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Increased tibiofemoral rotation on MRI with increasing clinical severity of patellar instability

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Abstract

Purpose Tibiofemoral rotation through the knee joint, specifically relative external tibial rotation, has been identified as a potential contributing factor to patellar instability. The purpose of this study is to investigate the relationship between severity of instability with degree of tibiofemoral rotation in three clinical cohorts: fixed or obligatory dislocators (in which the patella either is constantly laterally dislocated or laterally dislocates with every instance of knee flexion, respectively), standard traumatic instability patients, and normal controls.

Methods A retrospective study was performed with three cohorts from April 2009 to February 2019: fixed or obligatory dislocators, standard traumatic instability patients, and controls with normal magnetic resonance imaging (MRI) of the knee. All fixed or obligatory dislocation patients from the study time frame were analyzed; controls and standard traumatic instability patients were randomly selected. Inclusion criteria were age under 18 years and qualifying diagnosis; exclusion criteria were outside institution MRI and previous MPFL reconstruction or tibial tubercle osteotomy. Tibiofemoral rotation was measured blindly on initial axial MRI using the posterior femoral and tibial condylar lines. Tibial tubercle to trochlear groove distance (TT–TG) was measured. Intraclass correlation coefficient (ICC) was calculated among four measurers.

Results A total of 100 patients were included, 20 fixed or obligatory dislocators, 40 standard traumatic instability patients, and 40 controls. Median age was 13.2 years (range 10–17 years), with 55 females. Age was significantly higher in the standard traumatic instability group than both the control ($p < 0.001$) and fixed or obligatory dislocator groups ($p = 0.003$). ICC for TT–TG and tibiofemoral rotation were 0.92 and 0.96, respectively. Fixed or obligatory dislocator patients averaged 8.5° external tibiofemoral rotation, standard traumatic instability patients 1.6° external tibiofemoral rotation, and controls 3.8° internal tibiofemoral rotation. Both tibiofemoral rotation and TT–TG were highest in the fixed or obligatory dislocator cohort, followed by the standard traumatic instability cohort, and lowest in the controls ($p < 0.0001$ for tibiofemoral rotation and TT–TG). Multivariate analysis showed no correlation between age and tibiofemoral rotation.

Conclusions Measurement of tibiofemoral rotation was reproducible with excellent interrater reliability. The degree of tibiofemoral rotation is correlated with severity of patellar instability, with the greatest external tibiofemoral rotation in fixed or obligatory dislocator patients, followed by standard traumatic instability patients, and slight internal tibiofemoral rotation in controls. High external tibiofemoral rotation may be an important pathoanatomic factor in fixed or obligatory dislocators, and with further understanding may become a prognostic factor or surgical target.

Level of evidence III.

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Introduction

Pediatric patellofemoral instability can vary in presentation from a single dislocation event to severe cases of either fixed lateral dislocation or obligatory dislocation in flexion, where every time the knee is flexed, the patella dislocates laterally

[15, 19]. Fixed or obligatory dislocators have a more severe manifestation of the disease than the more standard patellofemoral instability patients who have one to several traumatic dislocations [12]. Multiple factors contribute to the pathogenesis of patellar maltracking and patellofemoral instability, including trochlear dysplasia, soft tissue integrity particularly of the medial patellofemoral ligament (MPFL), coronal alignment (genu valgum), and axial malalignment in the form of increased tibial tubercle to trochlear groove distance (TT–TG).

Recently, tibiofemoral rotation through the knee joint (distinct from femoral or tibial torsion arising from within the respective bone) has been identified as a potential contributing factor to patellar instability [2, 4, 9, 11, 18]. A recent study of 41 pediatric patients found that external tibiofemoral rotation (relative external rotation of the tibia in relation to the femur at the level of the knee) was significantly higher in patients with patellar instability compared to age- and sex-matched controls [4]. It is speculated that tibiofemoral rotation may contribute to patellofemoral instability because external rotation of the tibia results in lateralization of the tibial tubercle, increased lateral tilt, attenuated medial soft tissues, and altered force vectors, all of which contribute to decreased lateral stability of the patella [11].

Tibial tubercle osteotomy (TTO) is often performed to correct axial malalignment manifested by high TT–TG; however, this procedure is avoided in patients with open physes. Additionally, simple translation of the tibial tubercle may not fully address the physiologic consequences of rotational deformity, such as the relative rotation of the trochlea in relation to the tibia, or the effect of rotational tensioning of the medial and lateral soft tissues of the knee. Some authors have suggested, based on biomechanical data, the potential need for a derotational osteotomy in cases of severe internal femoral torsion, in addition to more traditional patellar stabilization procedures [10]. While prior studies have predominantly assessed bony torsion (such as femoral anteversion), these findings suggest that tibiofemoral rotation through the knee joint could be a useful factor in deciding proper surgical management or in prognostication and counseling of the patient and family. There are no studies to date that explore the effects of differing degrees of tibiofemoral rotation on the clinical severity of patellar instability. An improved understanding of the rotational relationship of the femur and tibia at the level of the knee joint in patients with varying degrees of patellofemoral instability will improve the current knowledge of the pathoanatomy of patellofemoral instability and may help identify clinically relevant prognostic indicators or therapeutic targets.

The purpose of the present study is to evaluate tibiofemoral rotation using axial MRI, and to investigate the relationship between the severity of patellofemoral instability and magnitude of tibiofemoral rotation. The hypothesis is that fixed or obligatory dislocators, the most symptomatically severe diagnostic category in pediatric patellar instability, will have the greatest external tibiofemoral rotation, followed by standard traumatic instability patients (who have one to several traumatic instability events), followed by normal controls.

Materials and methods

Approval was granted by the Hospital for Special Surgery institutional review board (IRB# 2018-1784) to conduct a retrospective review of preexisting, previously collected patient data from patient charts and imaging records. Patients of the senior author from three cohorts, from April 2009 to February 2019, were identified: fixed or obligatory dislocators, standard traumatic instability patients, and normal controls. All patients in the fixed or obligatory dislocation group from the study time frame who met inclusion and exclusion criteria were analyzed, as this group represented the smallest cohort. Within the fixed or obligatory dislocation group, initial screening yielded 30 patients, 10 of whom were excluded due to limited quality MRI or MRI done outside the study institution. Patients in the fixed or obligatory dislocation group were not excluded based on underlying diagnosis, as numerous conditions can be associated with fixed or obligatory patellar dislocation in pediatric patients; we included all underlying diagnoses to increase the number of fixed or obligatory dislocator patients in this study, as the disease process with respect to the patellar dislocation is similar regardless of the underlying diagnosis.

Controls and standard traumatic instability patients were then randomly selected to achieve a 1:2:2 ratio of fixed or obligatory dislocators:standard traumatic instability patients:controls (twice as many patients in the control and standard traumatic instability groups as the fixed or obligatory dislocator groups). Standard traumatic instability patients were randomly selected from the study time frame, from the cohort of patients who had a history of traumatic patellar instability without severe clinical features (i.e., fixed or obligatory dislocation). Controls were randomly selected from patients who initially sought consultation for knee complaints and were found to have normal magnetic resonance imaging (MRI) of the knee. Patients were included if they were under 18 years of age, had a diagnosis corresponding to one of the cohorts, and had an MRI from the study institution of adequate imaging quality. Patients were excluded if they had previous patellar realignment surgery (including MPFL reconstruction and TTO), or if they had outside institution MRI scans.

A total of 100 patients were included, 40 controls, 40 standard traumatic instability patients, and 20 fixed or obligatory dislocation patients. Average age among all study

subjects was 13.3 ± 2.3 years, with 55% females and 47% left knees.

Radiographic measurements

Images were acquired using a 3.0 T Excite GE MRI scanner (General Electric Healthcare, Milwaukee, Wisconsin), with the patient supine and knee extended inside a knee coil. For patients with multiple MRI scans, the scan closest in time to the index visit was used. All measurements were made in a blinded fashion using axial proton density projections. Tibiofemoral rotation was measured by comparing the angle between the posterior femoral and tibial condylar lines (Fig. 1). The posterior femoral condylar line was drawn at the level of the widest antero-posterior diameter of the condyles. The posterior tibial condylar line was drawn at the level of the posterior cruciate ligament insertion into bone. Angle measurements were made using the measurement tools in the Sectra IDS7 imaging analysis software (Linköping, Sweden), which provides accuracy to one decimal point. A negative value was assigned for internal tibiofemoral rotation (relative internal rotation of the tibia relative to the femur), and a positive value for external tibiofemoral rotation (relative external rotation of the tibia relative to the femur). TT–TG was measured according to previously described standard landmarks.

Statistical analysis

Power calculation was performed for comparison of paired differences, for a power of 80% and $\alpha = 0.05$, to determine the sample sizes needed to detect meaningful differences in tibiofemoral rotation between individual groups, using standard methods [14]. The expected effect size used for the calculation was 3°, based on a previous study of tibiofemoral rotation in patellofemoral instability [4]. The power calculation was performed for an enrollment ratio of 2:1. For adequately powered detection of a 3° difference in tibiofemoral rotation between groups, the required sample size was 19 patients from the fixed or obligatory dislocator group, and 38 patients from the control and standard traumatic instability groups separately.

For both tibiofemoral rotation and TT–TG, a two-way random single measures intraclass correlation coefficient (ICC) with absolute agreement was calculated among four measurers. Descriptive statistics were calculated, and comparative analysis of tibiofemoral rotation and TT–TG was conducted using two-tailed t test, ANOVA, Pearson's correlation coefficient, and multiple linear regression with significance set at $\alpha = 0.05$ using SPSS statistical software (IBM, Armonk, NY).

Results

Average age differed significantly among groups ($p < 0.001$), with the standard traumatic instability group being older on average (14.5 ± 1.9 years) than both the control (12.6 ± 1.9 years, $p < 0.001$) and fixed or obligatory dislocation groups (12.6 ± 2.9 years, $p = 0.003$), which had similar average age (n.s.). In the overall study population, and within each cohort, there was no gender predilection, with 55% of all subjects being female (n.s.). Within the fixed or obligatory dislocation group, eight patients had known underlying diagnoses at the time of initial evaluation, including rickets (2), nail patella syndrome (2), melorheostosis (1), Rubenstein–Taybi syndrome (1), Ehlers–Danlos syndrome (1), and multiple hereditary exostoses (1).

The ICC was 0.96 (95% CI 0.93–0.98) for tibiofemoral rotation and 0.92 (95% CI 0.84–0.96) for TT–TG. Tibiofemoral rotation was significantly different among the three groups ($p < 0.0001$). There was $3.8° \pm 5.4°$ internal tibiofemoral rotation in controls, $1.6° \pm 5.1°$ external tibiofemoral rotation in standard traumatic instability patients, and $8.5° \pm 16.2°$ in the fixed or obligatory dislocator group; all differences between groups were statistically significant

Fig. 1 Measurement of tibiofemoral rotation using proton density axial MRI. **a** The posterior femoral condylar line at the level of the widest anterior–posterior diameter of the condyles is drawn. **b** The angle of the posterior femoral condylar line is drawn against the posterior tibial line, at the level of the posterior cruciate ligament insertion onto the bone. In this example, the tibiofemoral rotation is 5.6 degrees external (tibia externally rotated in relation to femur)
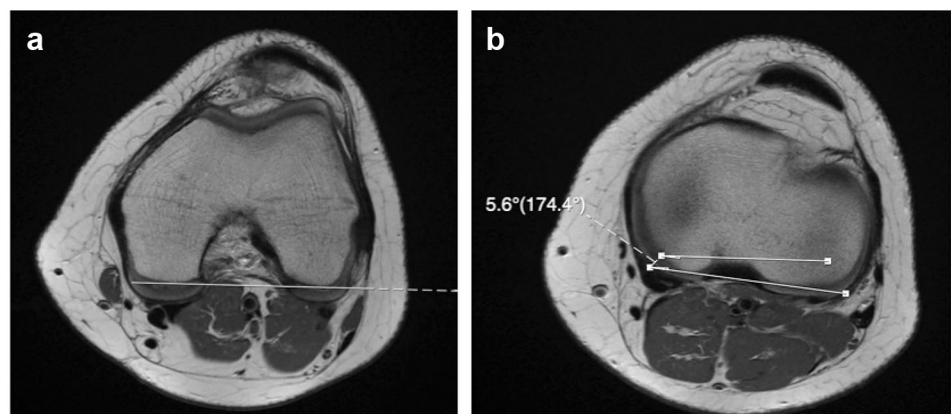
(Fig. 2a). Fixed or obligatory dislocation patients had on average 12.3° greater external tibial rotation than controls, while standard traumatic instability patients had 5.4° greater external tibial rotation. TT–TG was significantly different among the three groups ($p < 0.0001$). TT–TG was lowest in the controls (8.6 ± 3.2 mm), followed by standard traumatic instability patients (15.1 ± 2.9 mm), and greatest in fixed or obligatory dislocator patients (18.6 ± 6.5 mm); all differences between groups were statistically significant (Fig. 2b).

Pearson's correlation analysis for the overall study population (all 100 patients together) showed a statistically significant moderate correlation between TT–TG and tibiofemoral rotation ($r = 0.65$, $p < 0.0001$), but no correlation between age and tibiofemoral rotation ($r = 0.15$, n.s.), or age and TT–TG ($r = 0.049$, n.s.). Correlation analysis within each cohort showed that the correlation between TT–TG and tibiofemoral rotation was strong in the fixed or obligatory

dislocator cohort ($r = 0.71$, $p = 0.0003$), moderate in the standard traumatic instability cohort ($r = 0.33$, $p = 0.04$), and did not show a statistically significant correlation in the control group ($r = 0.14$, n.s.). Results from single and multivariate regression analysis for the overall study population and the separate cohorts are presented in Table 1.

Discussion

This study aimed to evaluate the association between magnitude of tibiofemoral rotation and clinical severity of patellofemoral instability. Statistically significant differences were observed in tibiofemoral rotation among patellofemoral instability patients from three clinical severity groups, with fixed or obligatory dislocators having the greatest external tibiofemoral rotation, followed by standard traumatic
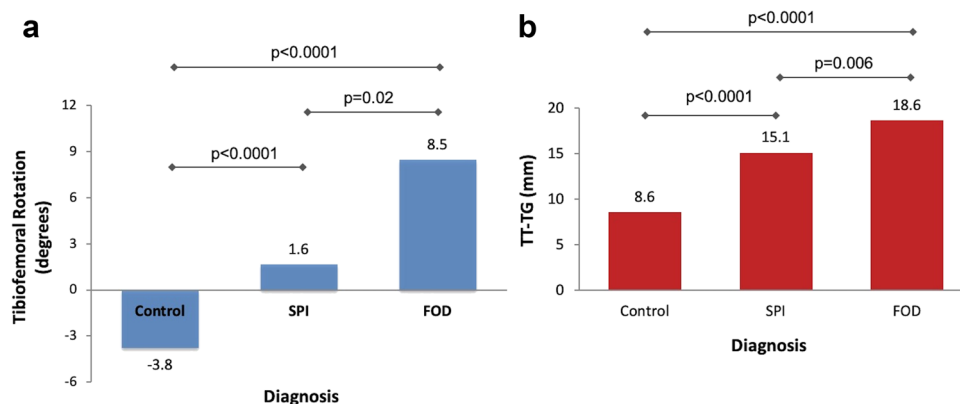

Fig. 2 Difference in tibiofemoral rotation (**a**) and TT–TG (**b**) among the control, standard traumatic instability and fixed or obligatory dislocator groups. A negative value for tibiofemoral rotation indicates internal tibial rotation relative to the femur, and positive values indicate external tibiofemoral rotation. Horizontal bars represent statistical significance between groups, $p < 0.0001$. *SPI* standard traumatic patellofemoral instability, *FOD* fixed or obligatory dislocator

Variables	Total	Control	Standard traumatic instability	Fixed or obligatory dislocators
Age vs. TT–TG[a]	$r = 0.049$ n.s	$r = 0.033$ n.s	$r < 0.0001$ n.s	$r = 0.22$ n.s
Age vs. tibiofemoral rotation	$r = 0.15$ n.s	$r = 0.15$ n.s	$r = 0.11$ n.s	$r = 0.25$ n.s
TT–TG vs. tibiofemoral rotation	$r = 0.65$ $p < 0.0001$	$r = 0.14$ n.s	$r = 0.33$ $p = 0.037$	$r = 0.71$ $p = 0.0003$
Multivariate[b]	$R^2 = 0.44$ $p < 0.0001$	$R^2 = 0.041$ n.s	$R^2 = 0.12$ n.s	$R^2 = 0.56$ $p = 0.0009$

Table 1 Multivariable correlation analysis of age, TT–TG, and tibiofemoral rotation

$r =$ Pearson's correlation coefficient

$R^2 =$ coefficient of determination (square of Pearson's correlation coefficient r)

[a]TT–TG = tibial tubercle–trochlear groove distance

[b]Multiple linear regression performed with tibiofemoral rotation as the dependent variable, and age and TT–TG as independent variables

instability patients, and least in normal controls. Greater external tibiofemoral rotation was associated with increased TT–TG, with a stronger correlation seen in the more severe patellar instability patients. Tibiofemoral rotation through the knee joint was a reproducible measurement, with excellent interrater reliability on blinded MRI measurements. The study was adequately powered based on sample size calculation for the projected effect magnitudes.

Fixed or obligatory lateral patellar dislocation is seen more frequently in the pediatric and adolescent population and is a challenging entity to treat. There are often several anatomic and constitutional abnormalities present, such as generalized ligamentous laxity, trochlear dysplasia, patella alta, and torsional deformities [5, 6, 15]. The results of the current study suggest that fixed or obligatory dislocators also have significantly increased external tibial rotation at the level of the knee joint, with several cases of extreme rotational deformity (of greater than 40° external rotation through the knee joint alone). On plain radiographs, this rotational deformity can produce an apparent coronal plane angular deformity, due to the abnormal rotation of the tibia in relation to the femur (Fig. 3). In this situation, treatment

Fig. 3 Representative radiographs of fixed lateral patellar dislocation with severe rotatory deformity at the level of the tibiofemoral joint. The patient is a 13-year-old male with a history of nail patella syndrome, with a fixed lateral dislocation on the left side. **a** Standing hip to ankle alignment film. **b** AP radiograph of the knee. Orange line represents mechanical axis (drawn from the center of the hip to the center of the ankle) and green lines represent anatomic coronal tibiofemoral angle. There is apparent valgus through the knee joint when assessing the distal femur and proximal tibia; however, the mechanical axis is neutral as it passes through the center of the knee. The apparent valgus deformity is a result of the rotatory deformity through the joint, as the AP projection of the distal femur corresponds to an oblique lateral projection of the proximal tibia. **c** Lateral radiograph of the knee, demonstrating an oblique AP view of the proximal tibia despite a lateral view of the femoral condyles. **d** Bilateral merchant view radiograph demonstrating a dysplastic distal femur and trochlea, and fixed lateral patellar dislocation
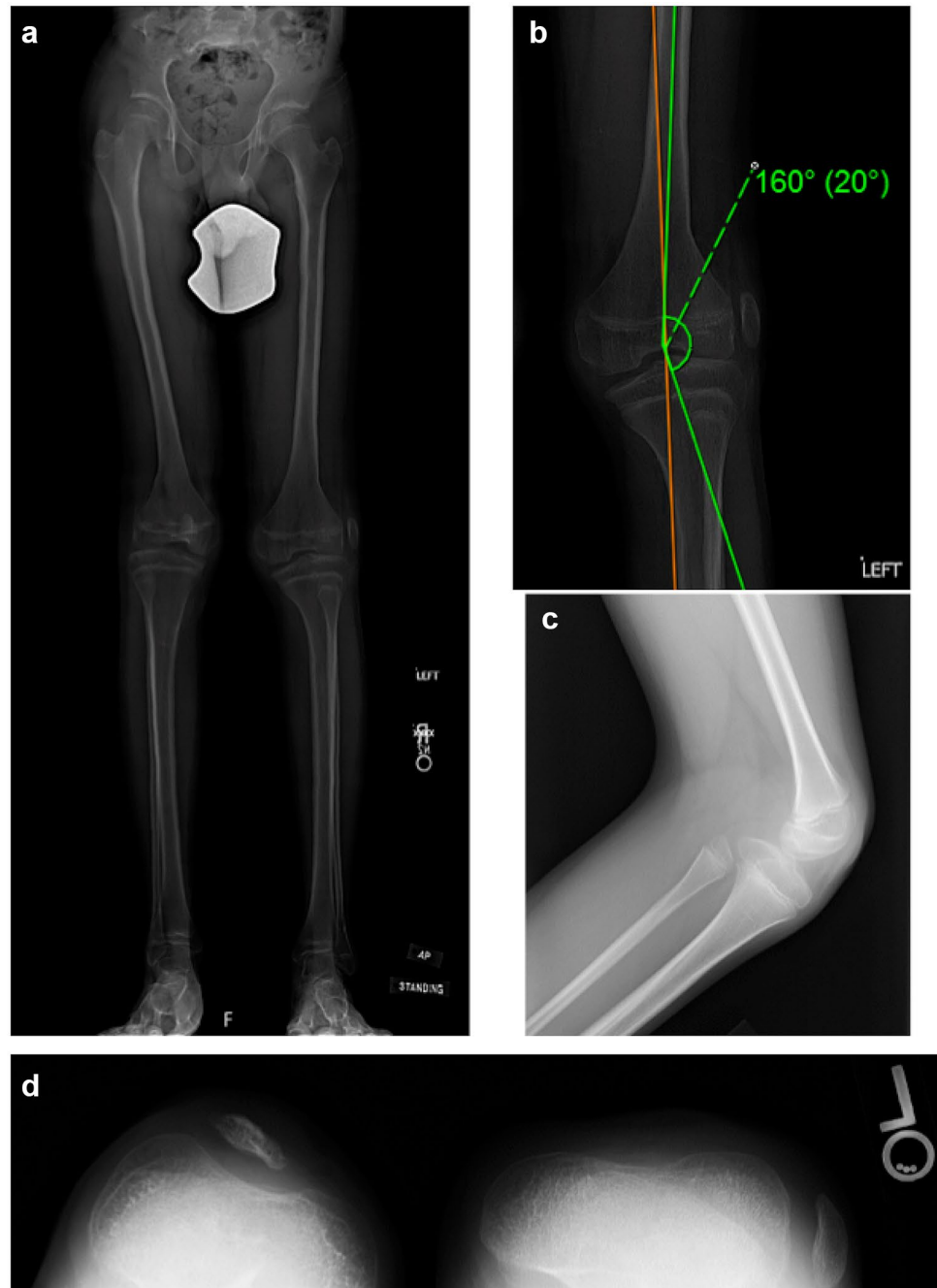
with guided growth for correction of the apparent angular deformity would be inappropriate. Furthermore, it is important to appreciate that in patients with a fixed lateralized patella, the normal force vector of the extensor mechanism is altered, so that instead of a direct axial pull to cause extension, it exerts a lateralizing and external rotatory force on the tibial tubercle (Fig. 4). Additionally, trochlear dysplasia, which is known to be one of the strongest anatomic contributors to patellofemoral instability, may be present in patients with abnormal tibiofemoral rotation (as seen in Fig. 4).

While rotational profile is known to be an integral component of patellofemoral kinematics and stability, the literature characterizing the effect of tibiofemoral rotation through the level of the knee joint is extremely limited. Much of the previous literature is based on total knee arthroplasty, and has established that distal femur rotational alignment affects patellar tracking and force distribution [1, 13, 16]. A recent study in native knees with patellar instability showed that femoral anteversion, specifically diaphyseal and distal anteversion but not proximal anteversion, had statistically significant moderate correlation with increased TT–TG [20]. Another recent study of native knees highlighted the complexity of bony parameters, including femoral and tibial torsion, TT–TG, and coronal mechanical axis, and their relation to each other, showing a statistically significant but weak to moderate correlation among all these factors [8]. These previous studies do not directly measure axial rotation of the tibia relative to the femur at the level of the knee joint.

To date, there has been one series that showed a difference in tibiofemoral rotation at the level of the knee joint between controls and pediatric patients with patellar instability [4]. The authors showed that patients with patellar instability on average had approximately 7.7° more external tibiofemoral rotation than controls. While that series established the relevance of tibiofemoral rotation in the field of patellar instability, it did not assess the impact of varying magnitude of tibiofemoral rotation on the severity of patellar instability symptoms. While the current study suggests that tibiofemoral rotation differences are seen in patients with varying severity of patellofemoral instability, the exact clinical relevance is unkown. Given the limited nature of the literature on tibiofemoral rotation, there are many unanswered questions, such as how tibiofemoral rotation relates to other commonly used measurements in patellar instability, how reliable of a measurement it actually is, and what the true clinical significance of tibiofemoral rotation is. Furthermore, it is possible that by surgically re-establishing tension in the MPFL, the increased medialized force vector on the patella exerts enough force to alter resting rotation of the tibia in relation to the femur. However, there are no studies investigating this phenomenon in the literature.

It is important to note that in this study population, age differed between standard traumatic instability and fixed or obligatory dislocation patients, with younger patients on average in the fixed or obligatory dislocator group. This difference raises the question of confounding, as tibiofemoral rotation was greatest in the fixed or obligatory dislocator group, but the fixed or obligatory dislocator group had a significantly smaller average age. Regression analysis showed that age was not independently associated with tibiofemoral rotation, in the overall study population or in any of the separate cohorts. Nonetheless, there are likely other

Fig. 4 Representative axial MRI of fixed lateral patellar dislocation. The patient is an 8-year-old male with a history of trisomy 21, who presented with bilateral patellar instability, with a fixed lateral dislocation on the right side. **a** Image at the level of the trochlea showing fixed lateral patella dislocation. **b** Image at the level of the tibial tubercle; arrow represents lateral and external rotatory force imparted on the tibial tubercle by the patellar tendon upon contraction of the quadriceps. **c** Combined overlay image showing 24.2° external tibiofemoral rotation, and the rotatory component of the vector of the extensor mechanism in the case of fixed lateral patellar dislocation. *T* tibia, *Fe* femur, *Fi* fibula, *P* patella
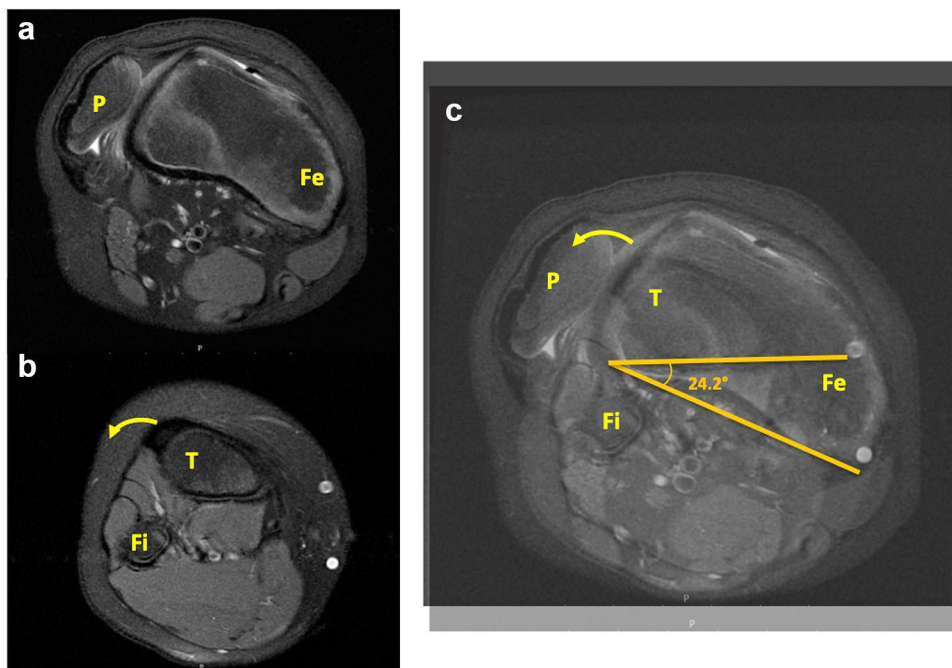
confounders of age that are at play, such as the presence of syndrome-associated patellar instability. While age is not independently associated with tibiofemoral rotation, it is possible that fixed or obligatory dislocation patients, who tend to have higher rates of underlying syndromes, tend to present with a severe phenotype of patellar instability earlier in life. While the typical patient with recurrent traumatic patellar dislocations often presents in adolescence, patients who become fixed or obligatory dislocators tend to present at younger age [3, 7, 17] and may represent a physiologically distinct population. The findings of this study suggest that tibiofemoral rotation may play a role in this physiologic difference.

This study has numerous important limitations. All patients were drawn from one institution, potentially creating a population that is different from the general population and thus introducing sampling bias. Additionally, although consecutive fixed or obligatory dislocator patients were included, the control and standard traumatic instability cohorts were selected randomly, which can potentially introduce selection bias. Because this study is a single time point study that did not require follow-up, there is no loss to follow-up; however, all of the outcomes reported rely on radiographic measurements. While TT–TG is a well-described measurement that is frequently used in research and clinical practice, measurement of tibiofemoral rotation is not a well-established technique. Although the interrater reliability among three independent blinded raters in this study was excellent, it is possible that this high reliability may not be as high when used by other providers. Finally and perhaps most importantly, there is undoubtedly confounding bias. The mean age of the groups was different, as addressed above, and multivariate analysis showed that there was no correlation between age and tibiofemoral rotation in our study population. However, despite moderate and strong correlations between TT–TG and tibiofemoral rotation, the multivariable regression model using age and TT–TG as dependent variables to predict tibiofemoral rotation had a coefficient of determination R^2 of 0.56, which suggests that 56% of the variance in tibiofemoral rotation can be statistically attributed to age and TT–TG. The other factors that are known to play a role in patellar instability that may affect tibiofemoral rotation include femoral and tibial torsion, soft tissue laxity or integrity (either with generalized conditions such as Ehlers–Danlos or with traumatic conditions such as MPFL rupture), and lower limb mechanical axis deviation. Additionally, there are other conditions and comorbodities that are not accounted for in our analysis such as sports participation, prior knee injuries, and family history. Additional studies are needed to truly understand the clinical impact of tibiofemoral rotation and its role in prognosticating and potentially indicating patients being treated for patellar instability.

Conclusion

Increasing external tibiofemoral rotation is seen with increasingly severe patellar instability, with greatest external rotation seen in fixed or obligatory dislocators, followed by standard traumatic patellar instability patients, and the lowest in normal controls. The correlation between TT–TG and tibiofemoral rotation was highest in fixed or obligatory dislocators, suggesting that in these patients, higher TT–TG values may be associated with greater degree of rotational deformity through the knee joint than in standard traumatic instability patients. Additionally, measurement of tibiofemoral rotation was reproducible on MRI with excellent interrater reliability.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest..

Ethical approval Approved under Hospital for Special Surgery IRB # 2014-189.

Informed consent Approved waiver of documentation of informed consent according to 45 CFR 46.116 (d).

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