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REVIEW

# Tibial Tubercle Osteotomy: Indications, Outcomes, and Complications

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**Abstract**

**Purpose of Review** The tibial tubercle osteotomy (TTO) is a versatile surgical technique used to treat a range of patellofemoral disorders, including patellar instability, painful malalignment, focal chondral defects, and patellar maltracking that have failed conservative therapies. TTO is a personalized procedure that can be tailored to the pathoanatomy of the patient based on physical examination and imaging. The complication rate associated with TTO strongly depends on the indication for surgery, the severity of the patient's condition, and the surgical approach. Despite the literature on TTO, to our knowledge, no single source has addressed the indications, techniques, outcomes, and complications of this procedure. The purpose of this article is to serve as such a valuable resource.

**Recent Findings** Highlights from recent studies we would like to emphasize are two-fold. First, maintaining a distal cortical hinge yields lower complication rates than osteotomies involving complete tubercle detachment with classic or standard techniques. Second, based on current evidence, TTO consistently provides symptomatic relief, and most patients can return to work or sport at their pre-operative level within 3 and 6 months, respectively.

**Summary** TTO is a personalizable surgical technique that may be utilized for multiple patellofemoral disorders and is associated with good outcomes.

**Keywords** Tibial tubercle osteotomy · Knee · Patellofemoral · Instability

## Introduction

The tibial tubercle osteotomy (TTO) was first described as a medial and distal relocation of the tibial tubercle to treat patellar instability [1]. Its application has since expanded and has become a well-recognized surgical option for addressing a variety of patellofemoral conditions, including focal patellar and trochlear chondral defects, osteoarthritis, and refractory pain in the setting of patellofemoral malalignment, with or without instability [2, 3]. The goal of the TTO is to improve the biomechanics of the knee by correcting patellar tracking, improving the stability of the patella within the trochlea, and offloading the chondral undersurface of the patella, ultimately reducing pain and improving function [4]. Although numerous clinical studies have highlighted the success of TTO, it is not without complications [5–9]. As such, the addition of TTO should be made on an individual basis with careful consideration of a multitude of factors. The purpose of this article is to present up-to-date indications for TTO, highlight various techniques, outline surgical complications, and assess the reliability of surgery for patients to return to work or sport successfully. A brief summary of relevant pathoanatomy, biomechanics, and clinical assessment will also be reviewed.

## Pathoanatomy and Biomechanics

Patients presenting with symptomatic patellofemoral pathology often have abnormal osseous anatomy and/or soft tissue imbalances about the knee. Understanding normal anatomy and biomechanical relationships is foundational to

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identifying pathoanatomy and ultimately determining appropriate surgical treatment.

The patella is a sesamoid bone located anteriorly in the knee embedded in the quadriceps tendon. As the knee flexes and extends, the patella glides in the trochlear groove, increasing the biomechanical leverage of the quadriceps [10]. The medial patellofemoral ligament (MPFL) provides static stability and is the primary restraint to lateral instability in the first 30 degrees of flexion. The trochlear groove also provides additional static stability essential for deep knee flexion. Dynamic stability comes from surrounding musculature and relies on a balance of forces across the knee [11]. Any morphologic insufficiencies or disruptions to the static and dynamic stabilizers may lead to patellar instability.

Trochlear dysplasia involves morphologic variation to the trochlear groove that can alter tracking and is defined by a sulcus angle of more than 145 degrees (Fig. 1) [11, 12]. The Dejour classification has been described to characterize trochlear groove morphological abnormality [13]. In brief, this classification comprises Grades A-D, which are determined by the presence of double contour, crossing sign, and/or supratrochlear spurs on lateral radiographs. Overall, this classification system has been heavily scrutinized for poor reliability, reproducibility, and limited clinical utility in treatment decision-making [14]. Notably, a recent study has demonstrated improved reliability when radiographic assessment is combined with advanced imaging such as CT or MRI [14, 15].

Patella alta also contributes to disrupted patellofemoral kinematics that can affect the angle of flexion at which engagement with the trochlea commences. Effectively decreasing osseous restraint through a larger arc of motion places patients at higher risk for patellar instability [16–18]. Patella alta changes the contact area and increases the mechanical stress of the joint [16, 19]. The preferred method to assess patella alta for the senior authors (RMF, SLS) is the Caton-Deschamps index (CDI) (Fig. 2a and b) [20, 21]. Patella alta is characterized by CDI > 1.2 as measured on an X-ray, computed tomography (CT), or magnetic resonance imaging (MRI) [17, 22]. Alternative patellar height evaluation includes the Insall-Salvati method, Blackburne-Peel method, plateau-patella angle, and extension of Blumensaat's line using conventional radiographs (Fig. 3a-c). More recently, the patellotrochlear index using sagittal MRI was introduced to assess for true patellotrochlear engagement of the articular cartilage surfaces (Fig. 3D) [23].

Axial forces applied to the patella are important contributors to patellofemoral alignment. Supraphysiologic lateral forces can predispose to patellofemoral instability, lateral patellar overload, and pain [16]. The Q-angle is the angle created between two intersecting lines measured using the vector of pull by the quadriceps from the middle of the patella to the anterior superior iliac spine and another line from the tibial tubercle through the center of the patella (Fig. 4) [10]. Historically, this angle served as an indicator of the lateral force vector, with normal values reported between 14–16 degrees for men and 16–18 degrees for women [24]. An excessive Q-angle outside this range increases the lateral pull of the quadriceps femoris muscle on the patella and potentiates patellofemoral disorders [25]. Q-angle was previously heavily utilized to guide the necessity for TTO; however, a wide degree of interobserver and intraobserver reliability has made it more clinically obsolete.

Q-angle has been replaced by the more sensitive tibial-tuberosity-to-trochlear-groove (TT-TG) distance described by Dejour [20]. Using superimposed axial CT or MRI slices, two parallel lines are drawn, with one line through the deepest point of the trochlear groove and the other through the center of the most proximal portion of the tibial tuberosity [26]. The distance between these parallel lines is measured on another line tangent to the posterior condylar axis. (Fig. 5a and b) [27]. The TT-TG distance in patients without patellofemoral symptoms in full extension is between 10 and 20 mm [21]. A TT-TG distance exceeding 20 mm is considered pathological and is

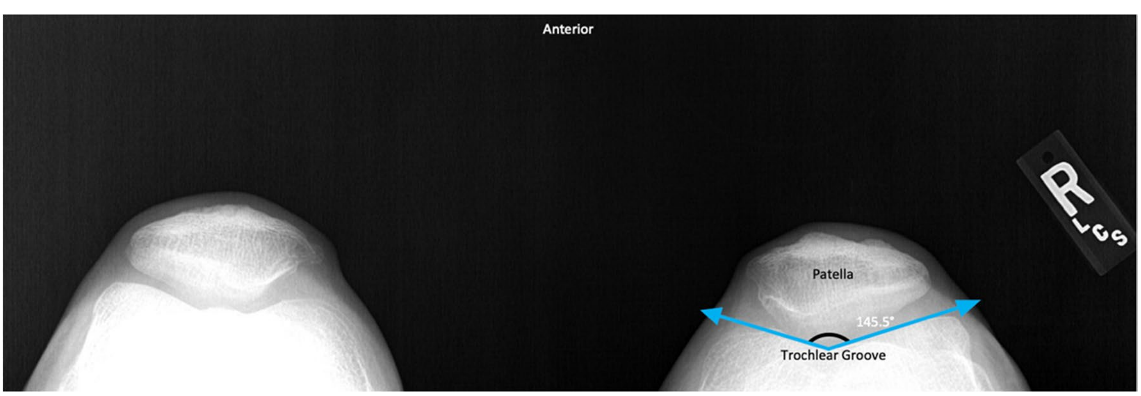


**Fig. 1** Sulcus Angle. Merchant view radiograph demonstrating an increased sulcus angle greater than 145° consistent with trochlear dysplasia of the right knee

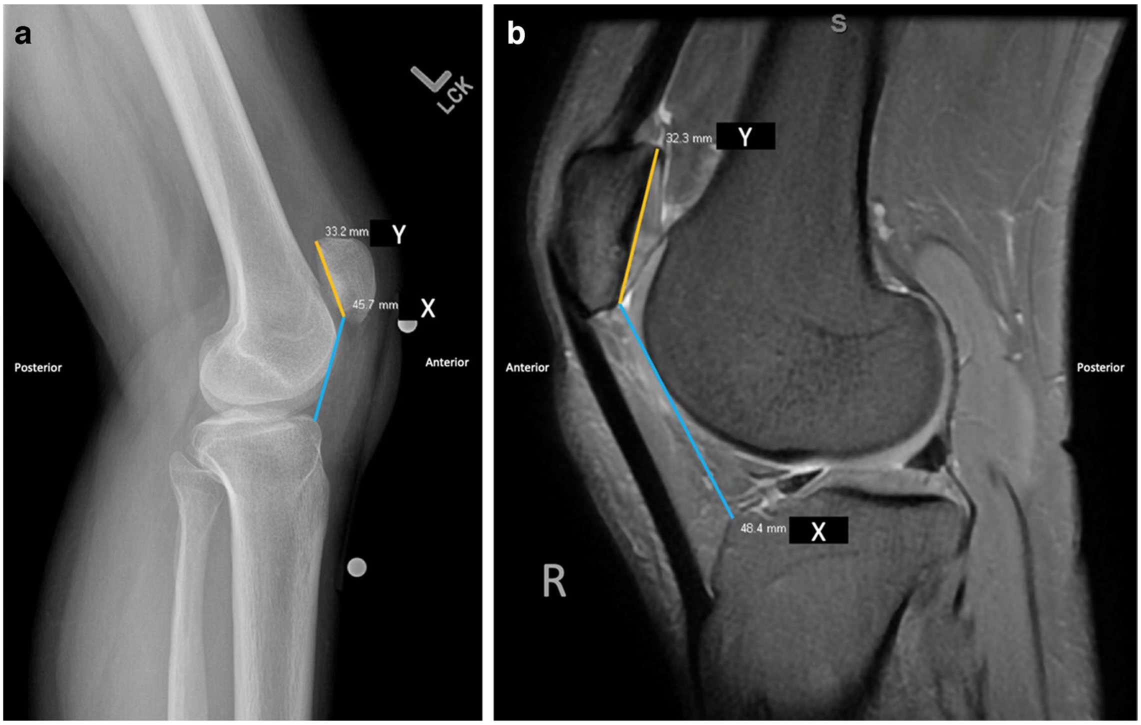


**Fig. 2** **a** Caton-Deschamps Index. Lateral radiograph of a left knee measuring the distance between the inferior patellar articular surface and the anterior angle of the tibial plateau (blue line) compared with the length of the patellar articular surface (yellow line). **b**: Caton-Deschamps Index. Sagittal T2-weighted MRI of a right knee demonstrating the Caton-Deschamps Index. A ratio (X:Y) greater than 1.2 indicates patella alta

associated with a greater risk of patellar instability, though the measurement of TT-TG is variable based on patient demographics, imaging modality, knee flexion angle, and weight-bearing status [21, 27, 28]. Additionally, TT-TG distance depends on the femoral reference point, and caution must be taken for patients with excessive femoral anteversion or tibial external rotation, as these deformities may misrepresent the TT-TG [16, 29].

Patellar tilt is also measured by superimposing two axial view images of the knee. It can be evaluated on Sunrise/Merchant or lateral radiographs, MRI, and CT [30]. The first image should be through the center of the patella and the second through the reference trochlear cut. Two lines are drawn, the first through the patellar axis and the second through the posterior condylar line. The tilt is the angle between those two lines (Fig. 6). The tilt is measured with and without quadriceps contraction. The tilt of the patella can lead to abnormal forces across the joint, whereas excessive overload can predispose to focal chondral degeneration [30, 31].

## Clinical Evaluation

A complete and thorough history and physical examination should be pursued, encompassing the onset, location, and duration of symptoms. Differentiating symptoms of instability versus pain is particularly important in guiding treatment. In patients who endorse patellofemoral instability, it is important to inquire about the mechanism of injury, frequency of instability events, and underlying medical history that may predispose ligamentous laxity. Reporting of mechanical symptoms or swelling may be suggestive of chondral injury.

Physical examination should involve a complete knee examination, as well as overall limb alignment, gait, and dynamic strength assessment. In the setting of patellar instability, assessment may demonstrate malalignment (e.g., knee valgus), hip and knee malrotation, increased passive patellar translation, patellar apprehension, and/or

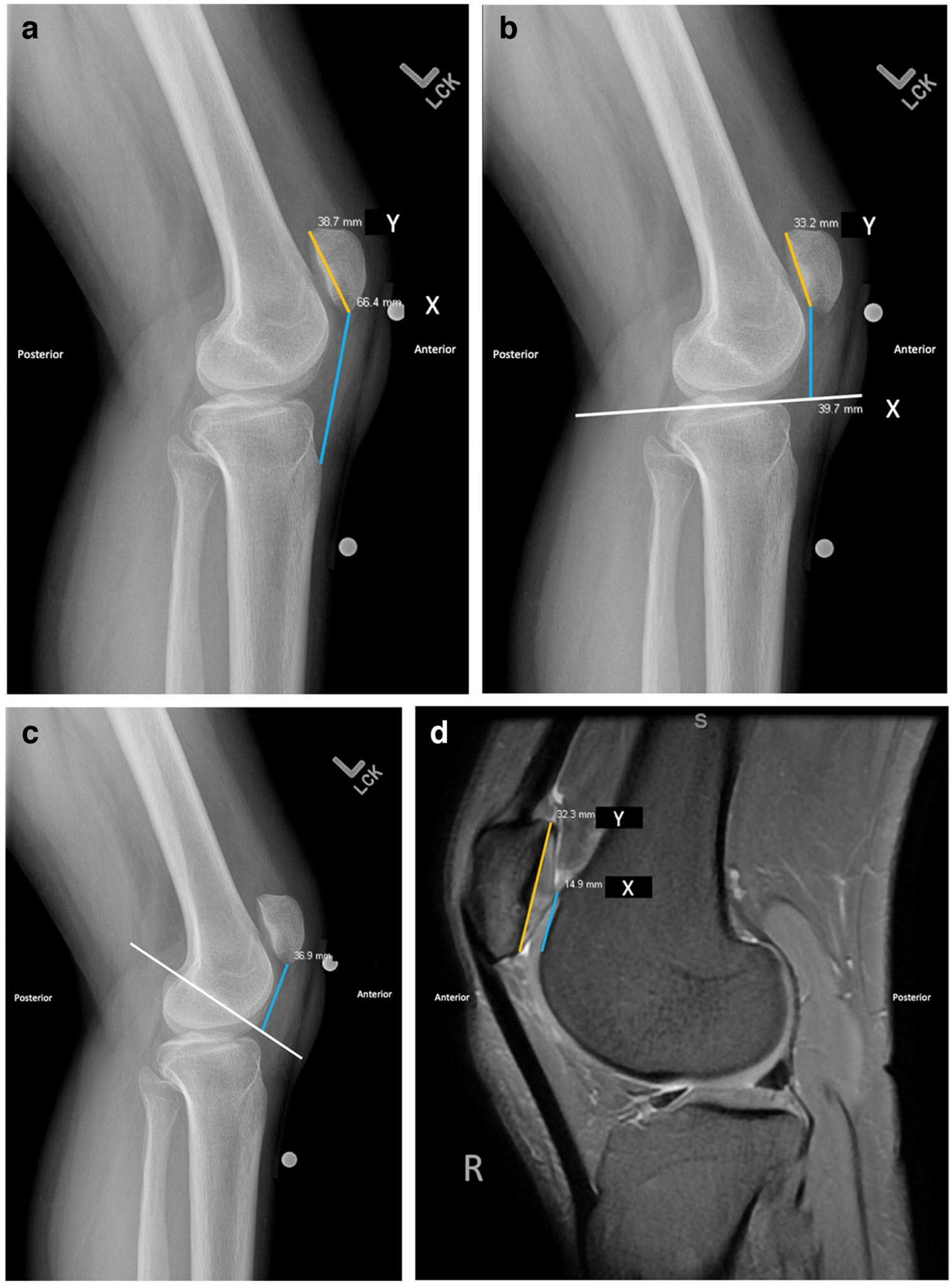


**Fig. 3** **a** Patellar Height Measurements. Lateral radiograph of a left knee demonstrating the Insall-Salvati Index (X:Y) by measuring the length of the patellar tendon (blue line) compared to the total patella length (yellow line). **b**: Patellar Height Measurements. Lateral radiograph of a left knee demonstrating the Blackburne-Peel Index (X:Y) by measuring the distance from the horizontal tibial plateau (white line) to the inferior patellar articular surface (blue line) compared to the length of the patellar articular surface (yellow line). **c**: Patellar Height Measurements. Lateral radiograph of a left knee demonstrating the Blumensaat Line by measuring the perpendicular distance from the intercondylar line of the femur (white line) to the inferior patella (blue line) **d**: Patellar Height Measurements. Sagittal T2-weighted MRI of a right knee demonstrating the patellotrochlear index by measuring the distance between the superior most trochlear cartilage to the inferior most patellar articular cartilage (blue line) compared to the length of the patellar articular surface (yellow line). A ratio (X:Y) less than 0.18 indicates patella alta

a J sign [17, 22]. It is important to assess for apprehension with knee flexion angle greater than 30° or the presence of a "jumping" J-sign, as these are poor prognostic indicators for soft tissue stabilization alone, and would warrant a bony procedure such as a TTO [32, 33]. In the instance of cartilage injury, the presence of a knee effusion, a positive compression test, and pain with deep knee flexion with or without crepitus are often present.

Standard radiographic imaging of the knee, including bilateral weightbearing anteroposterior, Rosenberg (posteroanterior view with 45 degrees flexion), low-flexion axial (e.g., Merchant), and lateral radiographs of the affected limb should be utilized to assess for any anatomic pathology contributing to patellar instability, including trochlea dysplasia and patellar malposition. Full-length lower extremity radiographs can be particularly useful in the setting of suspected coronal plane malalignment. Advanced imaging is also useful for preoperative planning. Magnetic resonance imaging (MRI) remains the gold standard for evaluating osteochondral surfaces, soft tissues (e.g., MPFL), and osseous contusions. Computed tomography (CT) is less commonly obtained but can be very helpful for pre-operative planning when rare significant torsional abnormalities are present [16].

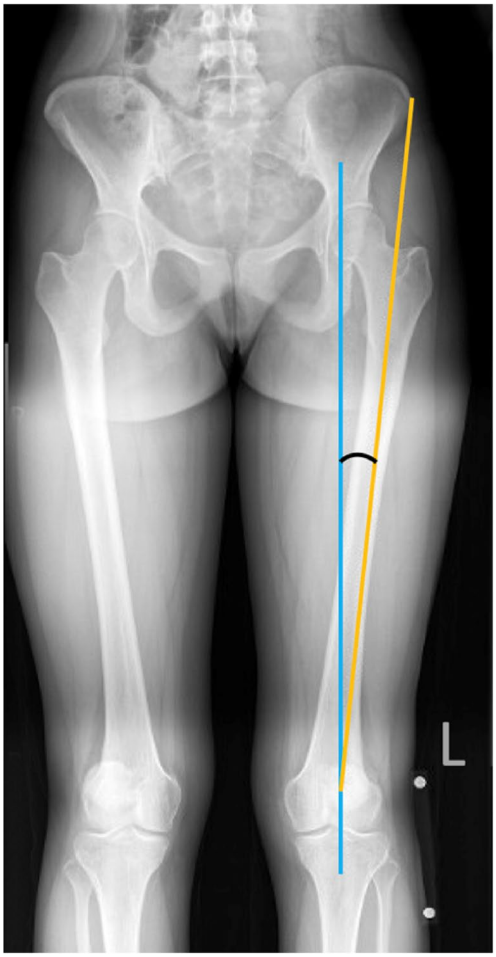


**Fig. 4** Q-Angle. AP radiograph measuring the angle between a line from the anterior superior iliac spine to the mid-patella and a vertical line connecting the center of the patella with the tibial tubercle. Normal values are between 14–16° for men and 16–18° for women

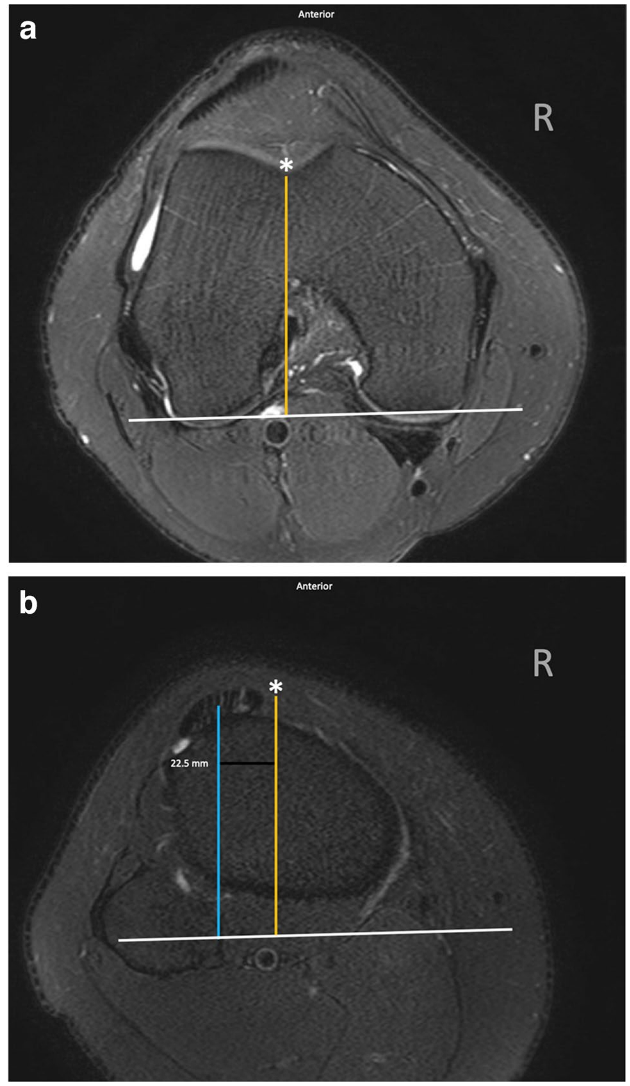


**Fig. 5** TT-TG. Axial T2-weighted MRI of a right knee demonstrating **(a)** the measurement between the deepest point of the trochlear groove (asterisk along the yellow line) along a line parallel to the posterior condylar axis (white line) superimposed with **(b)** the center of the tibial tuberosity (blue line). TT-TG values greater than 20 mm are considered abnormal

## Surgical Indications

Acute first-time patella dislocation has traditionally been treated with conservative measures, especially without evidence of a loose body or fracture [4, 34, 35]. These patients are managed with nonsteroidal anti-inflammatory drugs (NSAIDs) for pain and inflammation, activity modification, patellar stabilization utilizing a J-brace or sleeve, and physical therapy emphasizing quadriceps, gluteal, and core strengthening exercises [4, 11, 34, 36, 37]. Surgery is generally indicated for recurrent patella dislocation where anatomical abnormalities contribute to patellar instability or in those who have failed to respond to conservative therapy [4, 11, 34, 36, 37]. Early surgical intervention in the setting of first-time dislocation is typically only considered with unstable chondral injuries or in patients with a high chance of recurrent instability attributed to high-risk anatomy [16].

Well-defined and widely agreed upon surgical indications for tibial tubercle osteotomy remain to be seen. However, this procedure is typically pursued in combination with soft tissue balancing and/or cartilage restoration procedure in the setting of refractory patellofemoral pain/instability with underlying patellofemoral malignment and/or excessive patellar tilt [3, 16, 38]. The technique used for TTO is individualized, often multiplanar, and should be carefully chosen in reference to the clinical picture, position, and biomechanics of the tibial tuberosity, patella, and quadriceps tendon. In general, TTO can be considered in skeletally mature patients with excessive lateralized patellar force vector (TT-TG > 15–20) or

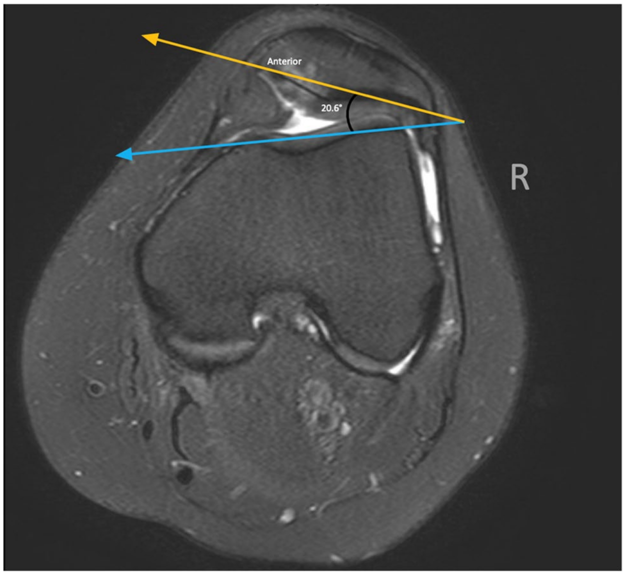


**Fig. 6** Patellar Tilt. Axial T2-weighted MRI of a right knee demonstrating lateral patellar tilt evaluated by measuring the angle between the anterior condylar line (blue line) and a line through the maximum width of the patella (yellow line). Patellar instability is often associated with a patellar tilt angle greater than 20 degrees

excessive patellar height (CDI > 1.2) in order to prevent recurrent patellar instability or to offload patellofemoral cartilage injury [3, 16]. TTO may also be considered with isolated lateral patellofemoral compartment overload that has failed conservative measures or prior arthroscopic intervention (i.e., lateral release) [39].

AMZ is useful in isolation to offload distal or lateral patellar chondral lesions or can be combined with cartilage restoration for medial, central, pan-patellar, and bipolar lesions [40]. In this setting, AMZ is effective in patients with an elevated TT-TG distance measurement (> 15 mm) to correct the lateralized force vector and unload the patellofemoral joint. The aim of TTO AMZ is to achieve a TT-TG distance closer to 10–12 mm or an intra-operative Tibial Tubercle -Sulcus Angle of 0° [40].

The risks of distalization are higher, and so should be the threshold for surgical intervention. With a complete detachment of the tibial tuberosity, damage to local vascularity and increased mechanical stress at the attachment site may lead to an increased risk of complications, including fracture, loss of fixation, delayed union, or nonunion [41, 42]. Most patients with low-grade patella alta can be managed without bony work and tend to do well from a clinical perspective. However, to evenly distribute forces concentrated on the distal aspect of the patellofemoral joint, distalization can be performed. One of the senior authors (SLS) recommends distalization for symptomatic patella alta with a CDI > 1.4 only with a post-surgical CDI correction goal of 1.1–1.2 [40].

## Techniques: A Historical Perspective

Roux carried out the first recorded operation for distal realignment, which involved a medial transfer of the lateral half of the patella tendon [20, 36, 43]. Using an osteotome to create a mid-line patella tendon split, the lateral half of the tendon was detached from the tibia while sparing a distal periosteal hinge and slid medially under the intact medial half of the patella tendon. Goldthwait described a similar distal patellar realignment procedure, and thus, medialization of the patellar tendon became known as the Roux-Goldthwait procedure [44–46].

Several modifications to the Roux-Goldthwait procedure have since been described. Elmslie and Trillat popularized the flat axial plane osteotomy of the tibial tubercle for medial transfer aimed to mitigate instability secondary to patellofemoral malalignment and increased lateralized force vector of the patella [36, 47]. Hauser proposed another modification, including a distal and medial patella shift to further increase constraint and reduce the risk of lateral instability [48]. Unfortunately, this procedure was shown to result in a high incidence of late osteoarthritis resulting from increased patellofemoral pressure and has become essentially obsolete [49–51].

For pain associated with patellofemoral arthritis, Maquet first described a straight anteriorization osteotomy, which requires an iliac crest bone graft to allow for the proper degree of anteriorization [52, 53]. Maquet recommended 2–2.5 cm of anterior tibial tubercle elevation to decrease the cartilage contact pressure. Despite early success, this procedure has largely fallen out of favor due to long-term follow-up studies demonstrating high rates of soft tissue and wound complications [54, 55].

Ultimately, Fulkerson popularized the idea of anteromedialization (AMZ) by using an oblique osteotomy to anteriorize (Maquet concept) and medialize (Elmslie-Trillat concept) the tibial tubercle in a multiplanar fashion [56]. In this approach, anteriorization and medialization for the planned correction are considered separately and calculated preoperatively [57]. The AMZ osteotomy is performed either free-hand or with a proprietary cutting jig and the degree of obliquity can be modified depending on the desired amount of AMZ. An oblique cut is extended from the medial origin of the patella tendon to the tibial tuberosity. The tuberosity is fully released using a reciprocating saw for the medial and lateral proximal cuts and osteotomes to release the patella tendon at the distal insertion. The mobile osteotomized tibial tuberosity is translated medially to the desired position using a ruler based on pre-operative calculations. The tuberosity fragment is then secured using screw fixation [16, 57]. This technique has been commonly used to address both instability and offloading pressure in osteoarthritis [58]. The advantage of the Fulkerson combined shift is that it addresses the increased patellofemoral forces with the anteriorization component and then addresses the mechanical alignment issues and efficiency of the patellofemoral mechanism with the medialization component [59]. Biomechanical models have shown that AMZ decreases chondral contact pressure on the lateral patellar facet, which may ultimately alleviate pain in patients with concurrent patellar instability [2, 20, 60]. Additionally, compared to isolated medialized TTO, AMZ TTO demonstrated significantly decreased medial compartment contact pressures in the setting of patellofemoral dysplasia [61]. This technique has the advantage that there is no requirement for bone grafting, and fewer complications arise due to the maintenance of a viable soft tissue envelope [52, 62].

Fulkerson also described an alternative straight anteriorization osteotomy based on the AMZ TTO. This approach does not require bone grafting, which potentially improves fixation and reduces the high complication rate associated with the classic Maquet anteriorization technique. Straight anteriorization osteotomy has been shown to decrease the mean trochlear contact pressures without a medial shift of the center of force [63]. While AMZ osteotomy has broader applications, straight anteriorization can be used in a subset of patients, particularly those with medial patellofemoral chondral defects [63].

Distalization is effective in cases of patella alta. In this procedure, the periosteum is cut 4 cm distally to the patellar tendon insertion, and a periosteal elevator is used to peel the periosteum distally. A V-cut is made, followed by a transverse cut in the proximal part of the tubercle. This tibial tubercle shingle is then moved distally and secured with self-tapping cortical bone screws [41]. Distalization effectively corrects patellar height, reducing the distal load on the patella and providing stabilization through earlier engagement of the patella in the trochlear groove [64]. This is typically performed in conjunction with AMZ to offload painful chondrosis.

Present techniques have evolved to include uniplanar (i.e., isolated anteriorization, distalization, proximalization) and multi-planar corrections as part of the wider armamentarium of TTO subtypes. Depending on patient selection and surgical objectives, multiplanar correction often includes medialization or AMZ combined with distalization [20, 60]. Merchant has developed a multi-directional TTO technique, offering surgeons the ability to precisely and reproducibly move the tibial tubercle in various directions while minimizing the risk of tibial stress fractures [65, 66]. In this technique, a compound wedge cut comprising the tibial tubercle and patellar tendon forms the primary wedge. For corrections involving medialization, a secondary wedge of bone is created just medial to the primary wedge. The primary and secondary bone wedges are then transposed, and the extent of the medialization is equivalent to the width of the secondary wedge. The primary wedge is secured using low-profile 3.5 mm cannulated screws. Anteromedialization TTO incorporates the aforementioned technique along with the placement of bone graft or bone void filler posterior to the primary wedge. Conversely, unidirectional TTO (anteriorization, distalization, or proximalization) involves repositioning the primary bone wedge, eliminating the need for a secondary bone wedge. This ensures a safe approach with minimal soft tissue dissection and reduced cortical violation. Additionally, this technique facilitates intra-operative modularity and offers a reproducible and teachable method to perform otherwise complex and multi-planar corrections. While evidence is mounting, there is still a paucity of mid-term and long-term follow-up to support routine use of the Merchant system. Additionally, bone voids require synthetic bone grafting in some cases, which adds cost and can be a major challenge in the setting of postoperative infection.

## Outcomes

Generally, TTO has been reported to have favorable outcomes in improving patellar stability, reducing patellofemoral pain, and restoring normal patellar tracking [5, 67]. The outcomes and success rates of TTO can vary depending on several factors, including the specific indication for surgery, the patient population, and the expertise of the surgeon. While it is essential to note the definition of success may vary across studies, the ability to return to work (RTW) or return to sport (RTS) is an important factor for patients undergoing elective procedures and contributes to patient satisfaction [1, 2, 68]. Therefore, physicians must advise their patients on their ability to RTW or RTS following surgery while considering the functional demands of the patient. The timing for RTW and RTS depends on individual healing and the nature of the job or sport [69–71].

Most patients RTW to their pre-operative capacity, although there is a significant difference in the time it takes for physically demanding jobs compared to sedentary professions. In a study evaluating an active military population who underwent TTO, 63% of patients successfully returned to military function. The remaining 37% were unable to return to modified military activity due to knee-related limitations [67]. Zarkadis et al. demonstrated that 78% of military service members were able to return to duty requiring moderate to very heavy occupational demand with significantly decreased patient-reported knee pain [72]. In a limited series of 36 civilian patients undergoing TTO, Buuck and Fulkerson reported that 19% of patients successfully resumed heavy labor, 25% moderate labor, and 50% sedentary occupations [73]. Notably, this study failed to report pre-operative occupational demand categories and included a comparatively heterogeneous patient population. Kingery et al. found over 95% of patients who underwent TTO had returned to work one year post-operatively with an average RTW of 3 months [1]. Patients with physically demanding jobs required slightly more time for recovery, with an average RTW of 4.99 ± 5.33 months [1]. In a retrospective study, Agarwal et al. reported 91.9% of patients were able to RTW by 2.8 ± 2.6 months following TTO [68]. Pestka et al. demonstrated a similar RTW (2.8 months) with a dose-dependent relationship between occupational intensity and time away from work [74].

The standardized TTO postoperative protocol instructs patients to maintain toe-touch weightbearing restrictions in a hinged knee brace locked in full extension for up to six weeks. It is essential to counsel patients regarding the minimum time needed to allow for healing and functional recovery. Advancements are dependent on individual progress, and this may vary depending on a variety of factors, such as occupation, age, and motivation. For example, the rehabilitative course has been shown to be more favorable in patients with sedentary or low-intensity occupations in their ability to RTW at a faster rate compared to those with physically demanding occupations [68]. Zarkadis et al. identified an appreciable connection between age and physical demand on the ability to RTW following TTO in a military population [72]. In this study, risk factors for failure to RTW were age less than 30 years and more physically demanding junior enlisted service positions compared to senior officer ranks. Additionally, socioeconomic status, disability coverage, workers' compensation, comorbidities, and health insurance coverage are among several other factors that impact motivation for a patient to RTW and should be considered pre-operatively [68].

Another important measure for a large population of patients indicated for TTO is the time to RTS [75–77]. This information is essential for surgeons and patients to establish realistic postoperative expectations. In a systematic review including 85 studies, Koshino et al. reported the most common RTS timeline in patients following TTO is six months postoperatively [69]. In a retrospective case series, Liu et al. found 83.3% of patients returned to at least one sport, and 62.5% of patients were able to resume more than one sport on average 7.8 months postoperatively. Of these, 77.5% believed they returned at the same or higher level. Despite TTO effectively returning athletes to competitive sports, significant strength deficits persist six months after surgery [78]. Physicians can use these results to counsel patients that returning to competitive sports is safe with good clinical outcomes. In a more recent study, Kingery et al. reported a mean time of 9.21 months to return to athletic activity [1]. Athletes should be advised that a slower recovery and extended recovery timeline may necessitate 9–12 months before safely returning to competition-level action.

## Complications

Tibial tubercle osteotomy is a complex surgical procedure with a significant risk of complication. The most common complications following TTO include infection, skin necrosis, delayed or nonunion, thromboembolic events, and tibial fracture [5–9]. Previous studies have suggested the rate of complication of TTO depends largely on the surgical approach and the direction of the tibial tubercle transfer [9]. Symptomatic hardware removal is the most frequently reported complication after TTO, with an estimated rate between 12.6% and 36.7%. The overall complication rate, excluding hardware removal and instability events, is estimated to be between 4.6% and 6.2% [9, 52, 79]. However, Johnson et al. found that smaller low-profile screws measuring 3.5-mm were less painful and less likely to need removal compared to larger screws [80]. Bio-integrative compression screws have the potential to reduce symptomatic hardware while improving the strength and stability of an osteotomy construct, though further clinical testing is needed.

It has been well documented that osteotomies involving complete detachment of the tubercle have an increased risk of complication compared with those in which a distal cortical hinge is preserved [9]. Kanamiya et al. suggested that periosteal insult after complete tibial tubercle detachment arrests the blood flow and increases the risk for nonunion [81]. Notably, Luhmann et al. found complications decreased from 5.9% to zero when intact periosteum was left at the distal portion of the osteotomy [82]. Avoiding distal "step cuts" and ensuring a proximal buttress with bone grafting can mitigate the risks of distalization.

Nonunion is a serious complication following tibial tubercle osteotomy [9]. Fortunately, rates of nonunion found within the literature are low and overall reassuring [83]. Choi et al. observed radiographic union in 46/51 TTOs (90.2%) [84], Le Moulec et al. in 59/63 (93.7%) [85], Mendes et al. in 64/67 (95.5%) [86], Young et al. in 41/42 (97.6%) [87], and Zonnenberg et al. found that union was achieved in 22/22 TTOs (100%) [88].

Despite high rates of union, it is essential to consider technique and relocation of the tibial tubercle to minimize the risk of nonunion. It has been hypothesized that distalization of the tibial tubercle may increase stress on the osteotomy site and ultimately contribute to nonunion [35, 73]. A thin bone shingle and small proximal buttress can compromise union rate and lead to fracture [73]. Improper technique resulting in periosteal stripping or thermal necrosis decreases bone perfusion and higher rates of nonunion [73]. Various methods of fixation of the tibial tubercle have been proposed. Regardless of the technique, adequate fixation must be ensured. In a study by Cosgarea et al., it was concluded that insufficient fixation of the TTO consequentially results in nonunion [89]. Hence, care should be taken to place screws perpendicular to the osteotomy site to ensure maximum contact and compression of the two surfaces. Payne and colleagues found that compression screw fixation limits the risk of nonunion at the osteotomy site to 3.7% [9]. Certain patient factors such as obesity, smoking, lack of compliance, and aggressive rehabilitation may also predispose to nonunion [9, 90].

Another recognized risk of tibial tubercle osteotomy is proximal tibia fracture. Similar to the risk of nonunion, the risk of fracture has been related to surgical technique, osteotomy size, osteotomy tools, and rehabilitation protocols [8, 91, 92]. The reported fracture rates of the proximal tibia range from 2.6–8% [20, 92]. Large cortical defects or the improper use of surgical instrumentation can increase the risk of fracture or propagate the osteotomy distally or posteriorly [73]. Rapid and aggressive physical therapy may also increase fracture risk. By allowing patients to weightbear as tolerated, Stetson and Fulkerson et al. reported a higher tibial fracture rate of 8–11% [91]. Alternatively, in a case series by Bellemans and Stetson, there were no reported fractures after 12 weeks post-operatively with the implementation of weightbearing restrictions [92]. This stresses the significance of protected weightbearing, early activity restriction, and progressive rehabilitation to mitigate the risk of tibial fracture [36].

Complications following TTO can be minimized with preoperative assessment and planning, careful attention to detail, technical execution, and postoperative rehabilitation compliance.

## Future Direction

Given the complexity of patient presentation, imaging findings, and indication for surgical intervention, TTO remains a highly personalized procedure with multiple high-risk complications and a long postoperative course. Based on patient-specific bony morphology and underlying pathology, TTO can be used in isolation or in conjunction with additional procedures, including cartilage restoration and soft tissue balancing, to address malalignment associated with patellofemoral overload, instability, and/or symptomatic chondral defects. Moving forward, advancements in surgical techniques and tools may lead to more minimally invasive approaches, which reduces the risk of infection and rate of complications. Novel techniques should continue to mitigate soft tissue dissection, optimize bone cut stability, and incorporate improved materials such as bone grafting and fixation devices. Artificial intelligence, machine learning, and improved imaging technology may also refine risk stratification for recurrence or enhance pre-operative planning that allows surgeons to tailor the procedure to each patient's unique anatomy. Furthermore, future research and the development of personalized medicine may focus on predicting patient outcomes and assessing potential risks more accurately. This may ultimately help surgeons better identify suitable candidates for elective TTO and manage patient expectations. It is important to remember that a myriad of approaches exist for various pathologies, and this must be considered to truly compare outcomes across the literature.

## Conclusion

Although TTO is a relatively frequently performed procedure amongst orthopedic surgeons, specific guidelines for surgical indication and postoperative management continue to develop. Methods for diagnosis and treatment will continue to vary based on individual patient presentation, pathology, comorbidities, and personal factors. Surgeons should continue to counsel their patients on the risks and benefits of TTO to guide the shared surgical decision-making process and establish realistic patient expectations.

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B.P.E. (Contribution: conceptualization, visualization, writing – original draft, writing – review & editing)

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S.L.S. (Contribution: conceptualization, resources, supervision, validation, visualization, writing – review & editing)

R.M.F. (Contribution: conceptualization, resources, supervision, validation, visualization, writing – review & editing)

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