Three-dimensional Analysis of Patellar Instability: A Review of Current Concepts

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Abstract: Patellar instability presents diagnostic and treatment challenges despite advances in imaging and surgical techniques. Given the link between patellar instability and trochlear dysplasia, the key to understanding instability may lie in subtle morphological variations in the trochlea. Traditional 2-dimensional methods of understanding instability can suffer from issues of geometric alignment. As a result, 3-dimensional analysis has an emerging role in understanding the pathogenesis of patellar instability. One 3-dimensional metric, the entry point-transition point angle, is used to quantify the degree of lateralization of dysplastic trochlear grooves. This angle is measured on 3-dimensional reproductions of computed tomography scans and can be used for surgical decision-making in instability patients. Further research should investigate how to best incorporate 3-dimensional metrics in surgical decision-making.

Key Words: three-dimensional, patellar instability, trochlear dysplasia

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Patellar instability involves abnormal movement of the patella out of its anatomic location in the trochlear groove. This condition often results from a combination of predisposing anatomic features and trauma that compromises the patella's stability. Patients with patellar instability may experience recurrent episodes of the patella subluxating or dislocating, causing pain, swelling, and disability.[1] In severe cases, dislocations can damage articular cartilage and contribute to chronic knee degeneration.[2] Unfortunately, we still do not fully understand the complex interplay of all predisposing factors.

Various clinicians have attempted to elucidate the effect of the femur's trochlear morphology in stabilizing and guiding its overlying counterpart, the patella. Since Dejour's pioneering work on examining trochlear dysplasia on lateral radiographs, many researchers have searched for the origins of patellar instability. Advances in imaging—particularly with 3-dimensional (3D) reconstruction and dynamic imaging—and its increased accessibility—have heralded an exciting new era of patellofemoral research.[3,4] However, the exact relationship between trochlear structure and patellar instability has yet to be fully understood, mainly because of long-standing imaging limitations in 2 dimensions. In this article, we will explore the role of 3D patellofemoral joint analysis in understanding why patients experience dislocation, how it fits into the context of a holistic diagnosis of the knee, and what it can teach us about how to restore normal joint function optimally.

ANATOMY

Soft-tissue

There are multiple anatomical risk factors for why one would experience a first-time patella dislocation, including deficiency of the medial patellofemoral complex (MPFC).[5–8] Patients with normal underlying bony morphology may experience an insult to the medial soft-tissue structures that stabilize and constrain lateral movement of the patella.[9,10] In acute patellar dislocations, the prevalence of medial patellofemoral ligament (MPFL) lesions is 94.7%.[11] Multiple cadaveric dissections have provided insights into the intricate relationship between the medial patella and the femur. The proximal fibers of the MPFC, which includes the medial patellofemoral ligament (MPFL), make up the medial quadriceps tendon femoral ligament (MQTFL), which originate from the anterior adductor tubercle and attach to the vastus medialis tendon, with some fibers running to the vastus intermedius and rectus femoris (Fig. 1).[5,6,12,13] In fact, the entire MPFC interdigitates with the quadriceps expansion over the patella (a sesamoid bone) and, in this sense, is all MQTFL.

The lateral retinaculum consists of 2 layers of fascia on the anterolateral knee: the superficial oblique and deep transverse layer.[14,15] The MPFC and lateral retinaculum act as passive stabilizers on either side of the patella; consequently, lateral subluxation can result from both weakness of the MPFC and excessive tension in the lateral retinaculum (Fig. 1).[16] In cases of clear lateral patellar tilt, a lateral release or lengthening is therefore indicated. Lateral release or lengthening is often, but not always, performed in conjunction with other patella stabilizing procedures, such as a tibial tubercle osteotomy or an MPFL/MQTFL reconstruction, and can help relieve pressure on the lateral facet of the patella's articular cartilage.[17]

Trochlear Dysplasia

Between full extension and 20 degrees of flexion, the MPFC provides a key stabilizing force. At this point, the patella is funneled into the proximal trochlea, and by 30 degrees flexion, the patella should be centered in the trochlear groove with support from the MPFL, MQTFL, medial patellomeniscal ligament, and medial patellotibial ligament.[7,18] When a patient has patella alta, increased flexion is necessary for the patella to be

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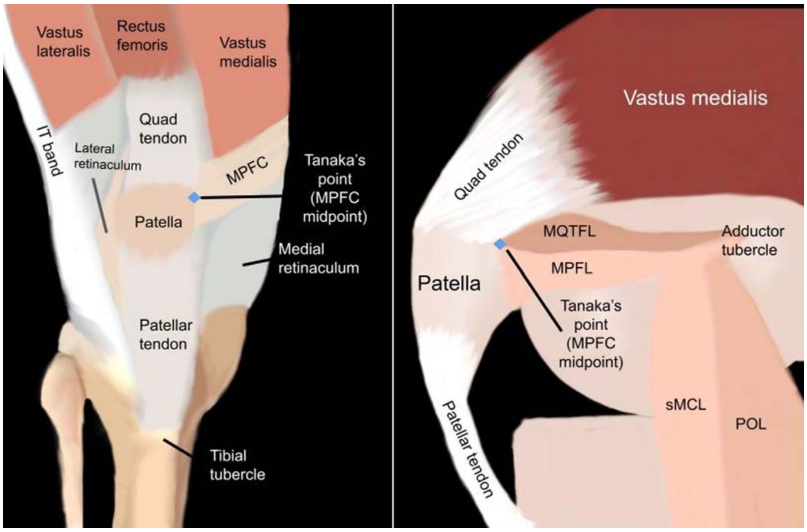

FIGURE 1. Knee anatomy and medial patellofemoral complex. IT indicates iliotibial; MPFC, medial patellofemoral complex; MPFL, medial patellofemoral ligament; MQTFL, medial quadriceps tendon femoral ligament; POL, posterior oblique ligament; sMCL, superficial medial collateral ligament. Images painted by Nancy Park on Picsart (Miami, FL).

safely supported by the trochlear groove, thereby increasing the risk of subluxation. In trochlear dysplasia, the trochlea loses bony stabilization due to flattening or convexity of the proximal trochlea, sometimes with a hypoplastic lateral femoral condyle (Fig. 2).[18] As a result, the proximal trochlea loses its "funneling" power, and the patella can become unstable. These morphological differences may manifest at stages of bone development during childhood, as dysplasia has been found in the medial femoral epiphyseal plates of patients with trochlear dysplasia.[19]

Excessive convexity of the lateral proximal trochlea, in particular, predisposes patients to redislocation after medial stabilization. Also, when a patella tracks laterally, redislocation and eventual lateral patellofemoral arthritis are more likely. The stability of a patella can be visualized as a ball at the top or bottom of a hill (Fig. 3). A normal trochlea provides a guide for where the patella should track, akin to a ball in the valley between 2 hills. In a dysplastic trochlea, this osseous reinforcement is weaker, and thus the patella is more likely to dislocate laterally. In laterally tracking patellae, the resting position of the ball would be on top of the hill, making it more prone to fall to either side.

DIAGNOSTICS

Dejour Classification

The Dejour classification qualitatively categorizes trochlea morphology by dividing trochlear dysplasia into 4 categories using 2D axial CT and lateral radiographs.[20–22] Others have used the sulcus angle to add a quantitative complement for describing the trochlear groove.[23,24] Nevertheless, both of these approaches still rely on 2D representations of 3D anatomical structures and thus can yield differing interpretations based on which CT slice is used.[25] The Dejour classification suffers from a low inter-rater reliability of 0.21, while the sulcus angle fares better at 0.68.[25] Several researchers have attempted to bridge the gap between 2D and 3D morphology for a more global understanding of the trochlea. For example, Levy et al[18] simplified the Dejour classification to shallow, flat, or convex proximal trochleae based on 3D prints, and Yang et al[26] formalized 3D evaluation into a simple classification similar to the Dejour classification but using 3D criteria.

Entry Point Transition Point

The growing adoption of 3D modeling has proven increasingly valuable in discerning variations in trochlear geometry among patients with patellar instability, surpassing previous attempts in 2D and offering novel insights in the realm of trochlear dysplasia.[27] For example, based on 3D prints, Yu and colleagues associated increasing degrees of trochlea dysplasia with trochlear groove obliquity, decreased lateral trochlear convexity, lateralized proximal trochlea patella entry point, and medial ridge deformity. They also introduced the entry point-transition point (EP-TP) angle as a novel metric to describe this aberrant

FIGURE 2. Spectrum of trochlear dysplasia. Anteroposterior views of 3D reproductions of right knee CTs of patients with increasing degrees of trochlear dysplasia from left to right. As trochlear dysplasia increases, trochlear entry points (as defined in Fig. 4) and trochlear grooves lateralize.

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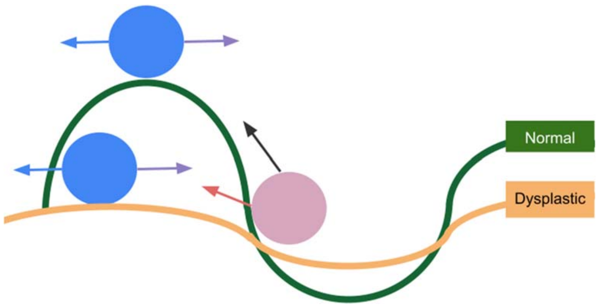

FIGURE 3. Schematic of ball on hill. In this representation, the pink ball represents a normally tracking patella. More force and energy (black arrow) are needed in a normally shaped trochlea (green) to bring the ball (blue) into a potentially unstable state than in a dysplastic one (orange, red arrow). In the unstable state, the ball/patella can go either way [ie, subluxating (blue) or restoring to normal tracking (violet)]. These states correlate with the axial depictions of femurs shown to the right.

morphology, particularly by accounting for lateral curvature and obliquity of the dysplastic trochlear groove (Fig. 4).[28,29]

Bony Alignment

EP-TP angle is just one addition to the considerable repertoire of anatomical measurements that surgeons have introduced to help predict patellar instability.[28] These metrics can assist surgeons in making well-informed decisions regarding the timing and approach for surgical interventions. For example, the Caton-Deschamps index (CDI) and Insall-Savati ratio provide a means to characterize a patella as positioned either abnormally high or low. In a normal patellofemoral joint, the patella rests within an area of the trochlea that functions as a funnel, guiding the patella through flexion and extension. In patella alta, the patella's resting position is moved out of this funnel and is thus more vulnerable to instability. Accordingly, such patients might be appropriate candidates for a tibial tubercle osteotomy with distalization to get the patella deeper into the funnel.[30,31]

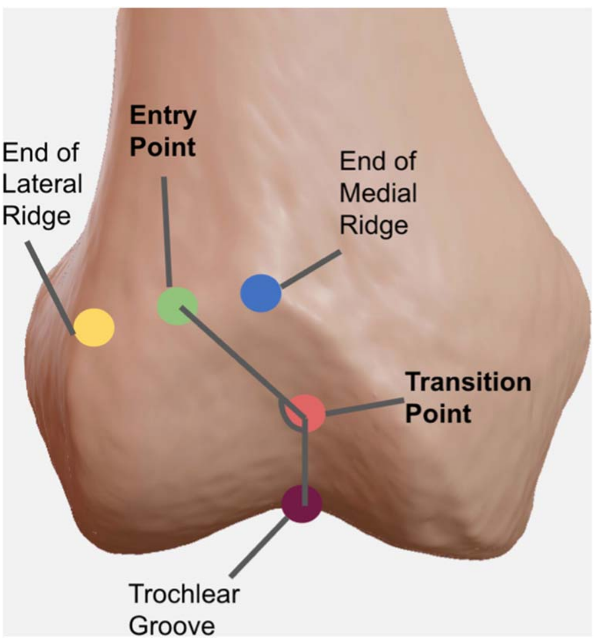

FIGURE 4. EPTP measurement. A, Anteroposterior view of 3D reconstruction of a distal femur. The entry point is the midpoint between the ends of the lateral and medial ridges. The transition point is the point along the trochlear groove at which the groove shape changes from an oblique orientation proximally to one more vertical distally. EPTP is defined as the supplementary angle (180 angle) between a line from the apex of the trochlea groove to the transition point and a line from the transition point to the entry point.[28]

Other measurements help establish the lateral forces acting against the constraints provided by the trochlear groove and the MPFC on the patella during movement (Fig. 4). The quadriceps angle, or Q-angle, elucidates the direction of quadriceps force acting on the patella.[32] On the distal side, the tibial tubercle to trochlear groove (TT-TG) distance helps quantify increased lateral force exerted on the patella. Traditionally, TT-TG distance has played a pivotal role in assessing the appropriateness of correcting an anomalous lateralized patellar force through a tibial tubercle osteotomy (TTO) with transfer of the tubercle and patella medially, distally, anteriorly or a combination of these.[33,34] TT-TG is advantageous due to its relative ease of measurement, resulting in higher inter-rater reliability than the Dejour classification. Nonetheless, TT-TG measurement is susceptible to notable inaccuracies attributable to factors such as leg positioning within the CT scanner gantry, knee flexion, variable rotation across the tibia and femur, and selection of the axial slice used to define the trochlear groove.[35–37] Measuring TT-TG by choosing landmarks on 3D models can help reduce variations in measurements, but current 3D methods still do not correct for differences in leg positioning or flexion. Consequently, no decision on operating upon a patient should be made upon a single metric. Instead, a holistic approach, based on all available anatomic factors should be undertaken, preferably using 3D reproductions.

Dynamic Imaging

Insights made in 3D are still incomplete without considering motion. Precisely measuring joint kinematics in vivo is crucial in understanding the trajectory of aberrant patella tracking and the relationship between articular form and function. Traditional motion capture techniques using skin surface markers provide limited data due to the disconnect between the motions of knee skin and that of the underlying patellar bone.[38–40] In recent years, dynamic imaging techniques, such as dynamic computed tomography or biplanar videoradiography, have emerged as exciting new tools in enhancing our 4D understanding of patellar tracking but are not yet widespread in standard clinical practice.

These modalities offer real-time visualization of the true kinematic trajectory of the patellofemoral joint, providing crucial insights into the dynamic factors contributing to patellar instability that static imaging alone cannot capture, but each carries with it certain advantages and disadvantages.[41] Dynamic CT, for instance, directly yields 3D animations of the patella's movement within the trochlear groove during knee flexion and extension, revealing any abnormal tracking patterns or malalignment. However, this method is limited by low frame rates, yielding snapshots every half-second, precluding its use for imaging of functional tasks such as jumping or turning.[42] By contrast, biplanar videoradiography permits observation of patellofemoral tracking without a high radiation dosage or low temporal resolution, enabling observations of joint kinematics during a wider variety of behaviors.[40] This method, however, requires the manual or software-assisted alignment of CT-derived bone models to x-ray videos to generate 3D animations, and this process remains labor-intensive despite technological advances.[43]

TREATMENT

Medial Patellofemoral Complex Reconstruction

Historically, isolated lateral release was used to treat patellar instability, but has been shown to be inferior to medial patellofemoral complex reconstruction in long-term studies.[44,45] Various surgical approaches have been proposed to address patellar instability by restoring the integrity of the MPFC.[46] Specifically, MPFL reconstruction has gained widespread acceptance.[47–49] However, its patellar fixation carries the risk of iatrogenic fracture.[50–52] Another method, a quadriceps tendon turndown, avoids the need for patella bone tunnels, but the patella origin of the MPFC is more distal, posterior, and medial compared to the reflected patella origin of a quadriceps autograft.[53] Another alternative method, MQTFL reconstruction circumvents the MPFL reconstruction's risk of patellar fractures by routing the graft beneath the vastus medialis obliquus and securing it to the midpoint of the MPFC, or Tanaka point.[5,12]

In practice, precise placement of this graft is crucial to both sufficient stabilization and avoiding medial subluxation. Excessive graft tensioning and incorrect positioning of the femoral tunnel pose the risk of overcorrecting lateral patellar tracking, which may result in the occurrence of medial subluxation.[54] In the experience of the senior author, we have attributed the absence of this complication in our MQTFL patients to meticulous adjustment of graft tension, a process guided by the natural anatomical reference points of the MQTFL. In vivo studies using 3D reconstructions of CT scans have shown that there are 2 acceptable femoral anchor points: the midpoint between the medial epicondyle and adductor tubercle or 10 mm inferior to the adductor tubercle apex; both of these points show the least change in graft length throughout flexion and extension. We aim for the sulcus between the medial epicondyle and adductor tubercle, as it has a narrower margin of error.[55] In our experience, 3D reconstructions from CT are useful in preoperative planning, especially in regard to planning accurate dissection of this landmark.

Tibial Tubercle Osteotomy

In cases where a soft-tissue graft alone will not relieve patellar instability, a bony realignment should be considered.[56] Planning patella stabilization surgery requires the greatest possible understanding of patellar height and laterality, trochlear curvature, flatness, and convexity. Multiple other factors pertain, including connective tissue laxity, tibiofemoral rotation, varus and valgus, neuromuscular status, and core stability.[18,57]

Currently, the senior author's approach for deciding when a tibial tubercle transfer is needed is based on the premise that trochlear shape and the resulting patellofemoral tracking path are determined largely—but not exclusively—by function during development; Wolff law

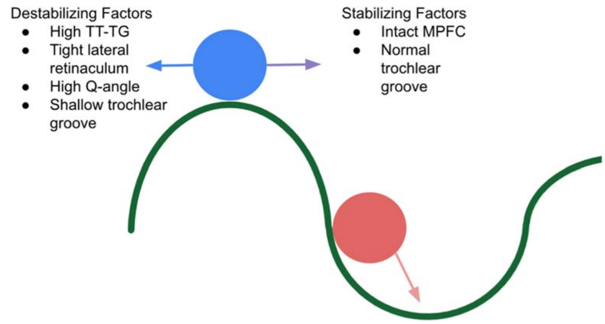

FIGURE 5. Stabilizing and destabilizing factors in patellar instability. An unstable patella may be destabilized (blue arrow) or stabilized (purple arrow).

states that form follows function.[18,19,58] Nonetheless, one must also consider underlying genetic predisposition. Liu et al[56] demonstrated that medial patellofemoral ligament reconstruction alone works well for patella stabilization in dislocators regardless of trochlear dysplasia in patients for whom a tibial tubercle was not deemed necessary for alignment. This study showed that trochlear deepening trochleoplasty is not necessary for flatness or dysplasia of the trochlea alone. So, when should a tibial tubercle transfer be added instead of deciding that soft-tissue modification is enough?

Knee 3D reproductions provide an opportunity to study patella height, patella laterality, trochlear curvature, and trochlear contours in exquisite detail. Determining patellar height, how far a patella must go to engage the trochlea (entry point-trochlear groove relationship), the obliquity/curvature the patella must travel to engage the trochlea (EP-TP angle), distal vector determinants (relationship of tibial tubercle to the trochlea groove), and the contours of the proximal trochlea (Dejour classification with added 3D knowledge of trochlea contours) are all important in determining when to do more than a medial reconstruction (Fig. 5).[20,28–30] When comparing 3D models reconstructed from scans taken at both 0 and 20 degrees of flexion, one can examine whether the patella starts to medialize as it heads further down the trochlear groove or if it continues to follow the lateral trochlear ridge.

Factors to consider:

- Patient clinical history
- J-sign on clinical exam
- Entry point-transition point angle
- Tibial tuberosity-trochlear groove distance
- Caton-Deschamps index (CDI)
- 3D proximal trochlea ridges and Dejour classification

Then, all factors should be synthesized to make the best possible decision about when to move the tibial tubercle. Furthermore, 3D imaging improves understanding of the proximal medial ridge "spur," and whether some recession of the spur or anteriorization of the tibial tubercle to lift the patella distal pole over it might be indicated at the time of TTO, distally and/or medially.[59] Whenever possible, a tibial tubercle transfer is preferred over femoral derotation. Particularly in excessive femoral rotation, femoral derotational osteotomy is an alternative, as excessive anteversion plays a role in lateral patella tracking as well (Fig. 6).[60]

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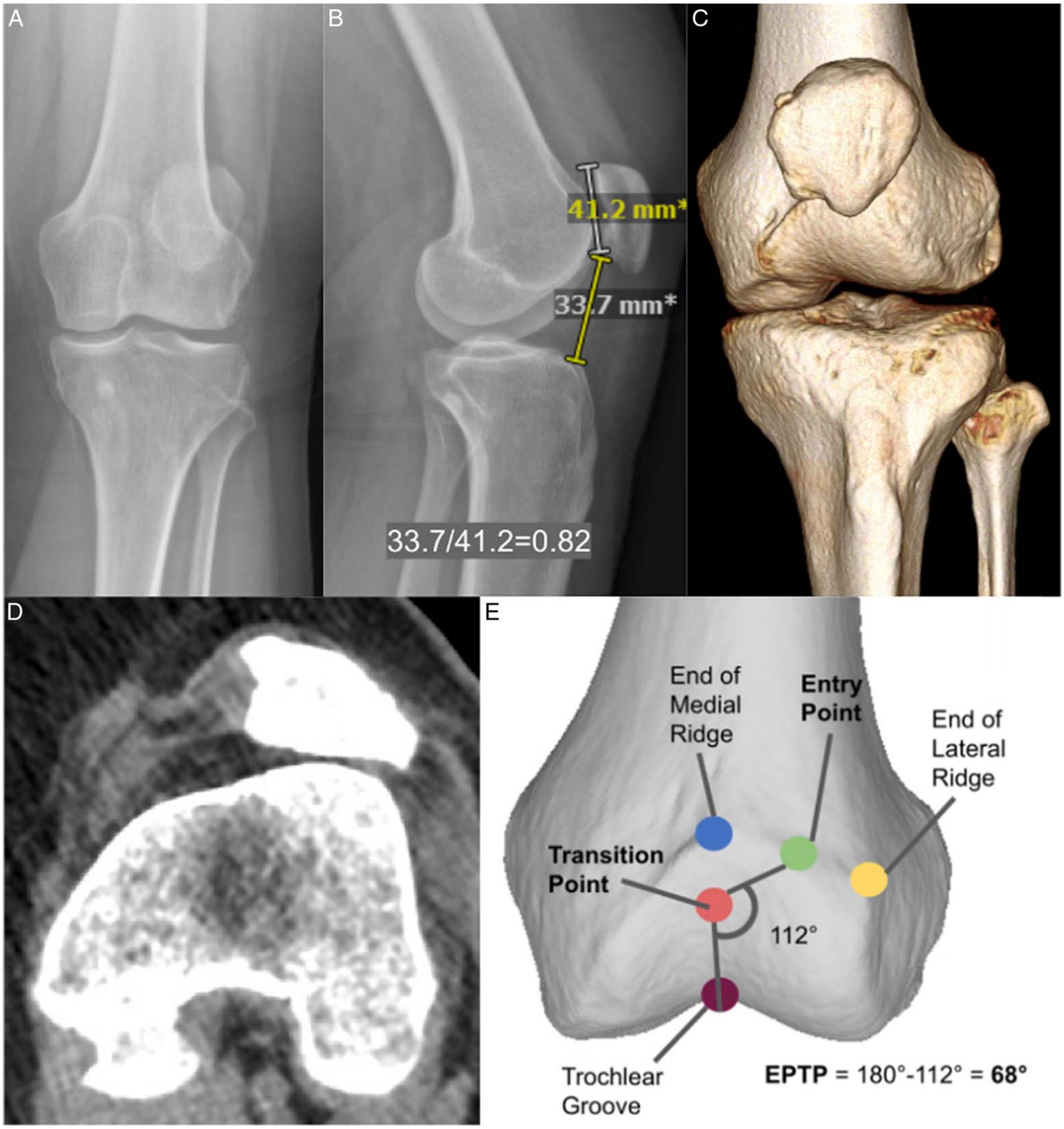

FIGURE 6. Patient imaging. A, Anteroposterior x-ray view of the knee showing lateral patella. B, Lateral x-ray showing Caton-Deschamps calculation. C, Three-dimensional reproduction CT showing the location of the patella. D, Axial CT cut showing Dejour B. E, EPTP measurement performed on the 3D model.

CONCLUSIONS

In conclusion, 3D analysis plays a pivotal role in understanding and addressing patellar instability. An understanding of the patellofemoral joint's 3D morphology can provide valuable insights into the complex relationship between articular anatomy, function, and appropriate surgical treatment, offering a more holistic perspective on this challenging condition. It is important to note that there are currently no published studies of how EPTP relates to clinical outcomes or thresholds for how EPTP relates to surgical decision-making. Further research and clinical application of 3D analysis techniques will be essential to further advance our knowledge of patellar instability and improve our understanding of surgical indications.

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