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The complexity of bony malalignment in patellofemoral disorders: femoral and tibial torsion, trochlear dysplasia, TT–TG distance, and frontal mechanical axis correlate with each other

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Abstract

Purpose Several anatomic risk factors associated with patellofemoral disorders have been described. The purpose of this study was to analyze the relationship between bony parameters commonly used to analyze and define patellofemoral malalignment.

Methods Patients with patellofemoral disorders presenting between 2016 and 2018 who underwent a standardized radiographic workup including conventional radiographs, weight bearing full-leg radiographs, magnetic resonance imaging (MRI) of the knee, and torsional analysis using hip–knee–ankle MRI were initially included. Patients with a history of lower extremity fracture and a history of surgical procedures affecting bony alignment or partial/total arthroplasty were subsequently excluded. Radiographs and MRI of all included patients were analyzed by four independent observers. Parameters of interest were: femoral torsion, tibial torsion, trochlear dysplasia, tibial tuberosity–trochlear groove (TT–TG) distance, and frontal mechanical axis. All parameters were compared between patients with low grade and high grade trochlear dysplasia as well as between female and male patients. Correlation of continuous variables was assessed with the Pearson correlation coefficient. A binary logistic regression model was used for the calculation of odds ratio between different parameters. Interclass correlation coefficients (ICC) were calculated to determine the interobserver reproducibility.

Results A total of 151 patients could be included for detailed analysis. Group comparison revealed that patients with high grade trochlear dysplasia showed significantly higher values for femoral torsion (low grade: 9.8° ± 11.0°, high grade: 16.8° ± 11.5°; $p < 0.001$) and significantly higher values for TT–TG distance (low grade: 19.0 mm ± 5.0 mm, high grade: 21.9 mm ± 5.4 mm; $p = 0.002$). No significant difference was found for age, tibial torsion, and frontal mechanical axis. With regard to gender, female patients had higher values for femoral torsion (female: 15.6° ± 11.3°, male: 11.0° ± 12.7°; $p = 0.044$). The correlation analysis found significant correlation between femoral torsion and tibial torsion ($r = 0.244$, $p = 0.003$), femoral torsion and TT–TG distance ($r = 0.328$, $p < 0.001$), femoral torsion and frontal mechanical axis ($r = 0.291$, $p < 0.001$), and tibial torsion and TT–TG distance ($r = 0.182$, $p = 0.026$).

Conclusion Bony malalignment in patients with patellofemoral disorder is a complex problem given the significant correlation between femoral and tibial torsion, trochlear dysplasia, TT–TG distance, and frontal mechanical axis. Advanced imaging to analyze rotational and frontal plane alignment is recommended in patients with trochlear dysplasia and/or increased TT–TG on standard radiographs and knee MRI. Understanding of the bony pathology in patellofemoral disorders is key to improve the therapeutic and surgical decision.

Level of evidence III, retrospective cohort study.

Keywords Patellofemoral Instability · Trochlear dysplasia · Femoral torsion · Tibial torsion · TT–TG

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Introduction

Stability of the patellofemoral joint is a complex interaction between muscle forces, passive soft tissues, surface geometry of the trochlea and patella, and limb alignment.

Therefore, patellofemoral instability is usually a multifactorial problem and patients suffering from recurrent patellar dislocation require a detailed analysis to identify all relevant factors.

There is growing evidence that the bony geometry of the lower limb plays a major role in patellofemoral instability. Trochlear dysplasia and high tibial tuberosity–trochlear groove (TT–TG) distance are well accepted risk factors for recurrence after first time patellar dislocation and for failure of isolated soft tissue-procedures. The role of torsional deformities and frontal plane malalignment is less well understood [20, 22], however, there is growing evidence that especially increased femoral antetorsion and valgus alignment promote lateral patellar instability [6]. For this reason, osteotomies to correct torsion and frontal plane alignment are increasingly performed with good results [4, 7, 11].

In a recent study, Liebensteiner et al. [15] have observed that high femoral antetorsion was associated with a dysplastic trochlear morphology. This observation corresponds well with the experience that abnormal bony geometry associated with patellar instability is only rarely limited to one parameter. We have treated several patients with high-grade trochlear dysplasia, who also showed increased femoral antetorsion, valgus deformity, and increased TT–TG. However, it remains unknown whether these parameters are correlated to each other. Understanding the bony pathology in patellofemoral disorders may improve the therapeutic and surgical treatment options.

The purpose of this study was to analyze the relationship between bony parameters commonly used to analyze and define patellofemoral malalignment (femoral torsion, tibial torsion, trochlear dysplasia, TT–TG distance, and frontal mechanical axis). The hypotheses were that trochlea dysplasia correlated with higher femoral antetorsion and that femoral antetorsion correlated with external tibial torsion, TT–TG distance, and valgus deviation.

Methods and materials

Study population

A retrospective cohort study was conducted to evaluate the relationship between bony parameters commonly used to analyze and define patellofemoral malalignment. The study was performed with the approval of the Ethics Committee of the Technical University of Munich (Nr.: 398/18 S).

All patients undergoing a standardized radiographic workup for patellofemoral disorders (patellofemoral instability, patellofemoral pain, lateral hyperpression) between 2016 and 2018 were retrospectively identified within the picture archiving and communication system (PACS). The standardized radiographic workup consisted of conventional radiographs of the knee in three planes, weight bearing full-leg radiographs, magnetic resonance imaging (MRI) of the knee, and torsional analysis using dedicated hip–knee–ankle MRI. Patients with a history of lower extremity fracture and a history of surgical procedures affecting bony alignment (e.g. tibial/femoral osteotomy, trochleoplasty, or transfer of the tibial tuberosity) as well as patients with partial/total hip or knee arthroplasty were subsequently excluded.

Radiographs and MRI of all included patients were analyzed on a PACS workstation by four independent observers (two special trained musculoskeletal radiologists, one orthopedic surgeon, and one medical student), except for trochlear dysplasia (see explanation below). Measurements (accuracy per pixel: 0.1 mm and 0.1°) were performed in a standardized technique as described in detail below. Parameters of interest were: femoral torsion, tibial torsion, trochlear dysplasia, TT–TG distance, and frontal mechanical axis. Parameters measured as Interclass correlation coefficients (ICCs) were calculated to determine the interobserver reproducibility and is given in the methods section.

Trochlear dysplasia

Trochlear dysplasia was graded according to the Dejour classification by a special trained musculoskeletal radiologist using axial T2-weighted MR images and lateral radiographs [2, 8]. Because of poor interrater reliability, a two-group grading system was selected, as proposed by Lippacher et al. [16]: low grade dysplasia (Dejour type A) and high grade dysplasia (Dejour types B, C, and D). For MRI grading, the most proximal image that included the entire width of the trochlea was selected.

Femoral torsion

Analysis of torsion was performed using a standardized MRI protocol with 8 mm thick axial slices through the hip, knee, and ankle on both sides. Femoral torsion was defined as the angle between a line parallel to the femoral neck and femoral head center (femoral neck axis) and the distal femur (tangential axis at the medial and lateral femoral condyles), as described by Schneider et al. [18]. Positive values indicated femoral antetorsion, whereas negative values indicated femoral retrotorsion. In the present analysis, interrater ICC for femoral torsion was 0.964.

Tibial torsion

Tibial torsion was assessed by measuring the torsional angle of the proximal tibia relative to the distal tibia, as described by Diederichs et al. [5]. At the proximal tibia, a tangential line was aligned at the posterior tibial cortex on the slice just proximal to the fibular tip. The distal tibial reference was set as a line through the middle of the medial and lateral malleolus on the most proximal slide of the talus. Positive values indicate external tibial torsion and negative values indicate internal tibial torsion. Interrater ICC for tibial torsion was 0.914.

Frontal mechanical axis

Standardized weight bearing full-leg radiographs were performed using a fully computerized three picture stitching system. The frontal mechanical axis was measured as the angle between the mechanical femoral and mechanical tibial axis, according to Strecker et al. [24]. Positive values indicated varus alignment and negative values indicate valgus alignment. Interrater ICC for frontal mechanical axis was 0.939.

Tibial tuberosity–trochlear groove (TT–TG) distance

The distance in millimeter (mm) between the most anterior part of the tibial tuberosity and the central part of the trochlear groove was measured on MRI [19]. Interrater ICC for TT–TG distance was 0.836. In severe dysplastic trochlea (type D), measurement of the trochlear middle was taken as an approximation of the middle point within the chondral surface.

Statistical analysis

An a priori power analysis was conducted. Between the two groups with low grade and high grade dysplasia, a mean difference of 5° femoral torsion was considered to be clinical relevant. In the literature, a standard deviation up to 10° is reported for measurement of femoral torsion using MRI, resulting in an effect size of 0.5 [5]. Assuming a group ratio of 1 (dysplasia type A) to 1.5 (dysplasia type B + C + D) after preliminary analysis, the required number of cases was 132 patients, with a significance level of 0.05 and a power of 0.8. All relevant data were entered in a spreadsheet program and statistically analyzed with SPSS software version 23.0 (IBM-SPAA, New York, USA). Continuous variables were calculated as means ± standard deviation. Normal distribution of all data was evaluated with the Kolmogorov–Smirnoff test. Group comparison (female vs. male patients; low grade vs. high grade trochlear dysplasia) was performed with Chi-square test, Mann–Whitney *U* test, or unpaired *t* test, as appropriate. Correlation of continuous variables (age, femoral torsion, tibial torsion, TTTG distance, and frontal mechanical axis) was assessed with the Pearson correlation coefficient. A binary logistic regression model was used for odds ratio between different parameters. Additionally, the interobserver reliability of the different measurements was analyzed by calculating intraclass correlation coefficients (ICCs) and results are shown in the methods section [14].

Results

Out of 210 patients, a total of 151 could be included for detailed analysis. The descriptive statistics of the demographical data and the main parameters are shown in Table 1. Patients with high grade trochlear dysplasia showed significantly higher values for femoral torsion (low grade: 9.8° ± 11.0°, high grade: 16.8° ± 11.5°; $p < 0.001$) (Fig. 1a) and significantly higher values for TT–TG distance (low grade: 19.0 mm ± 5.0 mm, high grade: 21.9 mm ± 5.4 mm; $p = 0.002$) (Fig. 1b). No statistically significant differences between both groups was found for age, tibial torsion, and frontal mechanical axis (Table 2). With regard to gender, female patients had higher values for femoral torsion (female: 15.6° ± 11.3°, male: 11.0° ± 12.7°; $p = 0.044$). No significant difference between both genders was found for the distribution of trochlea dysplasia, age, tibial torsion, TT–TG distance, and frontal mechanical axis.

Results of the correlation analysis are shown in Table 3 and statistically significant correlations are graphically highlighted in Fig. 2a–d. In summary, a statistically significant correlation was found between femoral torsion and tibial torsion

Table 1 Descriptive statistics of the demographical data and main parameters

Variable	Total patient cohort
Number of included patients	151
Gender	
Female	115 (76%)
Male	36 (24%)
Age (years)	23 ± 8 (12–56)
Symptoms	72% chronic patellofemoral dislocation 12% patellofemoral pain without dislocation 10% single non-traumatic patellar dislocation 6% lateral patellofemoral hyperpression
Trochlear dysplasia	
Low grade	49 (33%)
High grade	102 (67%)
Femoral torsion (°)	14.5 ± 11.8 (– 12.0 to 45.5)
Tibial torsion (°)	32.3 ± 9.7 (6.0–64.0)
TT–TG distance (mm)	21.0 ± 5.4 (6.0–47.0)
Frontal mechanical axis (°)	– 1.7 ± 3.7 (– 16.3 to 14.1)

Continuous variables are shown as mean ± standard deviation (range), categorical variables are shown as number of patients and percentages of the total patient cohort

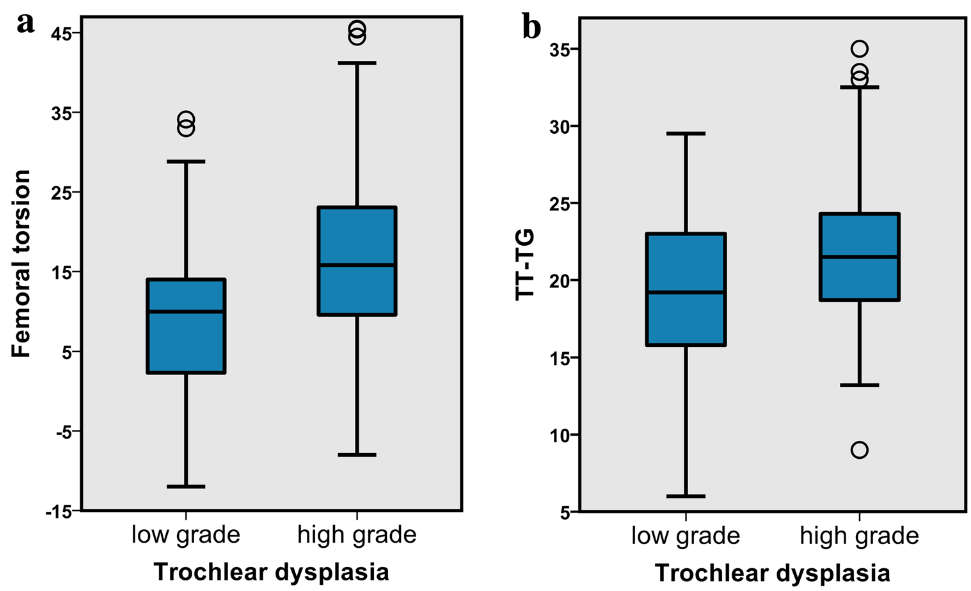

Fig. 1 Statistically significant differences between patients with low grade and high grade trochlear dysplasia. **a** Patients with high grade dysplasia showed significantly higher values for femoral torsion ($p<0.001$); **b** patients with high grade trochlear dysplasia showed significantly higher values for TT–TG distance ($p<0.002$)

Table 2 Comparison between patients with low grade and high grade trochlear dysplasia

Variable	Trochlear dysplasia		*p* value
	Low grade	High grade	
Gender			n.s.
Female	36 (73%)	79 (77%)	
Male	13 (27%)	23 (23%)	
Age (years)	22.8 ± 7.7	23.4 ± 8.2	n.s.
Femoral torsion (°)	9.8 ± 11.0	16.8 ± 11.5	< 0.001[a]
Tibial torsion (°)	31.9 ± 9.7	32.5 ± 9.8	n.s.
TT–TG distance (mm)	19.0 ± 5.0	21.9 ± 5.4	0.002[a]
Frontal mechanical axis (°)	− 1.2 ± 4.6	− 2.0 ± 3.3	n.s.

Continuous variables are shown as mean ± standard deviation, categorical variables are shown as number of patients and percentages per group

[a]Statistically significant difference between both groups

($r=0.244$, $p=0.003$), femoral torsion and TT–TG distance ($r=0.328$, $p<0.001$), femoral torsion and frontal mechanical axis ($r=0.291$, $p<0.001$), and tibial torsion and TT–TG distance ($r=0.182$, $p=0.026$).

A binary logistic regression model was performed in regard to greater femoral torsion (> 20°). Significant odds ratios were found for TT–TG greater than 20 mm, and mechanical axis (varus), but not significant for higher grade trochlear dysplasia and female gender (Table 4).

Discussion

The most important finding of this study is that higher grades of trochlear dysplasia showed higher values of femoral torsion and TT–TG distance. Second, femoral torsion was higher in females and showed a significant positive correlation to TT–TG distance, tibial torsion, and frontal axis, overall. The binary logistic regression model showed that TT–TG greater than 20 mm, small valgus or varus axis, and higher grades of trochlear dysplasia were risk factors for femoral torsion greater than 20°.

Biomechanics and kinematics of the patellofemoral joint are determined by several factors such as muscle forces, soft tissue restraints, and bony alignment. Historical and recent studies have highlighted the importance of the bony geometry in patellofemoral disorders, including TT–TG distance, trochlear dysplasia, and femoral and tibial torsion. High TT–TG distance is a well-accepted risk factor for recurrence after first time patellar dislocation and for failure of isolated soft tissue-procedures. Dysplasia of the femoral trochlea reduces lateral stability of the patella by up to 70% according to Senavongse et al. [21] and has been shown to be a major risk factor for recurrent patellar [1] and failed MPFL reconstruction [10, 13, 23]. Increased internal femoral torsion has been shown to produce a lateralizing effect on the patella in a biomechanical model by Kaiser et al. [12] and Diederichs et al. [5] have found a 1.56-fold higher mean femoral antetorsion in patients with patellofemoral instability compared with controls. Valgus alignment alters the force vector on the patella by increasing the *Q* angle and varisation osteotomies have produced good results in patients with patellofemoral instability or anterior knee pain [3, 7].

Table 3 Correlation analysis (Pearson) of continuous variables

	Age	Femoral torsion	Tibial torsion	TT–TG distance	Frontal mechanical axis
Age	–	$r=0.024$ n.s.	$r=0.087$ n.s.	$r=-0.029$ n.s.	$r=0.006$ n.s.
Femoral torsion	$r=0.024$ n.s.	–	$r=0.244$ $p=0.003$[a]	$r=0.328$ $p<0.001$[a]	$r=0.291$ $p<0.001$[a]
Tibial torsion	$r=0.087$ n.s.	$r=0.244$ $p=0.003$[a]	–	$r=0.182$ $p=0.026$[a]	$r=0.127$ n.s.
TT–TG distance	$r=-0.029$ n.s.	$r=0.328$ $p<0.001$[a]	$r=0.182$ $p=0.026$[a]	–	$r=0.021$ n.s.
Frontal mechanical axis	$r=0.006$ n.s.	$r=0.291$ $p<0.001$[a]	$r=0.127$ n.s.	$r=0.021$ n.s.	–

r correlation coefficient; *pp* value

[a]Statistically significant correlation

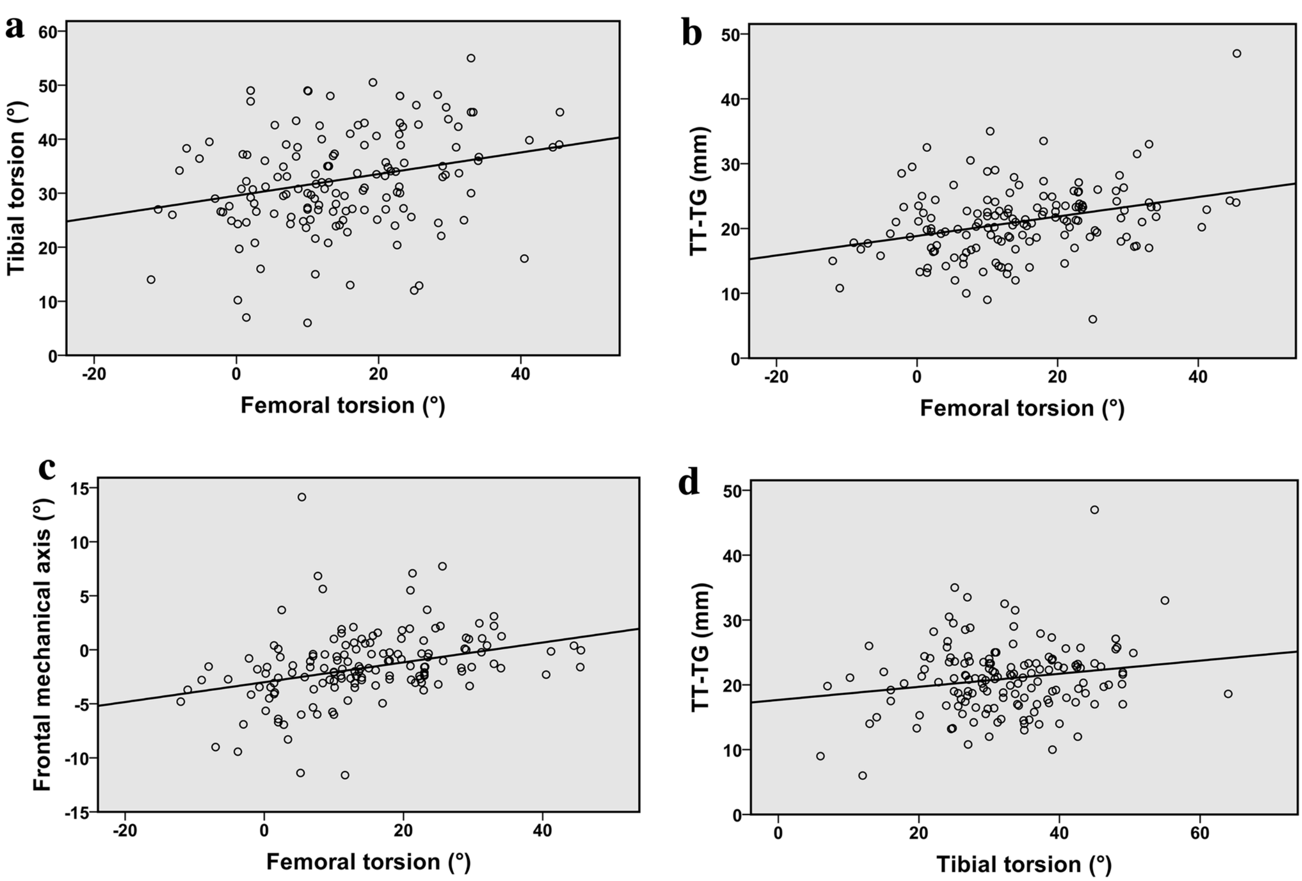

Fig. 2 Statistically significant correlations of continuous variables. **a** Femoral torsion was positively correlated with tibial torsion ($r=0.244$, $p=0.003$); **b** femoral torsion was positively correlated with TT–TG distance ($r=0.328$, $p<0.001$); **c** femoral torsion was positively correlated with frontal mechanical axis ($r=0.291$, $p<0.001$); **d** tibial torsion was positively correlated with TT–TG distance ($r=0.182$, $p=0.026$)

Abnormal bony geometry associated with patellar instability or maltracking is only rarely limited to one parameter. Steensen et al. [23] compared the prevalence and combined prevalence of anatomic factors in a group of patients with and without recurrent dislocation of the patella. The authors found that recurrent patellar dislocation was associated with

Table 4 Binary logistic regression model for greater femoral torsion (> 20°)

	Sig	Odds ratio	95% Confidence interval	
			Low value	High value
Gender (male, female)	0.22	0.55	0.21	1.43
Trochlear dysplasia (low, high grade)	0.11	2.04	0.86	4.81
TT–TG > 20 mm	0.03	2.50	1.11	5.67
Frontal mechanical axis (numeric)	0.003	1.2	1.06	1.35

Male patients showed an odds ratio of 0.5 versus female patients for greater femoral torsion. When TT–TG was greater than 20 mm, a significant association with an odds ratio of 2.5 was found for greater femoral torsion (> 20°). The numeric outcome of frontal mechanical axis revealed a high significant 1.2 odds ratio for every degrees of varus increase with regard to greater femoral torsion

an increased prevalence of patella alta, increased TT–TG distance, rotational deformity, and trochlear dysplasia. More importantly, the authors identified multiple abnormal anatomic factors in the majority of patients with recurrent dislocation. This study underlines the complexity of bony alignment in patellofemoral disorders and it is likely that several parameters are correlated to each other. However, only few studies have addressed this issue so far. Liebensteiner et al. [15] investigated the relationship between femoral antetorsion and trochlear morphology in 40 lower-limb CT scans and found that increased antetorsion was associated with a flatter, more dysplastic trochlea. These findings are in line with the present study as we also observed higher femoral antetorsion in patients with a high grade trochlear dysplasia. Diederichs et al. [5] investigated possible relations between rotational alignment and other anatomic risk factors in 30 patients with a history of patellar dislocation. In contrast to our study, the authors did not find a correlation between rotational alignment and trochlear dysplasia or TT–TG distance. We believe that this discrepancy is most likely explained by the small cohort of 30 patients. By analyzing 151 patients, the present study had a greater power and could observe a positive correlation between femoral torsion and tibial torsion, femoral torsion and TT–TG distance, femoral torsion and frontal mechanical axis, and tibial torsion and TT–TG distance.

With regard to the clinical implication of the present study, we have shown that patients with patellofemoral disorders may have complex bony deformities with a combination of torsional deformity, trochlear dysplasia, and valgus deviation. This finding is of clinical importance since patients suffering from patellofemoral disorders require a detailed analysis to identify all relevant factors. However, recommendations for imaging studies usually consist of standard radiographs and MRI of the knee. Weight bearing full-leg radiographs and torsional analysis using hip–knee–ankle MRI or CT are not routinely performed. Therefore, rotational malalignment and frontal plane malalignment may be underdiagnosed. Based on the findings of the present study, additional imaging with weight bearing full-leg radiographs and torsional analysis is highly recommended in patients with trochlear dysplasia and/or high TT–TG distance on plain radiographs and knee MRI, since these patients have a high risk for torsional deformities and valgus deviation. Femoral antetorsion and mechanical valgus axis showed a positive correlation. However, in a subgroup analysis of patients with higher grades of femoral torsion (greater than 20°), the results of frontal mechanical leg axis showed more varus axis. These kind of observations might be caused by the combined mal-rotated distal femur, tibial torsion, and higher grade trochlear dysplasia. These combinations aggravate exact frontal leg radiograph and make it difficult to perfectly measure frontal angles in a two-dimensional plane radiograph.

It remains unclear which factors contribute the most and should surgically be treated. In our experience, the concept of the "hip-down" model is more relevant than the "foot-up" model. A distal femoral derotational osteotomy is performed, if femoral antetorsion values exceed 25° and an internal-rotation-adduction moment of the knee is present in gait analysis [11, 17]. With regard to coronal alignment, mechanical valgus greater than 3° is also addressed [7]. With regards to severe trochlear dysplasia (type C and D), patients benefit from trochlear groove deepening and groove re-alignment and parameters such as TT–TG will automatically change to the positive. However, further studies with computer simulated angular and pressure changes after femoral osteotomie, TT–TG distance correction, and trochleoplasty may serve as a surgical recommendation.

There are several limitations of the study: first, the aforementioned inclusion criteria contain different entities of patellofemoral pathology. The clinical appearance might be variable. Furthermore, our data does not conclude that every patient with trochlear dysplasia and greater femoral torsion suffers from patellofemoral instability. Second, trochlear dysplasia was analyzed using a two-group grading system despite the commonly used four-group grading system of Dejour. However, this classification system has been shown to have a poor interrater reliability. Lippacher et al. [16] introduced the 2-graded criteria distinguishing between low grade and high grade trochlear dysplasia. The binary outcome showed more reliable results and a two-group Dejour classification might be useful in everyday clinics. Third, measurements of distance are variable when comparing height and gender of patients, whereas angles do not depend on length. Therefore, the well accepted TT–TG distance should be considered with care and TT–TG Index as postulated by Hingelbaum et al. might be favorable [9]. In view of the complexity of bony malformities in patients with patellofemoral disorders, this study cannot grade the severity of each parameter and cannot give any thresholds of pathological measurements. Therefore, no surgical decision-making can be drawn. However, the strength of the study shows the relationship of bony parameters, which might be underdiagnosed in these cases.

Conclusion

Bony malalignment in patients with patellofemoral disorder is a complex problem given the significant correlation between femoral and tibial torsion, trochlear dysplasia, TT–TG distance, and frontal mechanical axis. Advanced imaging to analyze rotational and frontal plane alignment is recommended in patients with trochlear dysplasia and/or increased TT–TG on standard radiographs and knee MRI. Understanding of the bony pathology in patellofemoral disorders is key to improve the therapeutic and surgical decision.

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Author contribution FI had the initial study idea, defined study setup and methods, and made substantial contribution to the manuscript. VF served as an investigator and made substantial contribution to the manuscript. ML served as an investigator and internal reviewer of the manuscript. AS is a special trained musculoskeletal radiologist and made substantial contribution to the study setup and served as an investigator. ME was an investigator of the radiological measurements and served as an internal reviewer with contribution to the manuscript. KW was responsible for radiologic parameters obtained retrospectively and made substantial contribution to the methods and served as an internal reviewer of the manuscript. AI made substantial contribution to the study setup and methods section and served as an internal reviewer of the manuscript. MF accomplished the statistics, contributed to the methods and the manuscript.

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Compliance with ethical standards

Conflict of interest The authors declared that they have no conflicts of interest in the authorship and publication of this contribution.

Informed consent Informed consent was obtained at the time of clinical and radiological assessment from all individual participants included in this retrospective study.

Ethical approval Ethical approval was obtained from the Ethics Committee of the Technical University of Munich (398/18 S).

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