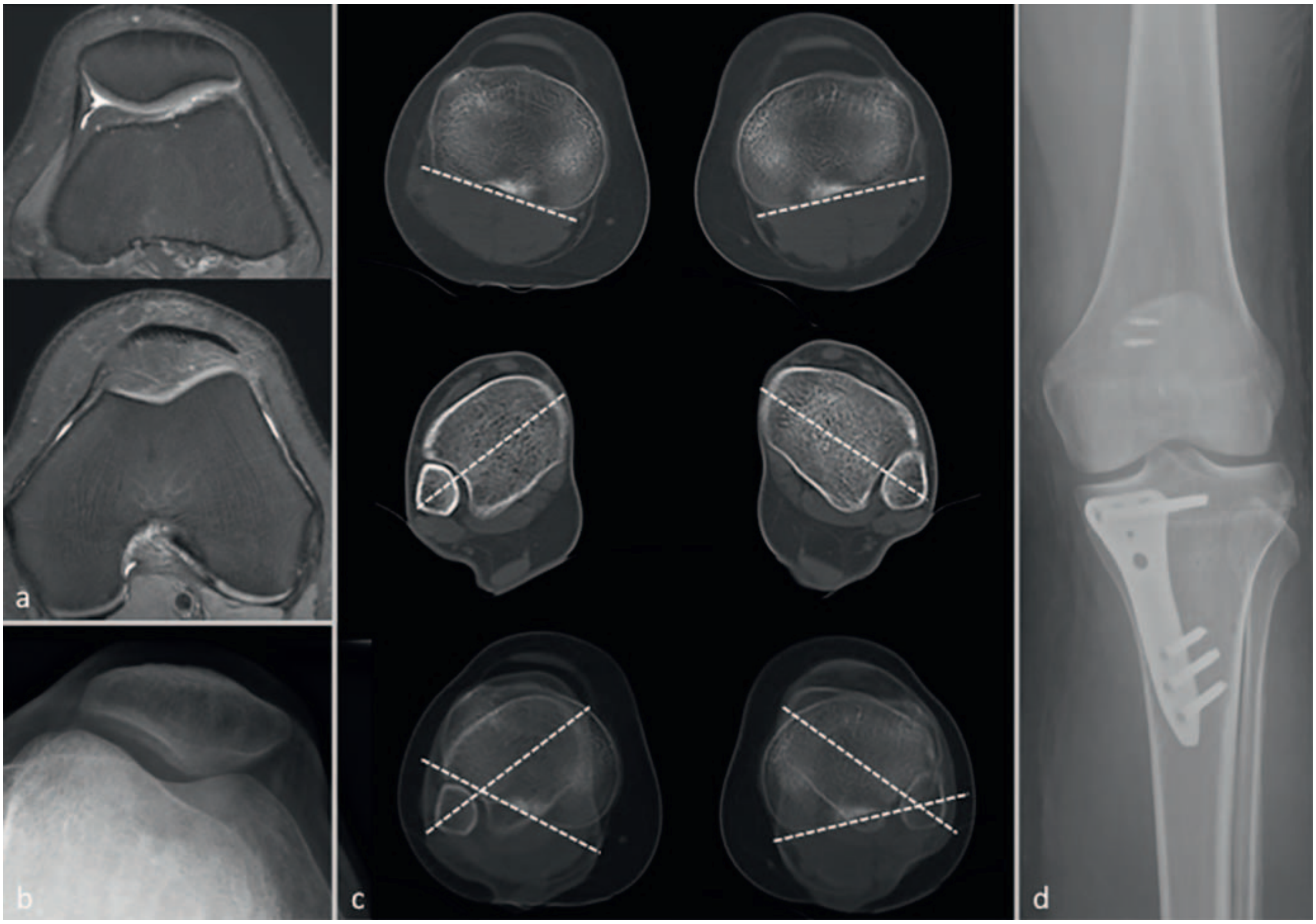
deviation of the axis of the leg from the physiological mechanical axis of the knee joint (Mikulicz line; connecting line between the center of the femoral head and the center of the upper ankle joint with a course 4 + 2 mm medial to the center of the knee joint) is registered for this purpose (▶ **Fig. 10**). Additional joint angles (e. g., mechanical lateral distal femoral angle, etc.) can be determined for further analysis of deformity caused by axial malalignment. Following surgery, the position of the osteosynthesis material can be monitored with respect to material defects or loosening (▶ **Fig. 9**). An essential quality feature when acquiring a full leg image is centering of the patella between the femoral condyles and strict extension of the knee joint, which is usually associated with an outward rotation of the feet of 8–10° [54].

MDCT

Multidetector CT (MDCT) is an established examination modality that primarily allows characterization of the bone structure and a detailed evaluation of bone injury patterns. MDCT is valuable with respect to diagnosis and treatment planning in rotational deformities and bony torsional deformities. Acquisition of selective axial CT images of the hip, knee, and ankle is a relatively simple and dose-reduced method for measuring a torsional deformity. To determine the femoral anteversion angle, the angle between the center of the hip joint and the center of an ellipse around the greater trochanter is measured [36]. The tibial torsion angle is the angle between a line drawn dorsal to the proximal tibial plateau and the axial transverse axis of the distal mortise (▶ **Fig. 8**). The measurement can also be performed with MRI, which should be used as a radiation-free alternative in young patients [37].

MRI

Today, MRI is considered a validated method for the diagnosis and characterization of PI [21]. It allows precise evaluation of the scope of injury after patellofemoral dislocation. A clear advantage is the ability to visualize associated injuries, primarily of the MPFL and articular cartilage [21, 38]. Patellofemoral maltracking can also result in fluid accumulation in the surrounding soft tissue due to constriction or abnormal mechanical stress. Therefore, edema in the superolateral Hoffa's fat pad can be an indirect indication of maltracking [39].

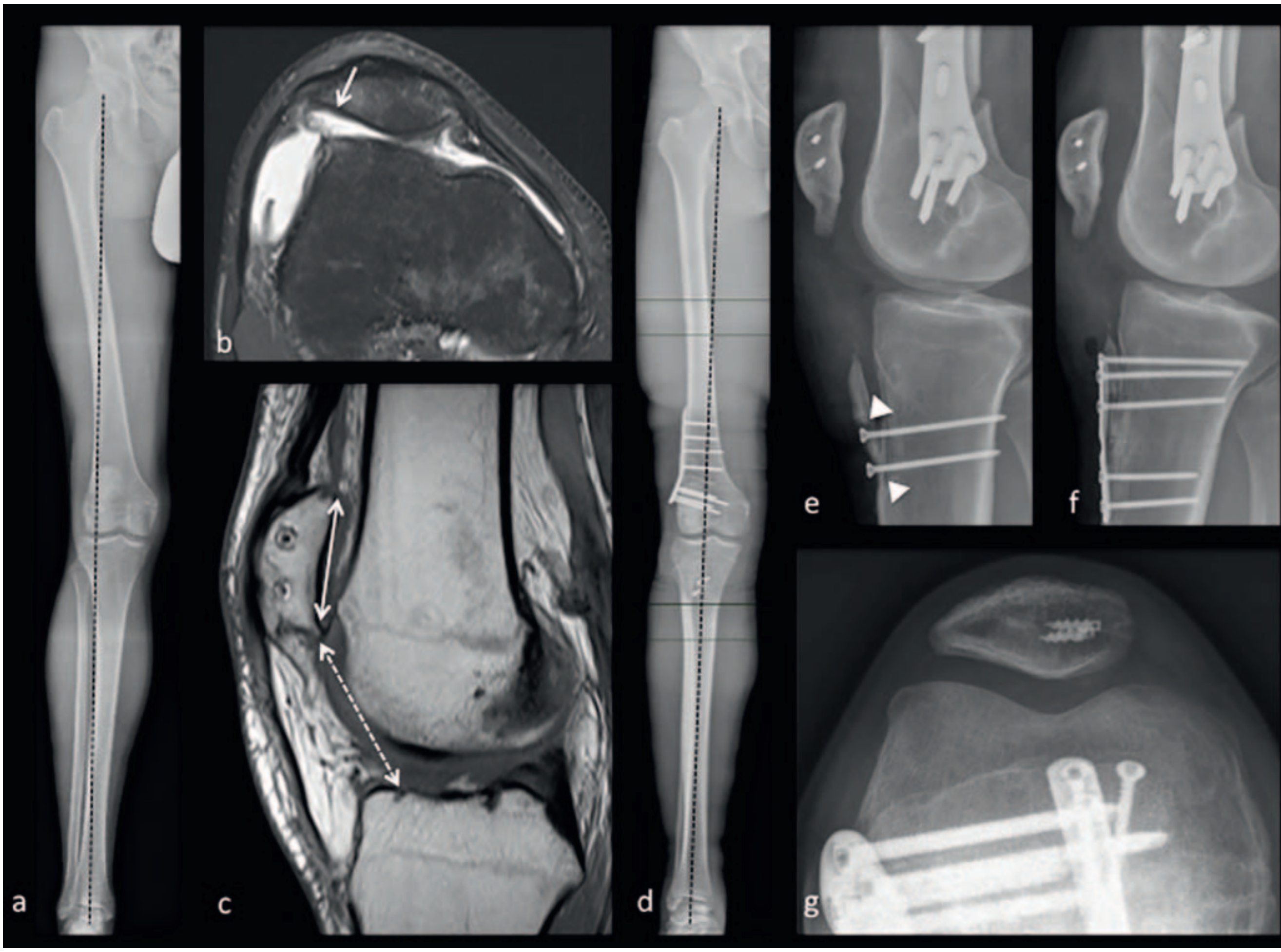


▶ **Fig. 8** 29-year-old female with severe left-sided knee pain with known patellofemoral instability and recurrent patellar dislocation. **a** MRI examination of the knee joint shows proper position of the patella with unremarkable cartilage finding. **b** Axial projection of the patella shows a torsion deformity with overlapping of the tibia and the femoral condyles. **c** CT for determination of the torsion angle shows abnormally high external torsion of the tibia, bilateral, with an angle of 56° on the right and 51°on the left. Due to the presence of symptoms exclusively on the left side, a decision was made to perform unilateral corrective surgery. An internal torsional osteotomy of the tibia (proximal to the tuberosity of the tibia) with a fixed-angle plate and MPFL reconstruction using ipsilateral autologous gracilis tendon were performed. Normal postoperative finding on radiological follow-up **d**.

When evaluating the severity of trochlear dysplasia, MRI yields higher interobserver agreement compared to conventional radiography [40, 41]. For the differentiation between mild dysplasia (type A according to Dejour) and more severe dysplasia (types B–D) that often represent an indication for surgery, an interobserver agreement of over 90 % can be achieved with MRI [38].. Additional quantitative measurements (sulcus angle, trochlear depth, trochlear inclination, and trochlear facet asymmetry) can help the examiner to determine severity [38].

MRI is currently considered the method of choice for determining the TT-TG distance. Compared to CT, similarly high reproducibility of TT-TG distance measurements can be shown for MRI [37]. However, it must be taken into consideration in an intermodality comparison that deviations in the TT-TG distance occur as a function of the degree of flexion when positioning the knee joint in the MRI coil. If possible, maximum extension of the knee joint should be ensured since current studies describe a reduction of TT-TG values in the case of a greater degree of flexion [15, 24].

A further advantage of MRI compared to conventional radiography and CT is the ability to evaluate the articular cartilage and thus the “true” geometric configuration of the joint[6]. Cartilage damage in the patellofemoral joint is one of the most common complications of PI [15]. In addition to structural defects, increases in the T2 signal intensity at the lateral joint facet can be detected as possible early degenerative cartilage changes in patients with PI [42]. In addition to morphological sequences, quantitative MRI examination techniques in cartilage tissue of the patellofemoral joint have been examined in recent years [43, 55]. Connections between changes in T2 / T1rho relaxation times and patellofemoral maltracking were able to be shown [43, 44]. The goal of this type of examination is to detect initial degenerative cartilage changes as a result of patellofemoral maltracking (▶ **Fig. 11**). Future studies must show the value of quantitative MRI for monitoring cartilage changes in the preoperative and postoperative course (e. g. after MPFL reconstruction) in patients with PI.



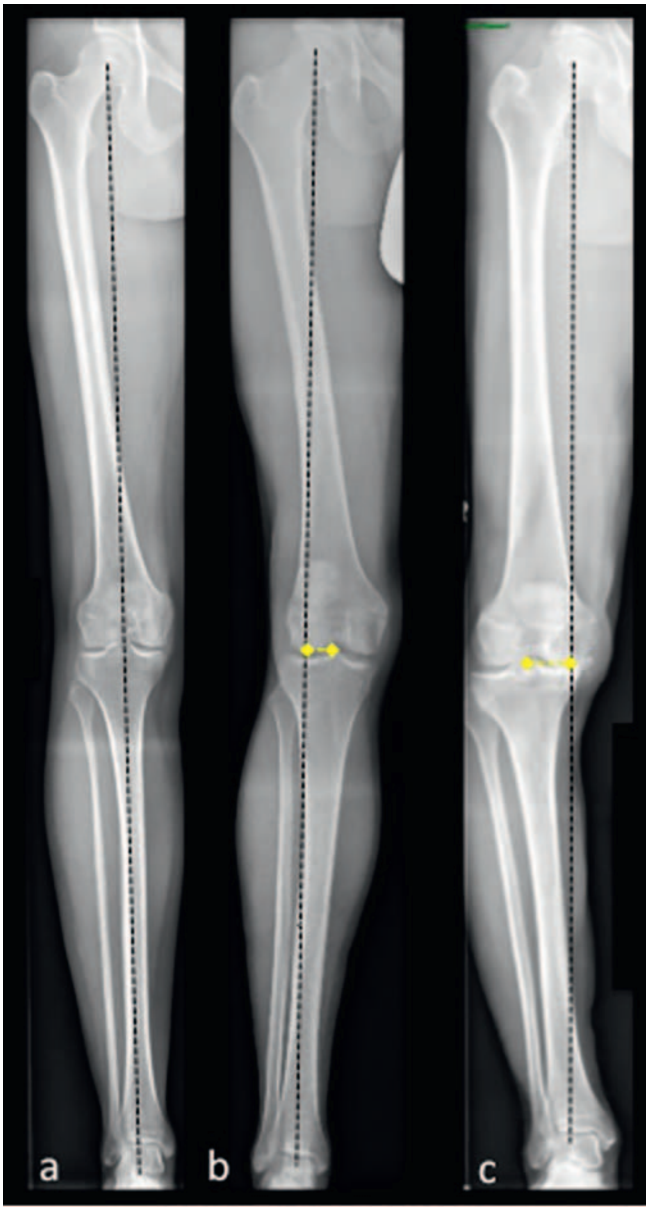
▶ **Fig. 9** 24-year-old patient after MPFL augmentation, external, in the case of habitual patellar dislocation approx. 8 years ago. Presented with persistent symptoms in the right knee. The full leg X-ray shows genu valgum with the Mikulicz line running approx. 25 mm lateral to the center of the knee **a**. MRI detected subluxation of the patella with chondropathy of the retropatellar articular cartilage (arrow) **b**. Sagittal T1-weighted MRI shows a high-riding patella with a Caton-Deschamps Index (CDI) of 1.3 **c**. In addition, excessive TT-TG distance (23 mm). MPFL reconstruction with lateral open wedge femoral osteotomy due to pathological leg length difference (right < left) and osteotomy of the tibial tuberosity with medialization were then performed. Postoperative conventional imaging showing complete correction of the prior genu valgum **d**, however detection of loosening of the osteotomy of the tibial tuberosity (arrow tips) due to a lack of compliance (premature use of the knee) **e**. Follow-up after revision showing correct position of the osteosynthesis plate on the tuberosity **f** and correct axial position of the patella in the groove **g**. Note: Due to the advanced cartilage damage, distalization of the tuberosity was not performed.

Kinematic imaging

Both kinematic MRI and 4 D CT allow evaluation of the sequence of movements of peripheral joints [45, 46]. Image data is acquired during flexion-extension with high spatial resolution. The first kinematic MRI for dynamic visualization of the patellofemoral joint was acquired by Shellock et al. in 1988 [45]. By acquiring sequential axial images during passive knee flexion, MRI visualization of maltracking was able to be achieved. In 2000, McNally et al. described a dynamic real-time examination of the patellofemoral joint on MRI using an inflatable plastic balloon that is continuously deflated during active knee extension [47]. In current feasibility studies regarding kinematic MRI during physiological knee flexion and extension, the clinical benefit of dynamic imaging for the evaluation of patellofemoral maltracking was able to be shown [48, 49]. Therefore, kinematic MRI was able to show significant differences in the mediolateral translation of the patella between healthy subjects and patients with maltracking. Furthermore, using the examination technique it was possible to show the effects of anatomical risk factors on maltracking during physiological movement and muscle contraction [45, 56].

Moreover, kinematic MRI is a robust and objective examination method for evaluating surgical success (▶ **Video 1, 2**). Dynamic imaging is currently the most sensitive examination technique even with respect to recurrent maltracking, which is usually initially clinically asymptomatic [49, 50].

However, it must be taken into consideration that even though the majority of cases of maltracking can be diagnosed based solely on kinematic imaging, conventional MRI should always be performed as a basic diagnostic method to determine objective radiological measurements (e. g. TT-TG distance, torsion angle, TD) [49]. There are also currently (not yet) any standardized

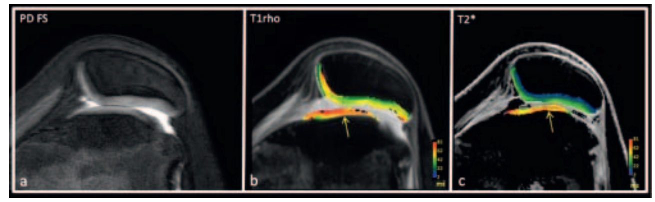


▶ **Fig. 10** Full leg images (right) to determine the axis of the leg: **a** Patient with normal mechanical leg axis (Mikulicz line runs through the center of the knee), **b** young patient with pathological outward angulation of the leg axis (lateralization of the Mikulicz line 25 mm from the center of the knee) and **c** patient with advanced gonarthrosis and varus angulation of the leg axis (medialization of the Mikulicz line 38 mm from the center of the knee).

examination conditions and established evaluation criteria for a kinematic imaging examination of the knee joint in routine radiological/clinical diagnosis.

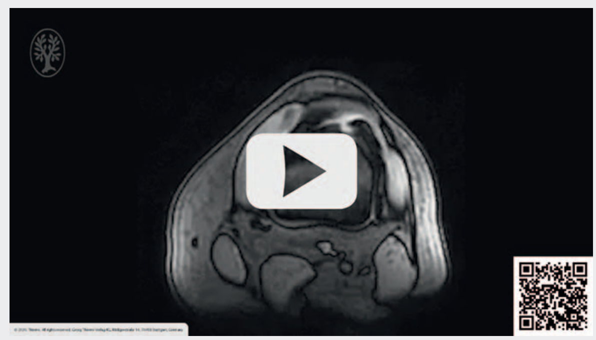
Summary

MRI is currently the method of choice for diagnosing patellofemoral instability and predisposing anatomical causes. In addition



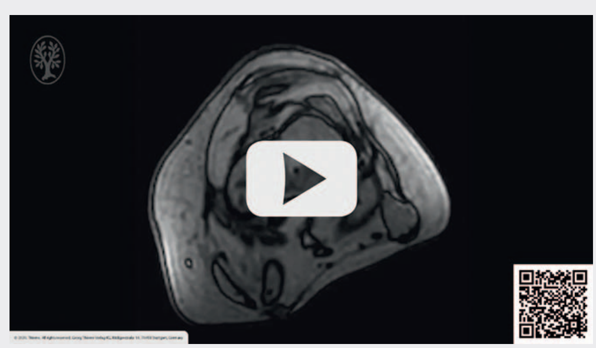
▶ **Fig. 11** MRI images of a 20-year-old patient with patellofemoral instability in the presence of trochlear dysplasia (type C according to Dejour) and a high TT-TG distance (23 mm). Proton-weighted MRI **a** shows morphologically intact articular cartilage without substance defects. The quantitative T1rho **b** and T2* measurements **c** show a pathological increase in relaxation times, particularly at the trochlear joint surface, indicating possible early degenerative changes in the cartilage.

OP-VIDEO



▶ **Video 1** Multi-slice GRE sequence with high time resolution in a 20-year-old patient with patellofemoral maltracking with a pathologically high TT-TG distance (21 mm), presence of trochlear dysplasia type C and insufficiency of the medial ligaments. Decision to perform surgical treatment with MPFL reconstruction and transfer of the tibial tuberosity.

OP-VIDEO



▶ **Video 2** Postoperative follow-up with successful correction of the previously pathological lateral translation of the patella in the trochlear groove.

to the exact visualization and quantification of anatomical risk factors, MRI makes it possible to detect associated structural injuries and subsequent damage caused by maltracking, e. g., to the articular cartilage. MDCT is used as a complementary method to MRI in the evaluation of bone structures.

With the help of modern kinematic MRI examination techniques and CT, the sequence of movements of the patella can be visualized in real time. Dynamic examinations have added diagnostic value because they visualize patellofemoral maltracking precisely and in a time-resolved manner and influence factors like quadriceps contraction during movement can be taken into consideration.

Particularly when multiple risk factors are present, radiological findings help to determine the dominant, causative pathology of patellofemoral instability and thus represent an important component of treatment planning.

Conflict of Interest

The authors declare that they have no conflict of interest.

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