

Tibial Tuberosity Osteotomy

Indications, Techniques, and Outcomes

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Tibial tuberosity osteotomy (TTO) is a well-described treatment option for a broad range of patellofemoral joint disorders, including patellofemoral instability, patellar and trochlear focal chondral lesions, and patellofemoral arthritis. The purpose of this article is to review the evolution of the TTO procedure, from the original Hauser procedure to the current anteromedialization procedure, as well as discuss the pertinent anatomy and radiographs that accompany this procedure. The article highlights the surgical techniques for some of the more commonly performed TTO procedures and discusses the outcomes of the various TTO techniques. Complications, as well as clinical pearls to avoid these complications, are also included.

Keywords: tibial tuberosity osteotomy; patellofemoral; knee; surgical management; biomechanics; instability; tibial tubercle; patellar tendon

Tibial tuberosity osteotomy (TTO) is a well-described treatment option for a broad range of patellofemoral joint disorders. Historically, these have included patellofemoral instability, patellar and trochlear focal chondral lesions, and patellofemoral arthritis. Intraoperative customization of the osteotomy can modify tracking and/or patellofemoral stress to effect the unloading of focal or diffuse chondral lesions, to correct patellar height abnormalities and suboptimal alignment, or to correct iatrogenic medial instability. Tibial tuberosity osteotomy may be performed in isolation or in conjunction with soft tissue patellar stabilization, biological treatment of chondral disease, or patellofemoral resurfacing. Biomechanical studies have confirmed the role of TTO in unloading the patellofemoral joint and correcting multiplanar suboptimal alignment.³⁵ Clinical studies have also demonstrated excellent outcomes with TTO for a variety of patellofemoral problems.²⁸ Complications, while infrequent, can include infections, deep venous thrombosis, nonunion, proximal tibial fractures, possible neurovascular injuries with aberrant anatomy, and compartment syndrome. With careful patient selection, detailed preoperative planning, and meticulous surgical technique, TTO is a valuable tool in the treatment of healthy patients with the proper indications, including symptomatic suboptimal alignment of the extensor mechanism.

EPIDEMILOGY OF PATELLOFEMORAL DISORDERS

Patellofemoral disorders are very common in the general population and are a frequent reason for orthopaedic

consultation. Patellofemoral pain has been reported in up to 30% of students aged 13 to 19 years, resulting in limitations of athletic activity in up to 74% of these patients.^{7,25} Chondral lesions of the patellofemoral joint have been reported in 60% of more than 25,000 patients who underwent knee arthroscopic surgeries.⁹¹ The spectrum of chondral disease varies based on patient-specific factors, with lesion characteristics ranging from focal cartilage defects to diffuse patellofemoral arthritis. Patellofemoral instability is also commonplace, with an estimated incidence of patellofemoral dislocations of 5.8 per 100,000, increasing to 29 per 100,000 in the 10- to 17-year age group.⁶¹ The recurrence rate of patellar instability after nonoperative treatment ranges from 15% to 44%, and surgical intervention is often required.⁶¹ Nomura et al⁶⁸ found that 95% of patients who sustained a patellar dislocation also had a patellofemoral chondral defect, with 57% having the cartilage defect caused by an osteochondral fracture. Whether the patient has patellofemoral pain with intact cartilage, a focal chondral lesion, diffuse arthritis, instability, or a combination thereof, it is often found that alignment plays a role.

HISTORICAL PERSPECTIVE

The surgical technique for TTO has evolved alongside our understanding of the biomechanics of the patellofemoral joint. In 1938, Hauser⁴⁵ first described distal and medial transfer of the tibial tuberosity. This procedure was effective in resolving instability, with good or excellent results reported in 67% to 74%.^{13,48} However, over time, several authors reported a high incidence of patellofemoral arthritis, believed to be secondary to the posterior translation of

the tuberosity.^{17,27,51} Dougherty et al¹⁹ and Grana and O'Donoghue³⁸ both reported modifications of the initial Hauser procedure to address lateral patellar instability in which they used a slot-block fixation method of the tuberosity, essentially creating a wedge in the tibia for the bone block to pass into, securing it in place without screw fixation. Cox¹⁶ further modified the technique by transferring the tuberosity medially without translating the tuberosity posteriorly with the Roux-Elmslie-Trillat procedure. A 10- to 15-year follow-up of the Elmslie-Trillat procedure recently showed 62.5% good or excellent results, with osteoarthritis occurring more frequently in patients who had higher grade chondral damage at the time of surgery.⁶⁷ Maquet^{58,59} modified the technique by elevating the tibial tuberosity anteriorly with the bone graft to decrease the patellofemoral joint reaction force⁷⁹ and increase the patellar moment arm.³⁵ This procedure was, at times, complicated by soft tissue injury and wound breakdown. In 1983, Fulkerson³³ introduced the anteromedialization technique and, later, straight anteriorization without bone grafts.

APPLIED SURGICAL ANATOMY/BIOMECHANICS

Osseous Restraints

The osseous structures of the patellofemoral joint consist of the trochlear groove of the distal femur and the patella, a sesamoid bone within the extensor mechanism. The patella contains the thickest articular cartilage of any joint at up to 7 mm.²⁰ Commonly, the articular surface of the patella is limited to its superior two thirds, with the inferior third occupied by the insertion of the patellar tendon. This ratio can change with variations in the patellar nose, the most distal point of the patella. The majority of the articulating surface of the patella can be divided into the medial (smaller) and lateral (larger) facets, separated by the longitudinal median ridge, although there is considerable morphological variation as noted with the Wiberg classification. The trochlear groove, formed by the medial (smaller) and lateral (larger) facets, deepens distally and

deviates laterally and distally in relation to the femoral axis.³¹

The osseous anatomy of the patella and the trochlear groove provides important contributions to patellar stability. Variations in these bony structures can affect tracking, possibly contributing to pain and instability.^{18,41} Dr Henri Dejour and colleagues¹⁸ subclassified trochlear dysplasia into 4 subtypes: grade A dysplasia has a more shallow than normal trochlear groove, grade B has a flat or convex trochlea with a proximal prominence called the supratrochlear spur, grade C has a convex lateral and hypoplastic medial facet, and grade D has an oversized lateral spur of the convex medial trochlear facet often described as a "cliff pattern."^{77,87} This classification system, which was popularized by his son, Dr David Dejour and colleagues,⁸⁷ is useful when advising patients prognostically and aids in the surgical decision-making process regarding trochleoplasty,⁸ as trochlear dysplasia is one of the contributing factors for patellofemoral instability.¹⁸

Soft Tissue Restraints

The soft tissue structures attached to the patella can be divided into those that attach distally, proximally, medially, and laterally. The quadriceps tendon, which inserts on the superior pole of the patella, is formed by the convergence of the rectus femoris, vastus medialis, vastus lateralis, and vastus intermedius muscles approximately 5 to 8 cm proximal to the superior pole of the patella.³¹ The patellar tendon originates from the inferior pole of the patella and inserts on the tibial tuberosity, which is lateral to the midline of the tibia. The mean width of the patellar tendon is 24 to 33 mm, and the mean length is 4.7 cm.⁴¹ The medial structures, which are physiologically more compliant than the lateral structures,⁵⁰ consist primarily of the vastus medialis obliquus (VMO), the medial patellofemoral ligament (MPFL), the medial patellotibial ligament, and the medial retinaculum. The MPFL, a thickening of the medial retinaculum, extends from a saddle between the adductor tubercle and the medial epicondyle to the proximal and medial surface of the patella and is

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a biomechanically important restraint to lateral patellar subluxation; the MPFL is responsible for 50% to 60% of the medial stability afforded to the patella during the first 30° of flexion.⁷² This structure is crucial for the maintenance of patellar stability.⁷ For the patella to dislocate, it must displace laterally a mean of 50 mm, while the MPFL ruptures after elongating, on average, 26 mm.⁶⁶ Thus, MPFL tearing occurs with almost all patellar dislocations,⁶⁶ and the MPFL's resultant patholaxity is a frequent contributor to recurrent lateral patellar instability.^{21,76} Laterally, the multiple layers of the soft tissues have been described by Merican and Amis.⁶³ For simplicity and surgical considerations, these can be grouped into a superficial and deep layer. The superficial layer consists of the superficial oblique retinaculum, which runs from the iliotibial band to the patella, while the deep layer is made up of the patellotibial band, the epicondylopatellar band, and the transverse retinaculum.⁸³

Patellofemoral Biomechanics

Proper function of the patellofemoral joint requires a complex interplay of the bony and soft tissue structures. Functionally, the patella increases the moment arm of the extensor mechanism by moving the attachment point for the quadriceps away from the center of rotation of the knee. Normally, in complete extension, aside from a small posteriorly directed force from the retinacula, no sagittal forces act on the patella. With increasing knee flexion, there is a proportionally increasing posteriorly directed force vector from the patellar and quadriceps tendons, which increases joint reaction force.⁴⁷ In most patients, the patella does not articulate with the trochlea until at least 10° of knee flexion; patella baja and alta would alter this relationship.^{47,72} As a result, during early knee flexion, the predominant restraints to excessive medial or lateral displacement are the soft tissues described above.³¹

Biomechanical abnormalities of the extensor mechanism may occur as a result of deviations in coronal or axial plane alignment, aberrations in patellar height, or excessive patellar tilt. The force vector on the patella in the axial plane is a critically important factor in patellofemoral alignment. Supraphysiological lateral force vectors are a risk factor for patellofemoral dislocations, chondral lesions, or patellofemoral pain. Clinically, the quadriceps or Q angle is a proxy measure of the lateral force vector. The Q angle is formed by a line drawn from the anterior superior iliac spine to the center of the patella and a line drawn from the center of the patella to the tibial tuberosity. This angle normally measures a mean of 14° ± 3° and 17° ± 3° in men and women, respectively.¹ For accuracy and reproducibility, this measurement should be performed with the knee at 20° to 30° to ensure that the patella is engaged in the trochlear groove. Greene et al³⁹ demonstrated that there is still wide interobserver and intraobserver reliability errors in the measurement of the Q angle. Nevertheless, the concept of the quadriceps resultant force vector is important and may be better quantified with magnetic resonance imaging (MRI)-based volumetric analysis of muscle mass as described by Salsich et al.⁸⁰

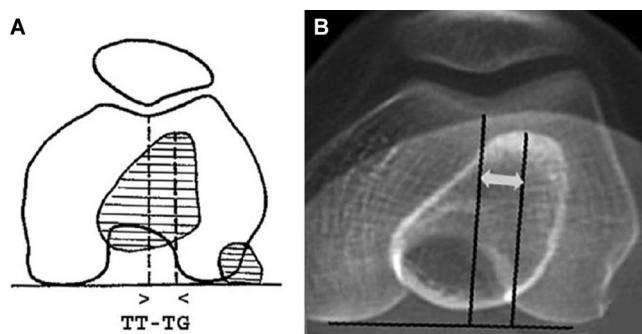


Figure 1. (A) Illustration demonstrating how to calculate the tibial tuberosity–trochlear groove (TT-TG) distance. (B) Computed tomography scan demonstrating how to calculate the TT-TG distance.

The tibial tuberosity–trochlear groove (TT-TG) distance is a radiographic measure of local patellofemoral alignment in the axial plane. This distance is calculated by superimposition of 2 axial computed tomography (CT) or MRI slices: one through the deepest aspect of the trochlea, and one through the center of the most proximal part of the tibial tuberosity.^{28,33} The distance between these points of both the tibial tuberosity and the trochlear groove is measured on a line parallel to the posterior condylar line⁸³ (Figure 1). The mean TT-TG distance in patients without patellofemoral symptoms has been reported from 10 to 13 mm.^{3,18} A measurement of ≥15 mm has been associated with a greater probability of patellar instability.⁸² A measurement of >20 mm represents an excessive lateral position of the tuberosity.⁷⁶ In one series, 56% of knees with at least 1 episode of dislocation had a TT-TG distance of >20 mm.¹⁸ Caution must be exercised when focusing locally to assess alignment. Excessive femoral anteversion or tibial external rotation may play roles. In addition, in patients with instability and trochlear dysplasia, by definition, there is no trochlear groove, and thus, the measurement is not possible. In these cases, there may be a role for an alternative measurement that references the posterior cruciate ligament (PCL), that is, the TT-PCL.⁸⁴ The TT-TG distance is a useful guide, along with the Q angle and patients' clinical examination findings, to help determine whether the patient will benefit from a TTO.

Patellar height abnormalities also influence patellofemoral biomechanics. Patella alta increases the angle of flexion at which the patella engages the trochlea, decreasing osseous constraint and placing the patient at a higher risk for patellar instability episodes.^{18,60} Patella alta also alters the contact area and thus increases stress.⁵⁶ Patella infera increases joint reactive forces on the patella and may be associated with motion limitation and patellofemoral pain in the absence of frank instability.²⁴ Patellar height can be determined by one of several classifications including the Insall-Salvati index,⁴⁹ the Caton-Deschamps index,¹² and the Blackburne-Peel index.⁶ The Caton-Deschamps index (Figure 2) is the preferred method, as this measurement can be made on radiographs or MRI scans and does not vary with the knee flexion angle. This



Figure 2. Lateral radiograph of the knee demonstrating the Caton-Deschamps index (B/A): The ratio of the distance between the inferior aspect of the articular surface of the patella and the anterosuperior angle of the tibia's outline (B) and the entire length of the articular surface of the patella (A).

can also be used to measure postoperative tuberosity position changes as opposed to the Insall-Salvati index.

Patellar tilt is dependent on both bony and soft tissue anatomic restraints. Lateral retinacular tightness can lead to fixed lateral patellar tilt (Figures 3A and 4A), causing biomechanical force overload of the lateral patella facet and focal chondral degeneration over time.^{32,71} In cases of lateral tilt and lateral facet overload, abnormalities of the Q angle or an increased TT-TG distance compound the problem by placing exceedingly higher forces on the lateral patellofemoral joint.³ Patellar tilt may also be present in patients with other underlying bony and soft tissue abnormalities that predispose to patellofemoral instability; in one study, 83% of patients presenting with patellar instability had a patellar tilt angle greater than 20°.¹⁸ Patellar tilt is measured by the angle formed by the posterior femoral condyles and the transverse axis of the patella (Figure 3).^{69,93} Patellar tilt can be evaluated on CT, on a Merchant radiograph (an axial view of the knee flexed to 30°), on MRI, and on a lateral radiograph.^{40,57}

Biomechanical Effects of TTO

As the position of the tibial tuberosity determines the direction and, to some degree, the extent of the distal forces



Figure 3. (A) Axial view suggests tilt, but a true tilt assessment requires a posterior condyle reference (per computed tomography or magnetic resonance imaging [MRI]) or a true lateral view. (B) True lateral view shows the minimal distance between the overlap of the medial ridge and the lateral facet, demonstrating a degree of tilt. Also, note the positive crossing sign of trochlear dysplasia. (C) The MRI scan shows what appeared to be tilt, but when referenced to the posterior condyles, the tilt angle was normal.

exerted upon the patella, the magnitude and direction of translation of the tuberosity at the time of TTO alter patellofemoral biomechanics. Anteriorization of the tuberosity decreases joint reaction forces by increasing the angle between the patellar and quadriceps tendons.⁵⁸ Contact area changes are complex and depend on height, medial/lateral position, and the degree of sagittal plane rotation from the tuberosity's elevation. A 2-cm elevation of the tuberosity reduces the patellofemoral compressive forces by approximately 50%.⁵⁸ Anteriorization rotates the patella on its horizontal axis and transfers the contact forces from distal to the proximal patella.⁵⁵ As little as 1.2 cm of anteriorization can reduce joint contact forces.⁵⁵ Medialization moves the contact pressure of the patella medially. In the setting of excessive lateral patellar tracking, this may improve overall congruity²⁷ and thus decrease overall contact pressures. It may also decrease lateral instability.¹⁴ However, in the setting of physiological tracking, medialization may interrupt a congruous joint and thus increase overall contact pressures and potentially lead to iatrogenic medial overload with an increase in medial forces in the medial compartment.⁵⁴ Distalization of the tibial tuberosity can be performed to correct isolated patella alta. This procedure allows the patella to engage in the trochlea earlier in flexion and thus increases osseous restraint to lateral translation of the patella in addition to shifting contact pressures distally.⁶⁰ Posteriorization should be avoided, as it increases stress across the patellofemoral joint and can lead to degenerative joint disease.³⁴

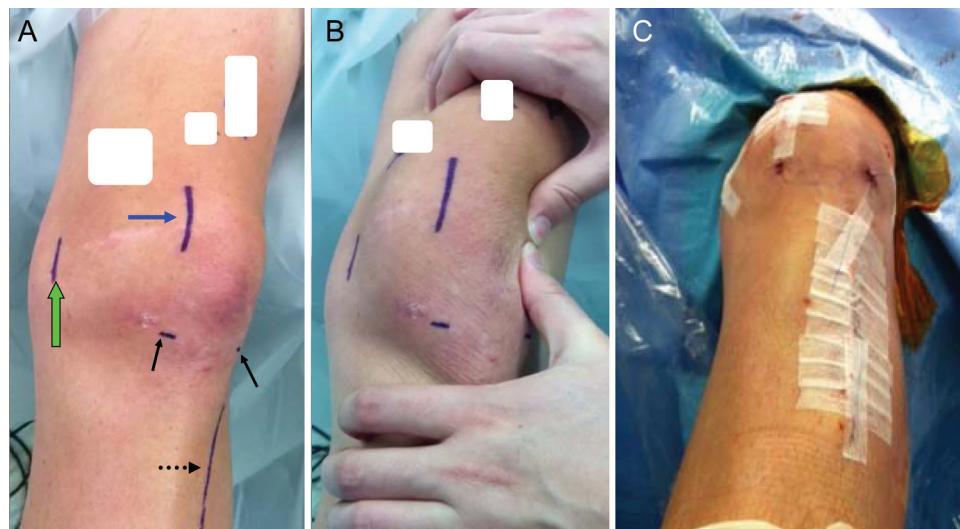


Figure 4. (A) Preoperative image of the knee, showing lateral patellar subluxation with incisions marked. Small black arrows: arthroscopic portals; dashed arrow: lateral tibial incision for anteriorization and medialization; blue arrow: medial patellar incision for patellar tunnel of the medial patellofemoral ligament (MPFL); green arrow: femoral incision for femoral tunnel of the MPFL. (B) Preoperative image of the knee with medial force on the patella, showing correctable deformity. (C) Postoperative image of the knee, showing the centralized position of the patella.

The posteriorization portion of the original Hauser procedure is believed to be the primary cause of the accelerated patellofemoral arthrosis seen clinically with this procedure.³⁰ In the setting of iatrogenic medial patellar overload due to an overzealous prior posterior medialization procedure (ie, Hauser), revision TTO with anterior lateralization of the tibial tuberosity could be considered.²⁷

In patients with an excessive lateral position of the tuberosity ($TT-TG > 20$ mm) associated with the lateral position of the patella in the trochlea in the setting of patellofemoral instability or pain due to a lateral chondral lesion, the combination of anteriorization and medialization (AMZ) can decrease lateral facet pressure, decrease overall patellofemoral contact stress by shifting the contact area proximally and medially, and improve patellofemoral tracking.^{9,35} Nevertheless, the instability is addressed with MPFL reconstruction. In patients who do not need the contact area shifted anteriorly, a simpler straight medialization can be performed instead of the more complex AMZ. Similarly, a patient with patellofemoral instability with an excessive TT-TG distance (> 20 mm) and patella alta (Insall-Salvati index > 1.2) may be a candidate for concomitant distalization with either a medialization or AMZ to correct all biomechanical factors associated with instability. However, in the patient with a proximal or medial patellar/trochlear defect, AMZ places more loads on the defect and has been shown to result in poor outcomes, unless accompanied by biological treatment of the chondral lesion at the time of alignment correction.⁷³ Likewise, AMZ tips up the inferior patella, which in turn unloads the distal patellar chondral lesion. Careful understanding of patellofemoral biomechanics will allow the surgeon to tailor the specifications of the osteotomy to the particular clinical situation.

CLINICAL EVALUATION

History and Physical Examination

Medical history should focus on the location (ie, diffuse anterior vs lateral facet), duration (ie, acute vs chronic), and onset (ie, traumatic vs insidious) of symptoms. Regarding patellofemoral instability, the number of events, severity (subluxation vs dislocation), mechanism of injury (ie, sport vs uneven ground), and need for reduction maneuvers should be documented. Careful attention should be paid to differentiating a chief complaint of patellofemoral pain from patellofemoral instability. Overlap conditions may occur, particularly in patients with chondral lesions after instability events. The presence of swelling or mechanical symptoms may also suggest underlying chondral lesions of the patellofemoral joint. Prior nonoperative treatment (nonsteroidal anti-inflammatory drugs [NSAIDs], injections, physical therapy, bracing) and surgical reports should be reviewed. Patient-specific variables such as age, body mass index, physical fitness, and emotional status (ie, expectations, motivations) are important prognostic indicators and may influence patient selection for TTO procedures. Patients should be asked about potential contraindications to TTO including smoking or ability to comply with the postoperative rehabilitation regimen.

The physical examination should begin with a focus on gait and the entire limb, assessing core proximal strength, dynamic limb strength, limb alignment (hip rotation and foot progression angle in the prone position), and foot mechanics. A standard complete knee examination includes an evaluation for effusion, tenderness to palpation, and ligamentous stability. Special tests for the

patellofemoral joint include assessment of the Q angle, patellar height abnormalities, and dynamic patellofemoral tracking. The J sign evaluates patellar tracking by demonstrating lateral deviation of the patella as the knee moves from flexion to full extension. A positive J sign is suggestive of possible underlying bony alignment issues, laxity or atrophy of the medial soft tissue restraints, tightness of the lateral structures, or some combination of the above abnormalities. A supine evaluation may help to differentiate patellofemoral pain from instability or may confirm suspicion for an underlying chondral disease or lateral facet overload. The patellar apprehension test is performed with the patient supine and the knee extended and the quadriceps relaxed. The examiner then attempts to passively displace the patella laterally. Asymmetric painful laxity, apprehension, and/or involuntary contraction of the patient's quadriceps muscle (ie, guarding) to avoid a dislocation signify a positive test result for patellofemoral instability. Iatrogenic medial instability may be assessed in a similar fashion, with a positive apprehension test result with lateral to medial patellar deviation after prior lateral release or overzealous TTO. Patellofemoral chondral disease may be considered in the presence of a knee effusion, pain with patellar compression, anterior crepitus, and pain with knee flexion. Restricted patellar mobility, isolated tenderness over the lateral facet, and fixed patellar tilt are suggestive of lateral overload syndrome. Significant overlap in physical examination findings may occur, requiring the clinician to use information from the medical history along with focused imaging studies to help formulate a diagnosis and treatment plan.

Imaging Studies

Standard radiographic series should be performed in all patellofemoral patients. This includes bilateral weight-bearing anteroposterior and flexed posteroanterior (Rosenberg), lateral of the affected limb, and bilateral low flexion axial views (eg, Lauren or Merchant).¹⁴ It is important to obtain a proper lateral view in which the posterior femoral condyles are overlapped, as rotation of the film can obscure the pathological changes. Mechanical axis views may be necessary if there is any suspicion of coronal tibiofemoral malalignment. Radiographs allow for the assessment of patellofemoral arthritis, patellar height, tilt, subluxation, and patellar and trochlear bony structures.

Advanced imaging studies are often useful for confirming the diagnosis and for preoperative planning. In fact, MRI offers superior definition of cartilage as well as soft tissue.⁴⁴ It can identify osseous contusions or edema patterns after patellar dislocations, osteochondral fragment avulsions, injuries to the MPFL and VMO, and joint effusion.^{11,14} Also, MRI is 85% sensitive and 70% accurate in detecting MPFL tears.¹⁴ Further, CT may be helpful to evaluate the 3-dimensional anatomy and relationships between the patella, trochlea, and tibial tuberosity. Measurements of TT-TG distance, patellar height, and tilt may be obtained from MRI, obviating the need for both studies in many scenarios.¹⁰ Contributory complex torsional abnormalities (ie, femoral anteversion), while rare, are still best evaluated by CT version studies of the femur and tibia.

SURGICAL INDICATIONS

The only operative indication after a first-time patellar dislocation is the presence of an unstable osteochondral lesion. Surgery is indicated for recurrent patellar dislocations despite adequate nonoperative treatment (ie, NSAIDs, brace, physical therapy, injection, taping).⁵⁴ For patellofemoral chondral lesions or arthritis, surgical indications include persistent pain, swelling, and/or mechanical symptoms despite following a reasonable trial of nonoperative treatment (ie, closed chain exercises, core strengthening, proprioceptive training, balance training, gait training, McConnell patellar taping, and patellar bracing).³⁷ Indications for the treatment of iatrogenic medial instability or lateral facet overload syndrome mirror the above scenarios, with surgery reserved for patients with persistent symptoms despite an adequate return of dynamic strength and flexibility with nonoperative measures (Figure 4, A and B).

For each of the above diagnoses and surgical indications, the rationale to include TTO is based upon patient-specific factors, lesion characteristics, and biomechanical abnormalities as outlined below. In general, TTO may be considered in cases of an excessive lateral position of the tuberosity (TT-TG >20 mm) or patellar height abnormality (Caton-Deschamp index >1.2) in patients with patellofemoral instability or to decrease stress at the patellofemoral joint in patients being treated for large focal defects of the patella or trochlea.

The specifications of TTO should be custom tailored to the patient's anatomy, based on radiographic measurements of alignment and location of any chondral lesions. Also, AMZ may be indicated in the setting of patellofemoral instability when the TT-TG distance is greater than 20 mm and the patella is positioned laterally in the trochlea (altered contact area). For an isolated AMZ, patients should have a normal proximal and medial cartilage surface or should be undergoing concomitant biological treatment for medial-based lesions at the time of osteotomy (eg, after the patellar dislocation event). The indications for AMZ in patients with borderline TT-TG distances (15–20 mm) with recurrent instability or after failure of previous soft tissue stabilization are less clear and should be fully vetted. In the treatment of lateral patellar or trochlear chondral disease or lateral facet overload syndrome, AMZ may play a role in cases of borderline tuberosity positions (TT-TG >15 mm), in which case the goal remains to normalize and not overmedialize. The angle of AMZ can be altered to provide consistent anteriorization with varied medialization based on patient- and lesion-specific factors. With constant anteriorization of 15 mm, a 60° slope creates approximately 9 mm of medialization, while a 45° slope would provide 15 mm of medialization. With slightly less anteriorization, there is less medialization. By varying these parameters, most excessive tuberosity positions may be normalized. Straight anteriorization is indicated to unload large distal patellar chondral lesions, bipolar kissing lesions, or arthritis in the setting of a normal TT-TG distance (<15 mm). Anteriorization is not a treatment for patellar instability. Medialization can be used in

patients with lateral patellar defects. Care must be taken not to overmedialize, which could possibly lead to abnormal patellofemoral tracking and increased contact forces. Distalization is indicated for patellar instability in the setting of patella alta. This may be combined with AMZ or anteriorization in selected cases. Lateralization or anterior lateralization is indicated in the revision setting to correct the iatrogenic excessive position of the medial or posterior medial tuberosity, respectively.

CONCOMITANT PROCEDURES

Concomitant procedures are often required at the time of TTO to correct coincident ligamentous, chondral, or other soft tissue injuries. In patients with patellofemoral instability, MPFL reconstruction treats the essential lesion common to all patients with lateral instability. In a subset of these patients with instability, tuberosity medialization may play a role, as results from MPFL reconstruction with concomitant medialization have shown 96% good or excellent results at 2 years.²¹ Nevertheless, excellent results have been shown with isolated MPFL reconstruction.⁸⁸ Thus, the soft tissue is of adequate strength to prevent recurrent instability. The open question is how to manage those patients with a laterally positioned patella and an excessive TT-TG distance. The MPFL is not used to pull the patella medially. Tuberosity medialization can normalize the patellar position and thus improve the contact area, with the long-term goal of diminishing the onset of degenerative changes; thus, only long-term studies will answer this question. In the setting of patellofemoral instability or lateral facet overload, concomitant lateral retinacular release or lengthening may be performed if there is tightness of the lateral soft tissue structures and fixed patellar tilt. Care must be taken, as the lateral retinaculum is a secondary stabilizer to lateral patellar translation and should not be disturbed unless a clear lesion is present. Lengthening may be preferred to rebalance the soft tissue without complete disruption of the lateral soft tissue envelope as performed with formal lateral release. In the setting of patellofemoral focal chondral lesions, TTO can also be used in conjunction with cartilage restoration procedures of the trochlea or patella to unload chondral lesions.²⁶ Many biological treatment options exist including debridement, microfracture, osteochondral autograft/allograft transplantation, autologous chondrocyte implantation (ACI), and DeNovo NT Natural Tissue Graft (Zimmer, Warsaw, Indiana, and ISTO, St Louis, Missouri). Debridement and microfracture work best for the treatment of smaller lesions, although results may deteriorate with a follow-up of greater than 2 years.⁹⁰ Kreuz et al⁵³ and Mithoefer et al⁶⁵ reported poor results for patellar microfracture. Osteochondral autografts may be considered for smaller lesions, but donor concerns and contour mismatch limit the utility for the patellofemoral joint. Osteochondral allografts are typically considered a salvage treatment for failure of previous cartilage procedures or for the treatment of large trochlear or near complete patellar lesions in young patients.²⁴ For the majority of well-shouldered

larger lesions of the patella or trochlea, cell-based techniques such as ACI or DeNovo NT Natural Tissue Graft are preferred.³⁷ In fact, ACI has the most literature support for the treatment of lesions of the patellofemoral joint.⁸⁹ Studies comparing results with and without TTO have confirmed that an unloading osteotomy significantly improves the subjective patient outcomes of ACI compared with cartilage treatment alone.^{36,89} Finally, in patients with patellofemoral arthritis, when patellofemoral resurfacing is performed, a very small subset may benefit from a concomitant TTO if there is lateral tracking or subluxation of the patella in the trochlear component (even with good function of the MPFL). There is a paucity of literature on this topic, and future studies are needed.

SURGICAL TECHNIQUES

Anteromedialization

While concomitant procedures may dictate many perioperative details, the technique described here is for AMZ performed in isolation. After induction of general anesthesia or regional blocks, the patient is positioned in the supine position with a lateral post, and the entire operative extremity is draped for intraoperative manipulation. Generally, diagnostic arthroscopic surgery is performed to assess the sites and grades of chondral lesions, as these may influence the type of tuberosity surgery. The surgeon may want to perform arthroscopic lateral release if lateral retinacular tightness is documented by CT/MRI and is definitely a contributor to the patient's symptoms, noting that some degree of lateral surgery is needed to allow for movement of the tuberosity without increasing tension in those structures. For tuberosity surgery, a thigh tourniquet improves visualization and decreases intraoperative blood loss. Infiltration of the skin with 0.25% bupivacaine before incision aids with postoperative pain management. For AMZ, the incision extends from the medial aspect of the tibial tuberosity to the lateral patella. If performed in conjunction with a patellar cartilage restoration procedure, the incision is midline and is extended superiorly to the proximal patella (Figure 5). After dissection through the subcutaneous tissues and the creation of full-thickness flaps, capsulotomies are made along the medial and lateral borders of the patellar tendon. The lateral capsulotomy is continued distally along the lateral border of the tibial tuberosity. A periosteal elevator can be used to elevate the anterior compartment muscles from the lateral tibia. A retractor is placed along the lateral tibia extending to the posterior tibia to protect the anterior tibial artery and deep peroneal nerve from damage during the osteotomy. Next, an oblique anteromedialization cut is made from a location at the medial proximal attachment of the patellar tendon to the tibial tuberosity, angling laterally and distally so that the cut ends through the lateral wall of the tibia with a pedicle length of 7 to 10 cm. The AMZ osteotomy should taper toward the anterior cortex of the tibia distally. Although this oblique cut can be made "free hand," a variety of commercially available jigs (Arthrex

T3 System, Arthrex Inc, Naples, Florida, and Tracker AMZ Guide System, DePuy/Synthes Inc, Raynham, Massachusetts) allow control of the slope of the osteotomy (Figure 5B). An osteotomy oriented closer to the sagittal plane will allow more anteriorization with displacement, while an osteotomy oriented closer to the coronal plane will allow more medialization with displacement. After the initial bony cut, the cutting jig is removed, and the initial cut is used to guide the saw to complete the distal cut and also a proximal cut 3 mm proximal to the patellar tendon insertion, ensuring that all fibers of the patellar tendon are attached to the osteotomy fragment. Osteotomes are then used to complete the osteotomy. Once the osteotomy fragment is freely mobile, the tibial tuberosity pedicle is translated anteriorly and medially. The degree of AMZ likely depends upon the patient in question, and we often repeatedly flex and extend the knee to allow congruence of the patellofemoral joint to guide the fragment into a physiologically optimal position. From this position, the osteotomy can be subtly manipulated, for instance, if the surgeon desires to offload a lateral patellar or trochlear chondral defect. Generally, there is 1 to 1.5 cm of AMZ needed to normalize the TT-TG distance to less than 15 mm. If the surgeon desires more anteriorization, Maquet⁵⁹ described interposition of a 2.5-cm section of an autologous iliac crest to further translate the tuberosity anteriorly, while Fulkerson³⁴ described a straight anteriorization without bone grafts.

Once in the desired position, the tuberosity is temporarily fixed in position using K-wires. Screw fixation is best achieved with lag by application techniques using noncannulated screws. Two to 3 partially threaded 3.5- to 4.5-mm cortical or cancellous lag screws can be used for interfragmentary fixation. Care is taken when drilling to avoid damaging the neurovascular structures present posterior to the tibia. Intraoperative fluoroscopy may be useful if any question develops regarding the screw positioning. A prominent medial edge of the transferred tibial tuberosity can be removed and used for autologous bone grafts placed in the proximal lateral aspect of the osteotomy. The wound is then copiously irrigated and closed in layers in a standard fashion. Previously, authors have recommended leaving the fascia of the anterior compartment open so as to reduce the risk of compartment syndrome postoperatively.³³ Others routinely pie crust the fascia with a No. 11 scalpel blade to achieve a similar effect.⁸³

Anteriorization

As previously mentioned, the classic anteriorization procedure is the Maquet procedure, which requires the iliac crest bone graft to allow for the proper degree of anteriorization. Alternatively, Fulkerson³⁴ described a straight anteriorization based on the AMZ technique. The limb is positioned with the leg neutral. A coronal plane (side) cut is made approximately 1 cm anterior to the posterior aspect of the tibia with a 90° saw. An osteotome or malleable retractor is introduced into this posterior cut to provide protection during the anterior to posterior second cut. The second cut is a vertical anterior to posterior cut, stopping

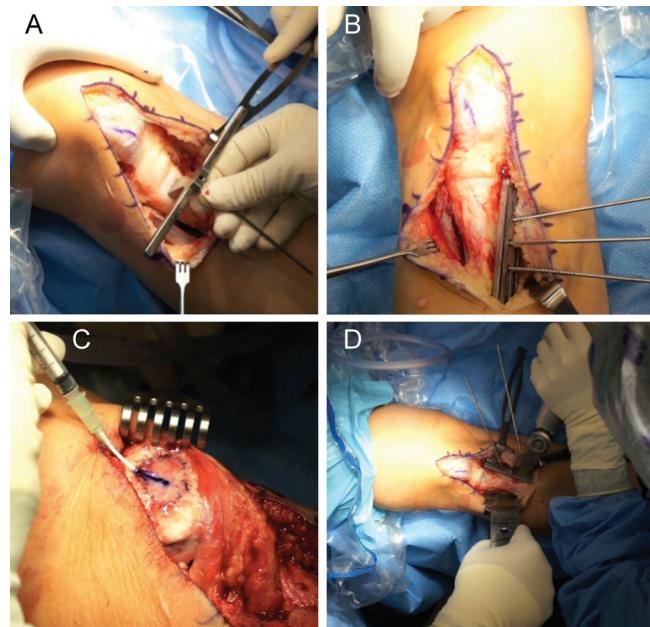


Figure 5. (A) Preparation to place the guide pin to help in placement of the cutting jig. (B) K-wires have the cutting jig fixed in place on the tibia. (C) Osteochondral patellar defect undergoing autologous chondrocyte implantation. (D) Tibial tuberosity undergoing medialization and anteriorization.

before the posterior tibial cortical bone (noting the protection inserted in step 1). The saw will now contact the osteotome rather than the cortex, thereby preventing penetration of the posterior cortex. The osteotomy is elevated and fixed as before with K-wires initially, followed by standard interfragmentary fixation. An alternative option is to make a standard AMZ cut at an extremely steep slope, followed by harvest of a local corticocancellous block. To ensure the medialization is neutralized, this block is cut at the thickness of the measured medialization component. The block is then inserted between the tuberosity and the tibial cut, resulting in direct anteriorization. The final product is again fixed with standard interfragmentary fixation lag screws.

Distalization

As with anteriorization and AMZ, the steps up to the bone cuts for distalization are identical. Once the exposure is adequate, 2 distal cuts are made with the saw before the bony tuberosity is cut. A more distal cut is made in which the tuberosity will be transferred with the distalization. The proximal cut is used to mark the amount of distalization that will occur, ideally normalizing the patellar height. Care must be taken not to overcorrect the height. The proximal cut can be made slightly oblique to allow for some medialization if this is desired. The oblique cut will allow the tuberosity and tibial cuts to fit flush once reduction with the lag screws occurs. Of note, obliquity factors in the rotation of the tuberosity. This can be altered as

the amount of rotation is evaluated intraoperatively. Finally, as before, a K-wire is inserted through the tuberosity's drill hole, which allows for rotation of the tuberosity. The osteotomy is fixed in place with standard interfragmentary fixation lag screws. Mayer et al⁶⁰ advocates tenodesis of the patellar tendon at the level of the original attachment, but no comparative studies are available to evaluate the advantages of tenodesis.

Postoperative Rehabilitation

To reduce swelling, patients are wrapped with compression dressing and treated with a cooling knee brace and elevation. In the early postoperative period, patients are generally made nonweightbearing with a hinged knee brace locked in full extension, and early quadriceps exercises are begun. Range of motion is increased based on patient tolerance. It is reasonable with good bone quality and acceptable body mass indices to allow patients partial weightbearing during transfers from sitting or lying positions to standing positions. Patients are kept touch-down weightbearing with crutches for the first 6 to 8 weeks to reduce the risk of tibial fractures.⁴ Once the surgeon has clinical and radiographic evidence of progression toward union, immobilization and weightbearing restrictions are discontinued, and the patient progresses to therapy. Return to sport is based on the patient, surgical procedure, and sport, with higher risk sports such as football involving a longer rehabilitation period.

SURGICAL OUTCOMES

The results of TTO have varied depending upon the amount of AMZ performed. While the originally described Hauser procedure with pure anteriorization led to recurrent dislocations in 17% to 20%¹³ and progression to osteoarthritis in 70%,⁴³ in modern anteromedialization procedures, good to excellent outcomes have been described in >80% of patients with short-term follow-up, with mild deterioration in >66% good to excellent outcomes with long-term follow-up.^{29,81} However, the complication rate of the Maquet procedure has been reported as high as 40%,⁵ including delayed wound healing and skin necrosis,⁶² tibial tuberosity and proximal tibial fractures, and nonunion at osteotomy sites.^{42,75} Numerous authors have identified patient selection and meticulous surgical technique as critical to achieving consistent success.^{15,16,23}

Excellent outcomes have been reported in AMZ performed for patellar instability. Buuck and Fulkerson⁹ showed 86% good or excellent results at 8.2 years postoperatively. Poor outcomes were observed in patients with Outerbridge grade III or IV lesions in the central or medial trochlea and in workers' compensation patients. Pritsch et al⁷⁴ reported on 55 patients who underwent TTO procedures for patellar instability or maltracking, describing 72.5% good or excellent results at 6.2 years' follow-up. Patients with preoperative pain and instability experienced inferior outcomes to those with isolated instability, and men did better than women. Palmer et al⁷⁰ evaluated 107 knees

at a mean follow-up of 5.6 years and found good or excellent results in 79% of patients. Seventy-eight percent of these patients presented with patella alta; thus, the majority of patients underwent AMZ with distalization.

The clinical results for AMZ performed for chondral lesions are dependent on the location of the lesion. Pidoriano et al⁷³ reported on 36 patients with chondral lesions in varying areas of the patella and trochlea and found that patients with distal or lateral patellar lesions had 87% good to excellent subjective results, and 100% would undergo the operation again. However, 55% of patients with a medial facet lesion, 20% with a proximal or diffuse lesion, and 0% with a central trochlear lesion had good or excellent results.

While no studies have randomized patients to realignment in isolation as compared with realignment with concomitant cartilage surgery, Farr²⁶ retrospectively compared his cohort of patients that underwent AMZ in conjunction with ACI to Pidoriano et al's⁷³ cohort, which underwent TTO alone for the treatment of patellofemoral chondral lesions. In his comparison, Farr²⁶ described 75% to 80% good to excellent results in patients treated with concomitant TTO and ACI for a type IV patellar lesion (proximal pole or panpatellar lesion), while Pidoriano et al⁷³ showed 0% to 20% good to excellent results for similar lesions. Several authors^{46,64} have noted similar trends.

Although the current Clinical Practice Guidelines of the American Academy of Orthopaedic Surgeons⁷⁸ are unable to recommend for or against TTO in the setting of patellofemoral arthritis, with thorough patient counseling regarding the uncertain outcome, it could be considered in the appropriate patient. Atkinson et al² reported on 40 patients (50 knees) with a mean age of 29 years who underwent TTO for the primary indication of symptomatic patellofemoral arthritis and demonstrated that 94% had improved pain scores and 77% had good or excellent results at a mean follow-up of 81 months. However, Silvello et al⁸⁶ reported only a 38% good result for patients who underwent TTO for isolated patellofemoral arthritis versus a 68% good result for those whose indication was chondromalacia.

COMPLICATIONS/PEARLS TO PREVENT COMPLICATIONS

A variety of complications have been described with TTO including delayed wound healing, infections, skin necrosis over the tuberosity (only seen with the Maquet procedure),^{58,62,86} tuberosity fractures, proximal tibial fractures, delayed union of the osteotomy, and the need for later hardware removal (Table 1).^{5,22,35,52,85} Excess anteriorization may increase the risk of incisional breakdown. Compartment syndrome has been reported, and surgeons must remain vigilant for this potentially catastrophic complication.^{16,92} Pulmonary emboli⁹² and deep venous thrombosis³⁵ have also been reported, although the role for chemoprophylaxis in these patients remains unclear. Arthrofibrosis, potentially requiring arthroscopic lysis of adhesions and/or manipulation under anesthesia,^{5,16,33} can also occur. Early motion²⁷ is imperative to prevent

TABLE 1
Pearls for Tibial Tuberosity Osteotomy^a

- Avoid excessive anteriorization to prevent incisional breakdown.
- Protect weightbearing for 6-8 weeks to prevent tuberosity fractures.
- Encourage early range of motion to prevent arthrofibrosis.
- Use a proper prophylaxis for deep venous thrombosis postoperatively.
- Pie crust the anterior compartment fascia during closure to avoid compartment syndrome.
- Consider MPFL reconstruction in cases with frank instability.
- Arthroscopically evaluate patellofemoral cartilage before the bony cut, as this can alter the degree of anteriorization/medialization.

^aMPFL, medial patellofemoral ligament.

this complication, and in selected situations, a continuous passive motion machine can be helpful.³⁵ Because the osteotomy site can serve as a stress riser, a period of restricted weightbearing is critical to avoid proximal tibial fractures.^{27,35} Nonunion at the osteotomy site is rare at 3.7% because of compressive interfragmentary fixation.^{28,60}

CONCLUSION

Tibial tuberosity osteotomy allows the surgeon to rebalance the forces acting upon the patella and to improve the patellofemoral contact area and contact pressure in patients with symptomatic patellofemoral suboptimal alignment. This procedure is particularly powerful when combined with cartilage reconstruction in the setting of a patellofemoral chondral lesion. With appropriate patient selection and meticulous surgical technique with customization of the osteotomy angle and translation depending upon the underlying lesion, excellent outcomes have been described with infrequent complications.

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