Published in final edited form as:

Am J Sports Med. 2017 April ; 45(5): 1110–1116. doi:10.1177/0363546516681002.

The Tibial Tubercle-Trochlear Groove Distance Is Greater in Patients With Patellofemoral Pain: Implications for the Origin of Pain and Clinical Interventions

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Abstract

Background—The distance between the tibial tubercle (TT) and trochlear groove (TT-TG distance) is known to be greater in patients with patellar instability. However, the potential role and prevalence of pathological TT-TG distances in a large cohort of skeletally mature patients with isolated patellofemoral pain (PFP) are not clear.

Purpose—To determine if the mean TT-TG distance is greater in patients with PFP, who lack a history of patellar dislocations, knee trauma, or osteoarthritis, relative to healthy controls.

Study Design—Cross-sectional study; Level of evidence, 3.

Methods—A total of 50 knees (38 patients) with PFP and 60 knees (56 controls) without PFP formed the basis of this study. Magnetic resonance imaging was used to determine the TT-TG distance from 3-dimensional static scans.

Results—The cohort with PFP demonstrated a significantly greater mean TT-TG distance, relative to asymptomatic controls (13.0 vs 10.8 mm, respectively; $P = 0.001$). Among the cohort with PFP, 15 knees (30%) demonstrated TT-TG distances ≥ 15 mm, and 3 knees (6%) demonstrated TT-TG distances ≥ 20 mm.

Conclusion—Most adult patients with isolated PFP have elevated TT-TG distances compared with controls, which likely contributes to the force imbalance surrounding the knee..

Key Terms

knee; MRI; patellar tendon

INTRODUCTION

Patellofemoral pain (PFP) is a prevalent cause of joint pain in young adults, affecting thousands of individuals worldwide.^{1, 15, 33} While some individuals report pain onset

following patellar dislocation or trauma, the majority develop PFP in the absence of a predisposing traumatic event.³⁶ As the symptoms of PFP commonly arise during participation in various forms of physical activity, including activities of daily living, PFP can have detrimental effects on the patient's physical, psychological, and emotional well-being.^{10, 11, 22, 29}

Currently, PFP is believed to result from lower extremity malalignment and force imbalances around the knee, which alter patellofemoral kinematics and cause increased joint contact pressures.³² The relationship between these factors is complex, with both dynamic and static forces acting on the patella in all three cardinal planes. While proximal alignment (e.g., Q-angle,^{40, 41} femoral rotation^{16, 43}) and muscle imbalances (e.g., vasti medialis-lateralis weakness,^{37, 50} altered EMG timing between the vastus medialis and lateralis^{9, 49}) have been extensively studied in cohorts with PFP, the potential contribution of lateralization of the patellar tendon in this population has not been evaluated in a large cohort of individuals with isolated PFP.

The distance between the tibial tubercle (TT) and trochlear groove (TG) (TT-TG distance) is an objective marker of the lateral pull of the patellar tendon. This parameter is frequently measured in patients with a history of patellar dislocations and is used clinically to optimize surgical recommendations for corrective osteotomy of the TT.¹² Both magnetic resonance (MR) imaging and computed tomography (CT) have been used to calculate TT-TG distances, with MR imaging offering the added advantages of soft tissue evaluations and no radiation exposure. The TT-TG distances obtained on MR images have been found to be 3 to 4 mm less than those obtained on CT.^{2, 20, 21} As a result, 15 and 20 mm have been proposed as thresholds for TT osteotomy using MRI and CT, respectively.^{3, 12, 47} While many prior studies^{13, 44, 48} have identified pathological TT-TG distances in patients with a history of patellar dislocations, the potential role and prevalence of this parameter in a large cohort with isolated PFP (ie, pain not secondary to patellar dislocations, osteoarthritis, or other knee trauma) are unclear. Yet, TT osteotomy has been performed in patients with isolated PFP without a clear understanding that the direction of pull on the patella from the patellar tendon is a likely contributing factor to PFP.^{4, 16, 17, 19, 24, 34, 47}

To address this gap in understanding, the primary aim of this study is to compare TT-TG distances in a robust cohort with isolated PFP against healthy age- and sex-matched controls. The null hypothesis is that the average TT-TG distance is not greater in subjects with isolated PFP, relative to matched controls. The secondary aim of this analysis is to explore the prevalence of pathological TT-TG distances in this population.

METHODS

MR imaging and clinical intake data for 120 skeletally mature knees (101 subjects) were collected from 2005 to 2016 as part of an ongoing IRB approved study. Of the 120 knees, there were 60 in the control cohort and 60 in the PFP cohort. However, 10 subjects with PFP were removed following imaging due to radiologic signs of osteoarthritis, leaving 110 total knees (94 subjects) for analysis (Table 1). Subjects with a clinical diagnosis of PFP were included if they reported pain for greater than six months and if they denied all of the

following exclusion criteria: prior patellar dislocation, clinically or radiologically diagnosed patellofemoral or tibiofemoral osteoarthritis (OA), rheumatoid arthritis, prior trauma or injury to the knee (e.g., meniscus, cartilage, ligament, iliotibial band), prior knee surgery, other lower limb pathology, unfused growth plates, or diagnosed generalized joint laxity (e.g., a clinical diagnosis of Ehlers-Danlos Syndrome or a Beighton score⁴² greater than five). Asymptomatic volunteers were recruited to comprise the control cohort. All controls met the same exclusion criteria, but denied a current or past diagnosis of PFP. If one knee failing to meet the inclusion/exclusion criteria, the participant was removed from the control cohort. The control database was matched to the database of subjects with PFP for age, height, and weight. If both knees met the inclusion/exclusion criteria and time permitted, both knees were scanned.

Prior to image acquisition, all subjects underwent a history and physical examination with targeted evaluation of the knee. As part of the assessment, each participant's height, weight, body mass index (BMI), visual analog scale (VAS) for pain during a typical day, VAS for pain at the end of the day, VAS for pain during provocative activities, and anterior knee pain (AKP) score were obtained (Table 1).

For image acquisition, subjects were positioned supine in a 3-Tesla MR scanner (Phillips Electronics, Eindhoven, The Netherlands) with the knee in an 8-channel knee coil. Custom heel holders were used to ensure that the internal-external rotation of the lower extremity was anatomically neutral and the same for all subjects.⁶ Cushions of varying thickness were placed under the heel holders to bring each patient's knee to full extension. Sagittal 3D Gradient Recalled Echo (GRE) MR images (spatial resolution=0.27×0.27×1.0mm, 512×512pixels), 3D sagittal GRE images with fat saturation (GRE-FS), and proton density weighted images were also obtained. All datasets were converted to 3D axial and coronal image sets using the raw data from the scanner. The axial plane was defined perpendicular to the longitudinal axis of the MR scanner. A musculoskeletal radiologist read all images to ensure the absence of knee injury, ligament damage, and arthritis. Any cases noted by the radiologist as having potential patellar, femoral, or tibial cartilage defects were referred to the senior musculoskeletal radiologist (XX) for grading according to the International Cartilage Repair Society (ICRS) criteria.²⁶ Subjects with > grade 2 pathology (i.e., <50% cartilage defect) were excluded from the study due to presumed underlying osteoarthritis.

The TT-TG distance was measured from the 3D GRE images using the Medical Imaging Processing, Analysis, and Visualization (MIPAV) software package (NIH, Bethesda, MD). The 3D Tri-Planar View tool in MIPAV allowed the points of interest to be determined simultaneously in all three planes (Figure 1).

The TT-TG distance was measured in accordance with the current gold standard methodology.^{7, 12} The axial image that demonstrated the largest epicondylar width with the deepest, yet most clearly defined, trochlear groove, was identified (Figure 2A). Of note, this axial slice typically coincided with a small notch on the posterior femoral condyles on the mid-sagittal images, and this anatomical marker was used to assist in locating the correct axial slice (Figure 2B). On the axial image, a tangent to the posterior femoral condyles was drawn (FM-FL). A second line on the same image was drawn perpendicular to the tangent,

passing through the deepest part of the trochlear groove (TG). This line was then transferred to the most superior axial slice depicting complete insertion of the patellar tendon on the tibia (Figure 2C). The TT was defined as the midpoint of the patellar tendon into the tibia. The distance between the TT and the transposed TG was measured to determine the TT-TG distance.

The intra-observer variability for TT-TG distances among 30 randomly selected knees (15 controls and 15 subjects with PFP) was assessed based on the Intraclass Correlation Coefficient (ICC),³⁹ a two-way mixed effects model, and Bland-Altman 95% limits of agreement (LOA).⁵ For statistical comparisons, generalized estimating equations (SPSS version 22; IBM Corp) were used to assess if parameters of interest were different between cohorts (PFP and control). The generalized estimating equations model the correlation between data acquired from the same patient (left and right knee) and then compensate for any lack of independence when calculating the P values. To enhance the utility of the data for future studies, the mean values for the female and male subgroups were also determined (Table 2).

RESULTS

Eleven knees in the cohort with PFP were flagged for review by the senior musculoskeletal radiologist. Of these, ten received an ICRS grade >2 in at least one section of the patella (medial, mid, or lateral), femur (anterior-medial, anterior-lateral, posterior-medial, posterior-lateral), or tibia (medial or lateral) and were excluded. The eleventh knee was retained in the study as it was determined to have grade 2 findings. Thus, data for 50 knees (38 subjects) with PFP and 60 knees (56 subjects) without PFP were included in the final analysis (Table 1). No demographic differences existed between the cohorts. The ICC for intra-observer variability was 0.991 with 95% confidence intervals of 0.981–0.996 (Figure 3). Bland-Altman analysis for intra-observer variability demonstrated a mean difference of 0.27mm with limits of agreement of –1.3 to 1.9mm.

Subjects with PFP demonstrated a greater TT-TG distance relative to healthy controls, ($13.0 \pm 3.6\text{mm}$ versus $10.8 \pm 3.0\text{mm}$, $p=0.001$, Figure 4). Within the PFP cohort, 15/50 (30%) of knees demonstrated TT-TG distances $\geq 15\text{mm}$. Of these 15, three (6%) of the total cohort demonstrated values $\geq 20\text{mm}$. Within the control cohort, 3/60 (5%) of knees demonstrated pathologic TT-TG distances. The range of TT-TG values for the PFP and control cohorts were 5.5–23.3mm and 5.0–17.6mm, respectively. Differences based on gender were not observed for either cohort (Table 2). Yet, the study was not originally designed to answer this question and a post hoc analysis revealed that the study was underpowered to detect such differences.

The correlation between VAS scores and TT-TG distances was determined to be 0.09, 0.09, and 0.11 for pain during a typical day, pain at the end of the day, and pain during a provocative activity, respectively.

DISCUSSION

As evidenced by greater TT-TG distances relative to controls, the lateral force from the patellar tendon likely contributes to the origin of pain in at least some skeletally mature patients with isolated PFP. This increased lateral force of the patellar tendon predisposes these patients to lateral maltracking and increased contact pressures between the lateral patellar facet and lateral TG during knee flexion and extension.⁴⁵ This study demonstrates that a large portion (approximately one-third) of skeletally mature knees with PFP display TT-TG distances of 15 mm.

Our study results concur with the findings by Wittstein and colleagues⁵¹; the TT-TG distance is greater in individuals with PFP. In this study the MR-based measure of TT-TG distance was 12.6 ± 1.1 mm for individuals with PFP ($n=15$), whereas the average for controls ($n=20$) was 9.4 ± 0.6 mm. These slightly decreased values relative to those observed in the current analysis may be a result of the small sample size or the mixed population investigated in this prior study. Specifically, 57% and 10% of the subjects in the PFP and control cohorts, respectively, were described as having "...the presence of signal heterogeneity or actual defects in the patellar cartilage on MRI." In addition, one individual in the cohort with PFP reported a history of patellar dislocation.

Another prior study²³ evaluated TT-TG distances among subjects with PFP ($n=40$) and controls ($n=10$) using CT imaging. Based on their findings, the authors recommended 9 mm as the critical value for diagnosis of TT malalignment. Subsequent studies,^{14, 31} including the current study, have shown that the average TT-TG distance for skeletally mature controls (10 mm) is higher than the recommended threshold. Thus, the proposed critical value is clearly too low. Additionally, this prior study did not exclude patients with a history of patellar dislocations. To identify factors that contribute to PFP, studies need to investigate cohorts composed exclusively of patients with specific, defined pathological abnormalities, as was done in the current analysis.

Two other studies^{27, 28} evaluated the TT rotation angle among subjects with PFP and controls. Although a higher TT rotation angle was observed for the cohort with PFP, these studies did not calculate the TT-TG distance. The current data from a large cohort of individuals with isolated PFP provides a more accurate description of the mean increase and prevalence of TT-TG in this population.

The current analysis demonstrates that a lateralized patellar tendon can contribute to the force imbalance at the knee in individuals with isolated PFP. Even a slight increase of the lateral tracking vector may cause dramatic increase of focal load on the distal patella upon entry into the lateral trochlea resulting in maldistribution of the load.⁴⁵ Thus, the TT-TG distance should be obtained in the clinical work-up of these patients. In addition, the greater TT-TG distance in patients with PFP may explain why some patients fail conservative therapy. As measured, TT-TG distances describe the passive force of the patellar tendon on the patella as if the joint were centered (Figure 5). It follows that conservative therapies (e.g., vastus medialis strengthening, patellar taping), which aim to reduce lateral maltracking, may increase the *in vivo* force of the tendon. The resultant valgus torque could

lead to excessive shear contact within the joint and persistent pain. Balanced quadriceps strengthening may achieve more normative patellar kinematics in the cohort with an elevated TT-TG distance, and future clinical studies investigating this therapy are encouraged.

Currently, no recommendation exists for the TT-TG distance that should prompt consideration for TT osteotomy in patients with intractable PFP, yet this surgical procedure is frequently performed after failed conservative treatment.^{4, 16, 18, 19, 24, 34, 47} Prior studies^{3, 8, 46} assigned a pathological threshold of 15mm for TT-TG distances when measured using MR images for individuals with a history of patellar dislocation. This value is approximately 1.5 standard deviations above the observed control average, and 30% of subjects with isolated PFP demonstrated TT-TG distances at or above this value. In addition, a recent cadaveric study⁴⁵ found that medial patellofemoral ligament reconstruction could only restore normal patellofemoral kinematics and contact mechanics when the TT-TG distance was <15mm. The authors concluded that TT-TG distances beyond this measure likely require TT osteotomy to rebalance the forces around the knee. Thus, the current and past work support a TT-TG distances 15mm as an appropriate threshold for consideration of TT osteotomy in patients with PFP after all conservative options have been exhausted. However future clinical studies are needed to confirm this recommendation.

It is important to emphasize that the pathological threshold for TT-TG distance set forth using the current data were established using MR imaging. Previous studies have indicated that TT-TG distance is 3–4mm greater when measured using CT images.^{2, 20, 21} Support for this increase is obtained from prior studies investigating patients with a history of patellar dislocation. Three MR-based studies that used the same measurement technique described in the current study reported TT-TG distances of 14.6 ± 4.6 mm (n=109)³, 14.7 ± 4.9 mm (n=34)⁸, and 14.7 ± 2.8 mm (n=32).⁴⁶ In contrast, Dejour and Walch¹³ studied subjects with a history of patellar dislocation using CT and reported an average TT-TG distance of 20.0 ± 1.6 mm (n=110).¹³ Based on these findings, TT-TG distances 15mm and 20mm have been proposed as the threshold for pathological categorization on MR and CT images, respectively, for patients with a history of patellar dislocation.^{3, 12, 14, 47} The current study supports using these two thresholds for pathological TT-TG distances in managing patients with PFP.

Although a pathological TT-TG distance should be considered in the etiology of PFP and can aid clinical decision making, caution needs to be applied when considering TT osteotomy for isolated PFP. Some prior studies^{4, 34, 47} observed excellent patient reported outcomes following TT osteotomy for individuals with intractable PFP and no history of patellar dislocation. However, other studies^{24, 30} reported only fair results in this population with a less favorable prognosis compared to individuals with a history of patellar dislocation. Patients who experience iatrogenic medial patellar instability present the strongest cautionary warning for using TT-TG distance in isolation for surgical decision making in populations with PFP.³⁵ This complication has been reported secondary to combined surgical procedures (i.e., TT osteotomy with lateral release) and inadequate pre-operative screening resulting in overcorrection. Thus, a TT-TG distance greater than 15mm may be a necessary, but not sufficient, criterion for considering TT osteotomy surgery in patients with isolated PFP who have failed conservative treatment.

In contrast to patients with patellar dislocation, for whom the lateral tracking pathology is made apparent by the dislocation, patients with isolated PFP lack clinical events that clearly identify lateral tracking pathology. Previous studies^{25, 38} have documented both lateral and medial patellar tracking profiles in subjects with PFP. Medialization of the patellar tendon may exacerbate the maltracking in the latter group. However, it is unknown if the primary measure used to identify surgical candidates for TT osteotomy (i.e., TT-TG distance) predicts dynamic medial-lateral tracking patterns. Thus, future work is needed to explore the predictive capacity of TT-TG distance for patellar tracking. If poor prediction is found, additional screening (e.g., dynamic tracking, static alignment, clinical exam) is likely required to optimize surgical outcomes for this population.

The primary limitation of this study is that these screening recommendations are based on skeletal anatomy and not surgical outcomes. Future randomized control treatment trials using the proposed protocols are encouraged for patients with intractable PFP and no history of dislocation.

In conclusion, skeletally mature individuals with PFP and no history of patellar dislocation demonstrate greater TT-TG distance relative to controls. This lateralized force likely contributes to the etiology of abnormal patellofemoral tracking patterns and contact pressures responsible for PFP. As such, measurement of TT-TG distance should be obtained in patients with intractable PFP to guide clinical decision making. However, the decision to perform TT osteotomy after failed conservative therapy should not be based solely on pathological TT-TG distance, as other anatomic variables may affect dynamic patellar tracking and influence surgical outcomes.

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What is known about the subject

The TT-TG distance is an objective marker for the force direction of the patellar tendon acting on the patella. This distance is known to be greater in patients with a history of patellar dislocation and is used to identify patients that are most likely to benefit from a tibial tubercle osteotomy.

What this study adds to existing knowledge

This study confirms that the TT-TG distance is greater in patients with patellofemoral pain and no history of dislocation. Thus, an excessive lateral force from the patellar tendon is a likely contributor to the etiology of patellofemoral pain.

Figure 1. Tri-Planar View Tool

used to determine points of interest simultaneously in all three planes at the level of the epicondylar width (above) and at the level of the insertion of the patellar tendon onto the TT (below).

Figure 2. The TT-TG distance on 3D GRE image

in a subject with PFP. **A:** An axial MR image of the left knee at the level of the femoral epicondyles. The perpendicular line (TG) meeting the tangent to the posterior condyles (FM-FL) and extending through the deepest aspect of the trochlear groove is shown. **B:** Mid-sagittal MR image of the same knee depicting the anatomical notch on the posterior femoral condyles used as a reference to identify the correct axial slice for determination of the TG. **C:** Axial MR image of the same knee at the level of insertion of the patellar tendon onto the TT depicting the distance between the midpoint of the patellar tendon and trochlear groove (TT-TG).

Figure 3. Intra-observer variability for measures of TT-TG distances.

Figure 4. Average TT-TG distances
with one standard deviation bars for controls and subjects with PFP.

Figure 5. TT-TG distance as defined on a 3D MR-based model for a subject with PFP in the current study. The TT-TG distance defines the lateral pull on the patella from the patellar tendon, as if the patella was centered in the groove. This subject had a large TT-TG value (20mm). The actual line of action of the tendon (dashed line) was less lateral than the TT-TG line (solid line) due to lateral patellar shift.

Table 1
Characteristics of participants

Where appropriate, the average value is provided with one standard deviation in parentheses. *The potential difference in the assignment of males and females to each cohort was evaluated using a 2-tailed Fisher's test.

Characteristic	PFP	Controls	p-value
Subjects (knees)	38 (50)	56 (60)	-
Age range (years)	15.9 – 55.1	15.5–54.6	-
Mean age (years)	27.4 (10.1)	27.0 (7.8)	0.55
Number of females:male subjects	28:10	42:14	>0.99*
Weight (kg)	64.0 (10.3)	63.7 (11.7)	0.65
Height (cm)	167.6 (8.9)	168.4 (9.0)	0.77
BMI (kg/m ²)	22.8 (2.8)	22.4 (3.0)	0.23
AKP	69.7 (17.2)	100	-
<u>VAS pain scores (out of 100)</u>			
pain during a typical day	29.3 (23.4)	0	-
pain at the end of the day	37.0 (29.4)	0	-
pain during a provocative activity	58.1 (28.7)	0	-

Table 2**TT-TG distances**

for the female and male subgroups.

Cohort	Female (mm)	Male (mm)	p-value
Healthy control	10.5 (2.8)	12.0 (3.6)	0.84
PFP	12.9 (3.7)	13.2 (3.5)	0.61