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Trochleoplasty: Groove-Deepening and Entrance Grooveplasty

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Trochleoplasty is a safe and effective surgical technique for addressing certain types of trochlear dysplasia in the setting of patellar instability. This article discusses groove-deepening trochleoplasty and entrance grooveplasty, including indications, associated procedures, outcomes, and complications.
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The stability of the patellofemoral (PF) joint is the result of a combination of osseous morphology and dynamic and static soft tissue stabilizers. The etiology of patellar instability is multifactorial and may include patella alta, coronal malalignment, torsional abnormalities, a laterally positioned tibial tubercle (TT), and incompetent medial soft tissue constraints.[1-3] Trochlear dysplasia, however, is increasingly recognized as the key anatomic risk factor for persistent patellar instability.

Trochleoplasty is a surgical procedure to reshape a severely dysplastic trochlea by deepening the trochlear groove (TG) and removing the supratrochlear spur, or prominence, thus improving patellar stability and providing a more uniform PF pressure distribution. It is indicated in select patients with trochlear dysplasia who have persistent patellar instability refractory to conservative treatment. The 2 primary types of sulcus- or groove-deepening trochleoplasty are the "thick-shell" technique described by Dejour[4,5] and the "thin-flap" technique popularized by Bereiter, Gautier, and Schöttle.[6,7] An alternative approach to reshaping of the articular cartilage of the groove was described in 1988 by Peterson et al, which he termed a proximal (entrance) trochleoplasty or grooveplasty.[8,9] The goals of this article are to discuss the preoperative planning and indications for sulcus-deepening trochleoplasty, present our technique for sulcus-deepening trochleoplasty, and briefly review the published results in the literature. A brief description of current indications and technical aspects of the grooveplasty will also be addressed.

Groove-Deepening Trochleoplasty Techniques

Masse et al initially described a sulcus- or groove-deepening trochleoplasty technique in 1978 which involved removing subchondral bone beneath the trochlea and molding the articular cartilage with direct impaction using a mallet.[10] Rouanet et al presented 15-year results for this technique in 34 patients and showed a 20% failure rate, including 7 patients that subsequently underwent arthroplasty procedure during the study period due to advanced PF arthritis.[11] Despite the high rate of PF arthrosis, which may be attributed to the trauma of forceful deepening of the groove with a mallet, the authors reported no recurrent instability episodes in their 34 patients.

The technique described by Masse was significantly modified and standardized by Henri Dejour in 1987.[4,5] Dejour emphasized protection of the trochlear cartilage while removing the supratrochlear bump and creating a more normal sulcus angle. His technique utilized a burr to undermine the cancellous bone behind the elevated convexity of the groove.

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He then osteotomized the trochlea in the midline, creating 2 independent osteochondral shingles. These shingles were then secured to the adjacent bone. Modification and variations of Dejour's sulcus-deepening trochleoplasty, including the technique is presented in this article, have been termed the "thick-shell" technique.

Bereiter and Gautier described another sulcus-deepening trochleoplasty technique, the "thin-flap" technique, in 1994.[6] This has been further popularized and refined by Schöttle.[7,12] An osteochondral flap composed of trochlear cartilage and a 2-3 mm thin osseous layer is elevated en bloc utilizing curved osteotomes. The underlying cancellous bone is then burred and deepened until the supratrochlear spur is removed, and the TG is flush with the anterior femoral cortex. This "thin-flap" is thinner and more flexible than the "thick-shell" and is depressed without the need of osteotomy. One initial concern regarding this technique was chondrocyte viability. However, Schöttle et al confirmed chondrocyte viability and normal cartilage architecture in biopsy specimens between 6 and 9 months following this technique.[12]

Proximal Entrance Grooveplasty Technique

Proximal (entrance) grooveplasty is a type of "bumpectomy" which removes the proximal convexity by excising the bump and reshaping the subchondral bone to form a sulcus, and then resurfacing the exposed bone with surrounding fat and synovial tissue. This flattens the groove but also shortens it. The removal of the convexity addresses lateral and anterior vectors that occur as the patella crosses over the convex spur in early knee flexion. If these vectors can be addressed in part by the resection, the remaining instability resulting from a merely flat trochlea can be addressed by standard stabilizing procedures such as medial patellofemoral ligament (MPFL) ± tibial tubercle osteotomy (TTO).

Advantages of the proximal trochleoplasty or grooveplasty technique are less technically demanding than conventional groove-deepening trochleoplasty; do not rely on bone healing; and preserve the shape and articular surface of the remaining trochlea thus retaining the individual's patella-trochlear congruity. With the "bump" resection, the proximal trochlea is modified to provide a flatter entry and transition to the more normal distal region. Disadvantages of the procedure are that the shape of the trochlea cannot be changed (groove cannot be deepened), cartilage is resected to remove the convexity with unknown consequences, and the groove is shortened.

Preoperative Planning

A thorough physical exam including inspection, palpation, range of motion, and provocative tests will further the understanding of the patient's instability. Patients will have a positive apprehension sign that remains positive with increased lateral translation as the knee is passively flexed, termed a moving apprehension test. The presence of apprehension past 45° is a soft indication that the bony walls of the sulcus are insufficient to restrain the patella against lateral translation. It is also important to assess for generalized ligamentous laxity. Nomura et al found that those with generalized laxity, which may be measured by Beighton criteria, are predisposed to recurrent dislocations regardless of trochlear morphology when compared to age- and sex-matched cohorts.[13]

The "J sign," indicative of pathologic patellar tracking, is also a critical finding on physical examination.[14,15] When the knee actively extends from a flexed knee position, the patella demonstrates a sudden lateral translation after it exits the TG when approaching full extension. The finding may due to trochlea dysplasia, patella alta, or a combination of both. In patients with Dejour B or D dysplasia, the J sign is seen when the patella "jumps" or "falls" off the supratrochlear spur. An especially large supratrochlear spur often leads to a more "dramatic" J sign. The presence of the spur is key, as a primary objective of trochleoplasty is removing the spur and bringing the height of the trochlea to a level "flush" with the anterior femoral cortex.

Plain radiographs are the initial study and are useful for classifying trochlear dysplasia, which can manifest as a flattened or shallow groove with a high sulcus angle. A "normal" sulcus angle is generally considered <145°, though this angle can vary based on imaging modality, degree of flexion, and location at which the measurement is obtained.[16,17] It must be emphasized that axial views with 45° of knee flexion, including sunrise or merchant views, may "miss" the more proximally placed dysplasia of the trochlea (Fig. 1). Furthermore, these axial views are highly technique dependent and potentially inconsistent across clinical sites.[18] A Laurin radiograph with the knee flexed 20° and the imaging beam directed from inferior to superior may be better for evaluating trochlear anatomy. The best assessment of trochlear morphology, however, is made with a combination of the 2-dimensional true lateral radiograph combined with three-dimensional imaging using computed tomography (CT) or magnetic resonance imaging (MRI).

Critical radiographic findings associated with trochlear dysplasia include the "crossing sign" and "trochlear bump," or supratrochlear "spur" (Fig. 2).[1] The line that represents the deepest part of the TG never crosses the anterior border of the 2 condyles on a lateral radiograph in a normal knee. The "crossing sign" occurs when this line joins the anterior part of the condyles. From this point extended proximally, the trochlea is essentially flat. A "spur" is present if this line continues anterior to the femoral shaft. This anterior spur can have important effects on maltracking and dislocation of the patella. This spur can act as a "ski ramp" and produce a lateral force, leading to patellar subluxation or dislocation in early knee flexion. This effect is magnified in individuals with patella alta and genu valgum. A "double contour sign" may represent a smaller, hypoplastic medial femoral condyle relative to the lateral femoral condyle.

Henri Dejour initially described a classification system for trochlea dysplasia following analysis of 1305 lateral radiographs of the knee.[5] This system was further refined by his son, David Dejour (Fig. 3).[4,19] This classification scheme

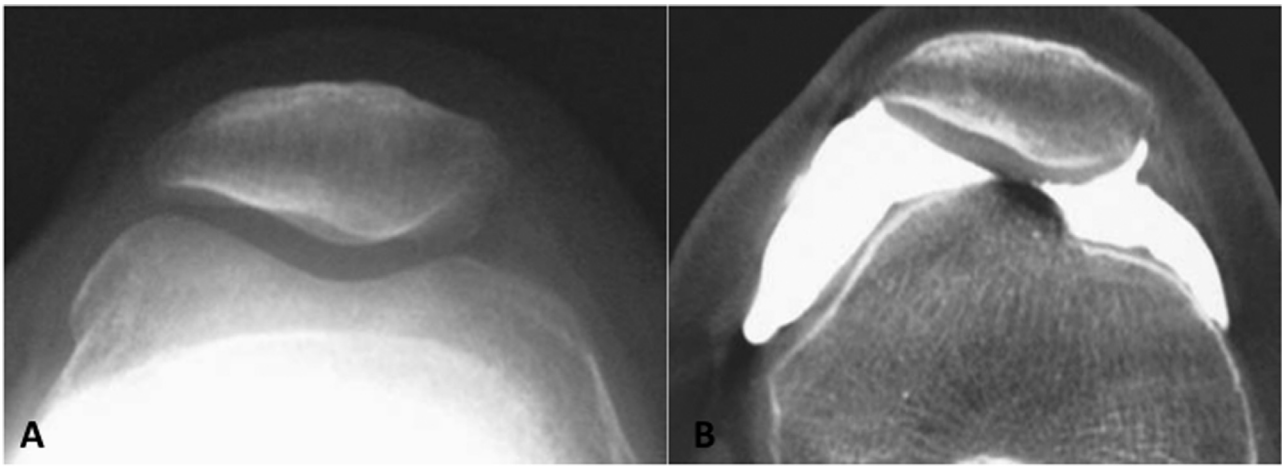

Figure 1 Imaging of the same patient. (A) Sunrise or merchant view at 45° fails to demonstrate the spur and underestimates severity of dysplasia. (B) Axial cut in extension from CT demonstrating severe dysplasia and large spur.

includes 4 types: type A – shallow or basically flat trochlea with presence of crossing sign; type B – flat but prominent trochlea with crossing sign and supratrochlear spur; type C – hypoplastic medial facet and convex lateral facet with crossing sign and double contour but no spur anterior to the femoral shaft; and type D – asymmetry of medial and lateral trochlear facets with supratrochlear spur, crossing sign, double contour, and a "cliff" between the hypoplastic medial and prominent lateral facet and spur.

Advanced imaging, such as CT or MRI, is critical for preoperative planning prior to trochleoplasty. Both modalities may be used to measure TT to TG (TT-TG) distance, more accurately characterize the trochlear morphology, assess for patella alta, and with MRI, assess for focal chondral injury. It should be noted, however, that measurement of TT-TG distance is most accurate using CT, as MRI can underestimate this measurement by up to 4 mm.[20] As discussed below, an elevated TT-TG distance plays a role in surgical decision making when considering adding a TTO.

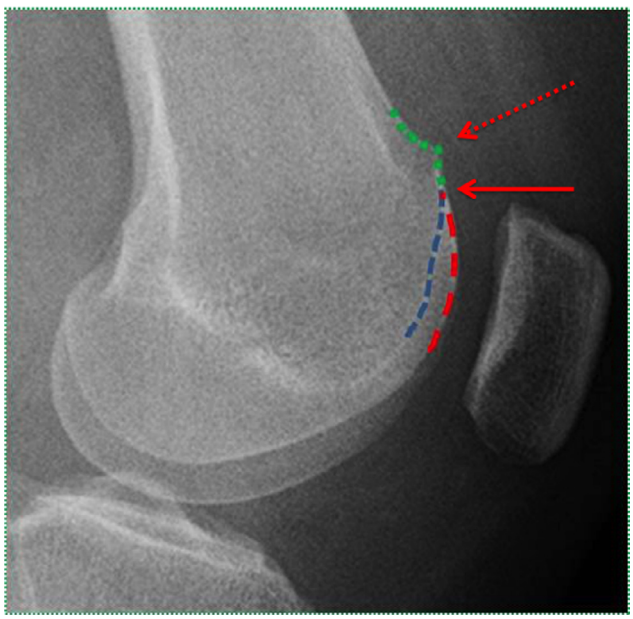

Figure 2 Lateral radiograph of a dysplastic trochlea. The green line and dashed arrow represent the supratrochlear spur. The trochlear groove (blue line) flattens, crosses over the lateral femoral condyle (red line), and is contiguous with the spur (green line). (Color version of figure is available online.)

Indications and Contraindications

Groove-Deepening Trochleoplasty Techniques

Correct patient selection in performing trochleoplasty is absolutely critical and the underlying etiology of the instability must be well understood. It must be emphasized that a shallow groove (or Type A dysplasia) is not an indication for trochleoplasty. The most commonly utilized indications for trochleoplasty include persistent patellar instability refractory to conservative treatment in patients with a Dejour type B or D trochlea and a supratrochlear spur >5-7 mm.[4,21-24] The spur is measured on the midsagittal MRI image, either the image demonstrating both cruciate ligaments or one image medially or laterally. This represents the deepest point of the trochlea. The key feature of these 2 specific Dejour types (type B and D) is the associated supratrochlear spur. As noted previously, this spur can act as a "ski ramp," producing lateral subluxation or dislocation of the patella as it encounters the spur when moving into flexion. In a cadaveric study, Van Haver et al demonstrated that Dejour B and D types had increased chondral contact pressures, decreased contact areas, and altered kinematics with resultant patellar instability during biomechanical testing.[25] The dysplasia type and severity of dysplasia are also associated with increasing PF arthrosis severity.[19,26]

As noted above, the presence of a J sign is also a critical finding on physical examination. In our experience, the presence of a large or appreciable J sign or significant patella alta (patellotrochlear index, PTI <0.20 or CD (Caton-Deschamps) ratio >1.4) lowers the threshold to perform a trochleoplasty in an

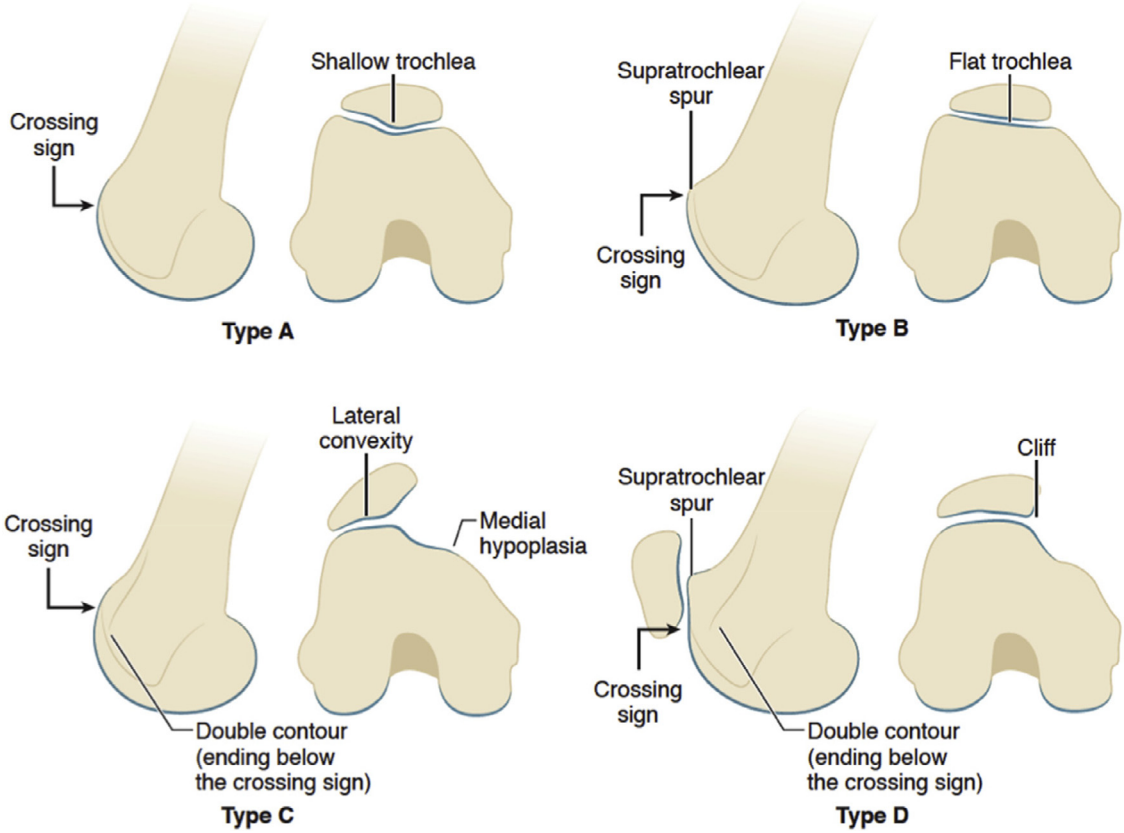

Figure 3 Dejour classification of trochlear dysplasia. (Reproduced with permission from Dejour D, Saggin PRF. Sulcus deepening trochleoplasty, in Scott WN, ed., Insall & Scott surgery of the knee, ed 5, Philadelphia: Elsevier, 2012;688-695).

otherwise-appropriate patient. The presence of patella alta magnifies the effect of the supratrochlear spur as the patella encounters this spur repeatedly in early stages of flexion, thereby having even greater influence on patella tracking. These are the patients with the pronounced lateral jump type of J sign on active knee extension and often debilitating instability.

Trochleoplasty should also be strongly considered in revision procedures in patients with Dejour B and D dysplasia who have previously undergone an isolated soft tissue procedure such as MPFL reconstruction or lateral release. Multiple studies have demonstrated an association between the severity of a patient's trochlear dysplasia and their clinical outcome and risk of persistent instability following an isolated soft tissue procedure such as an MPFL reconstruction.[27-30] Hopper et al noted that all 7 of their patients with Dejour C or D dysplasia treated with isolated MPFL reconstruction had persistent or recurrent instability.[31]

Contraindications to groove-deepening trochleoplasty include advanced (grade 4) trochlear arthrosis, significant growth remaining in a skeletal immature individual, and Dejour A and C dysplasia. Attempting to perform a trochleoplasty in the presence of brittle, eburnated, and sclerotic trochlear bone can lead to fracture propagation when attempting to cut the osteochondral shell with a scalpel or osteotome. This could result in unstable fragments that might require additional fixation or alterations to postoperative rehabilitation. If using the "thin-flap" technique, the flap may be too brittle or stiff to reshape properly. Indeed, the thin flap technique is technically less demanding when the cartilage is more supple, as is true in younger patients.

Open physes or skeletal immaturity is frequently cited as contraindications to trochleoplasty due to the risk of growth arrest or angular abnormality.[32] Interestingly, Nelitz et al performed "thin-flap" trochleoplasty in 18 adolescents with less than 2 years of growth remaining.[33] Notably, no cases of growth disturbance or recurrent instability were encountered. Additional research, however, is necessary before trochleoplasty can be advocated in skeletally immature patients and caution should be exercised.

Trochleoplasty is commonly combined with other procedures to fully address the multifactorial contributors to patellar instability. The medial soft tissue structures including the MPFL provide the primary restraint to lateral translation in the early stages of flexion. In patients with patellar instability, these medial structures are disrupted or attenuated. For this reason, an MPFL reconstruction should be included with any trochleoplasty procedure.[4,32] A distalizing TTO may be considered in patients with a CD Index (CDI) >1.3, a PTI <0.32,[32] or a sagittal PF engagement ratio <0.45.[34,35] Given the additional morbidity of a distalizing osteotomy, most surgeons (including the authors) generally accept a CD ratio greater than 1.4 or a PTI of less than 20% as an indication for a distalizing TTO.

As noted, the combination of patella alta and trochlear dysplasia is particularly problematic for the patella to engage the

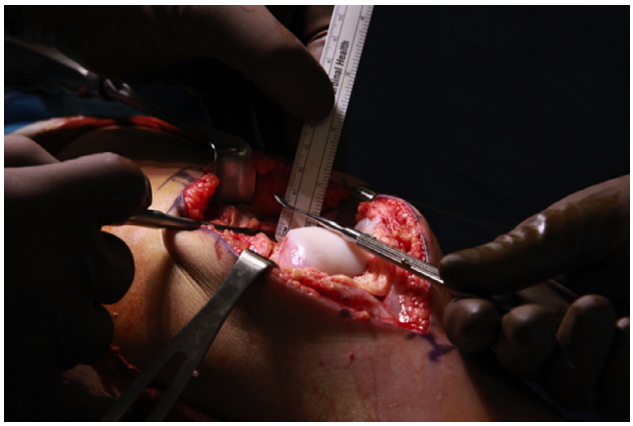

Figure 4 Intraoperative view of left knee demonstrating a significant supratrochlear spur/boss measuring roughly 14 mm in height from the anterior femoral cortex.

more normal, distal groove properly. For those patients with patella alta and moderate degrees of trochlear dysplasia (a supratrochlear spur less than 5-7 mm), or with Dejour types A and C, correcting the patella alta by tubercle distalization can be a very effective way to bring the patella closer to engagement in the more normal, distal trochlea. We have found that correcting patella alta is a less invasive method to manage these cases of moderate trochlear dysplasia than deepening trochleoplasty. However, we have also noted that the combination of patella alta and trochlear dysplasia seems to be the most problematic to overcome with any soft tissue procedure alone, lowering our threshold for some type of bony correction.

In patients who also have genu valgum or an excessively laterally positioned tibial tuberosity, the effect of trochlear dysplasia is also magnified. An elevated TT-TG >20 mm plus lateral patella tracking and tilt is often utilized as criteria for a bony procedure such as a TTO.[36,37] A large TT-TG, however, may reflect medialization of the proximal sulcus, leading to an excessive TT-TG. Some have promoted the use of TT-posterior cruciate ligament distance as a way to distinguish the location of the elevated TT-TG, that is, medialization of the proximal sulcus vs excessive lateralization of the TT.[38] Trochleoplasty may obviate the need for TTO in patients with Type B or D dysplasia and borderline elevated TT-TG. In our experience, the new TG achieved during trochleoplasty can be created up to 5-7 mm laterally, thus effectively decreasing the TT-TG. Thus, in the setting of a trochleoplasty, an elevated TT-TG of >24 mm combined with an elevated TT-posterior cruciate ligament may be considered a threshold for a medialization TTO given that a minimally elevated TT-TG (18-23 mm) can be normalized by lateralization of the newly created trochlear sulcus.

Proximal Entrance Grooveplasty Indications

Similar to groove-deepening trochleoplasty, current indications for the proximal grooveplasty include recurrent patella instability associated with abnormal patella tracking (with a pronounced clunk) associated with a supratrochlear spur/bump and/or a related osteophyte in this same region. Additional indications include dysplasia restricted to the proximal trochlea. In these cases, the groove deepens in early flexion so there is less need for a conventional groove-deepening trochleoplasty. Grooveplasty may also be indicated in patients with focal grade 4 arthrosis of the proximal trochlea, which would otherwise negate the ability to perform a conventional groove-deepening trochleoplasty.

Similar to groove-deepening trochleoplasty, contraindications to grooveplasty include Dejour A and C dysplasia as there is no "bump" to resect. If the proximal trochlea below the crossing sign is convex, grooveplasty will not address the underlying issue. Furthermore, if the crossing sign is very distal, there is too much bone and cartilage to resect proximal to the crossing sign.

Surgical Technique for "Thick-Shell" Groove-Deepening Trochleoplasty

Open Approach and Hamstring Harvest

After completion of the arthroscopic portion of the case, a longitudinal medial paramedian incision is made. This incorporates the medial arthroscopy portal. Full thickness flaps are raised, and adequate extracapsular dissection is performed medially to allow for completion of the trochleoplasty and MPFL reconstruction through this single utilitarian incision. In the setting of a TTO, this incision can be extended distally. As discussed above, we routinely incorporate a MPFL reconstruction. We have found gracilis autograft most useful, though allograft tissue is also an option based upon patient and surgeon preference. The hamstring tendons are directly palpated, and the gracilis is harvested in standard fashion. The graft is measured and the ends are prepared in standard running whipstitch fashion on the back table with #0 Vicryl (Ethicon, Cornelia, GA). While the length of the graft required for MPFL reconstruction is often dependent on patient size, we recommend a length of at least 24 cm.

Trochleoplasty

After the arthrotomy is performed, the trochlear cartilage is assessed for gross wear or damage. The actual height of the supratrochlear spur can be measured directly (Fig. 4). A sterile marking pen is used to determine the location of the native trochlea by rolling it back and forth in the groove. Frequently, the groove is flat, or even convex proximally and must be located at its distal aspect. The location of the new sulcus or groove is also marked. The anterior superior iliac spine and the shaft of the femur are referenced to mark the desired sulcus. This new sulcus can be lateralized by 5-7 mm, which effectively can decrease an elevated TT-TG distance as discussed in the indications section above (Fig. 5). The anticipated osteochondral flaps are then marked out, which will delineate the new medial and lateral trochlear ridges (Fig. 5). When viewing from the side, the inflection point at which the medial and lateral condyles peak in height and transition in curvature is selected and marked as the osteotomy sites. This is proximal to the sulcus terminalis. The distal extent of the osteotomy for the new central sulcus, and the intersection

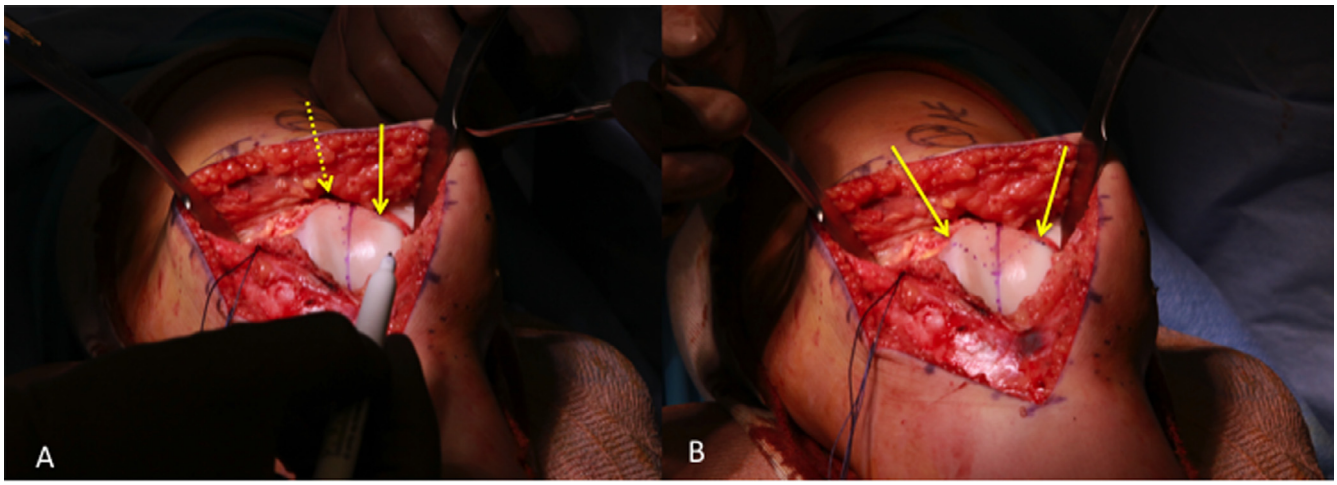

Figure 5 (A) A dashed line is drawn along the native sulcus (dashed yellow arrow) and an additional solid line (solid yellow arrow) is marked just lateral to this. In this case, a line is drawn to help lateralize the created sulcus by 5 mm in order to aid in patellofemoral tracking and articulation. (B) Additional dashed lines (yellow arrows) both medial and lateral (yellow arrows) have been drawn to delineate the anticipated medial and lateral osteochondral flaps of the trochlea. (Color version of figure is available online.)

with lines drawn for the medial and lateral condyles, is an imaginary line drawn distally from the anterior femoral cortex. This will allow complete removal of the supratrochlear spur that was above the height of the anterior femoral cortex and avoid getting too distal to risk cartilage perforation using straight burrs or drills for bone resection.

A cortical wedge of bone is removed around the articular margin of the trochlea using an osteotome and a rongeur. It is important to start this "cortical wedge" partially onto the articular surface such that following the resection the cartilage will sit "flush" with the surrounding bone. Additionally, starting well proximally at the base of the spur is important to allow the new trochlea to be flush with the anterior femoral cortex. This also allows access for the 3-mm egg-shaped high-speed burr. The bone removed is morselized and saved to later pack into any cavities under the shingles and to elevate the medial and lateral edges to provide greater trochlear depth.

A commercially available guide is also available which provides a 3 or 5 mm offset guide for use when removing and contouring the subchondral bone (Arthrex, Naples, FL). We use the 5 mm guide for the thick-shell technique. It is vital to not go beyond the marked flaps' most distal border. Creating a deeper apex in the center midline of the new sulcus and tapering it to the periphery medially and laterally will also help the leaflets to compress deeper into the sulcus upon fixation (Fig. 6). It is important to leave at least a 2-3 mm shell of subchondral bone to help limit cartilage injury and allow for adequate healing. A freer can be used to remove the bone "slurry" produced by this method and to check the resection for adequate depth and contour.

At this point, the proximal trochlea osteochondral shell should be ballotable by thumb depression. A no. 20 scalpel blade is then positioned on the marked new trochlear sulcus, and a bone tamp and a mallet are used to osteotomize the osteochondral shell of bone (Fig. 7). If there is a large cavity due to removal of a large amount of bone, an osteotome can be placed under the shell to limit bending as the shell is osteotomized. Making the central cut usually allows satisfactory deformation of the medial leaflet, which is almost always malleable enough to be depressed into the new position without making an extra cut.

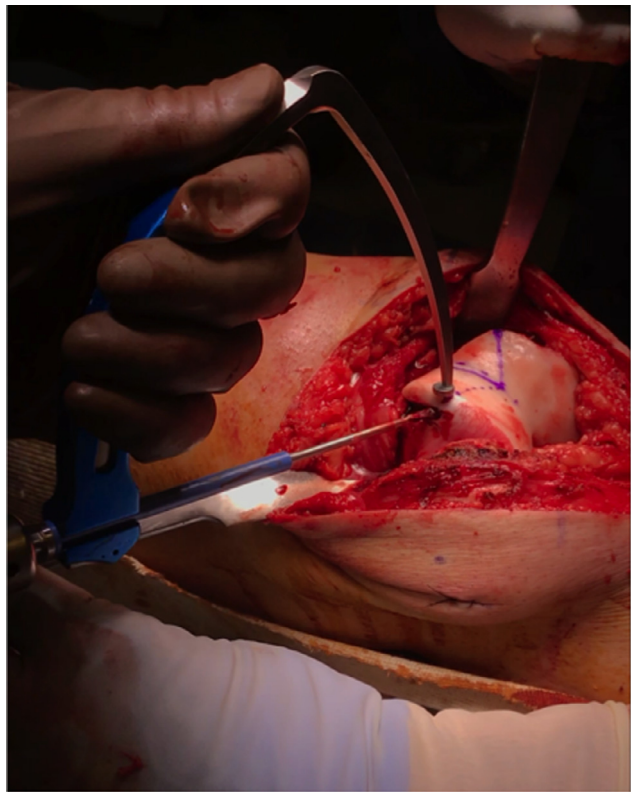

Figure 6 Commercially available guide. In this case, the 5 mm offset guide provides for a precise 5 mm "thick shell." This creates a cavity, deepest in the center, and tapered medially and laterally toward the periphery

Figure 7 A #20 blade is positioned along the central trochlear cut. A bone tamp and a mallet are utilized to provide gentle taps to the scalpel to complete the central cut.

However, a separate cut is usually needed on the lateral edge of the lateral leaflet. This cut should extend roughly halfway along its marked course to create a deformable lateral leaflet. It is critically important that the splits not connect at the distal base to avoid a free "shingle" of bone. The cortical wedges of bone that were initially removed with an osteotome are placed longitudinally into the defect at the most distal extent of the medial and lateral osteochondral flaps to improve the transition from the subchondral cavity to the unresected bone. Furthermore, small cortical bone segments are placed at the periphery along the far medial edge of the medial flap and the far lateral edge of the lateral flap to aid in sulcus angle maintenance while healing. The bone slurry removed at the time of burring is also placed deep within the trochlear defect to aid in healing.

A biocomposite suture anchor, such as a 2.9-mm knotless PushLock (Arthrex, Naples, FL), is placed roughly 5-10 mm distal to the most distal extent of the sulcus cut line. This anchor is double loaded with 2 no. 2 Vicryl (Ethicon, Cornelia, GA) sutures. A single pair of the sutures is then draped over the medial osteochondral flap at an angle of pull that will maintain flap reduction. It is also important that this suture be placed in a position where it will not slide into the central osteochondral cut line. This suture pair is placed into an additional biocomposite suture anchor placed proximally while maintaining adequate tension on the sutures so it provides compression of the medial leaflet. In a similar fashion, the other suture pair is draped over the lateral flap and secured in a third knotless suture anchor proximal to the lateral leaflet (Fig. 8). This completes the trochleoplasty and creation of a deepened sulcus. The wound is copiously irrigated. It is important, however, not to lavage the bone graft and "slurry" placed under the trochleoplasty leaflets.

MPFL Reconstruction

We universally perform MPFL reconstruction when performing a sulcus-deepening trochleoplasty. Multiple fixation constructs exist, though we prefer the use of drill tunnels though the patella and a blind socket at the anatomic femoral attachment. After exposing the medial patella, 2 short oblique 3.2 mm drill holes are placed. These are positioned just off the medial patellar cartilage and are angled obliquely and

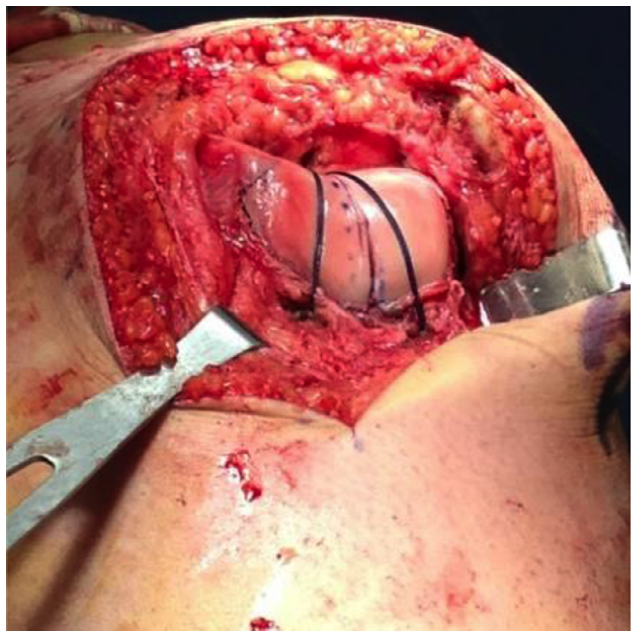

Figure 8 Final view of new sulcus after securing the osteochondral flaps with two #2 absorbable sutures.

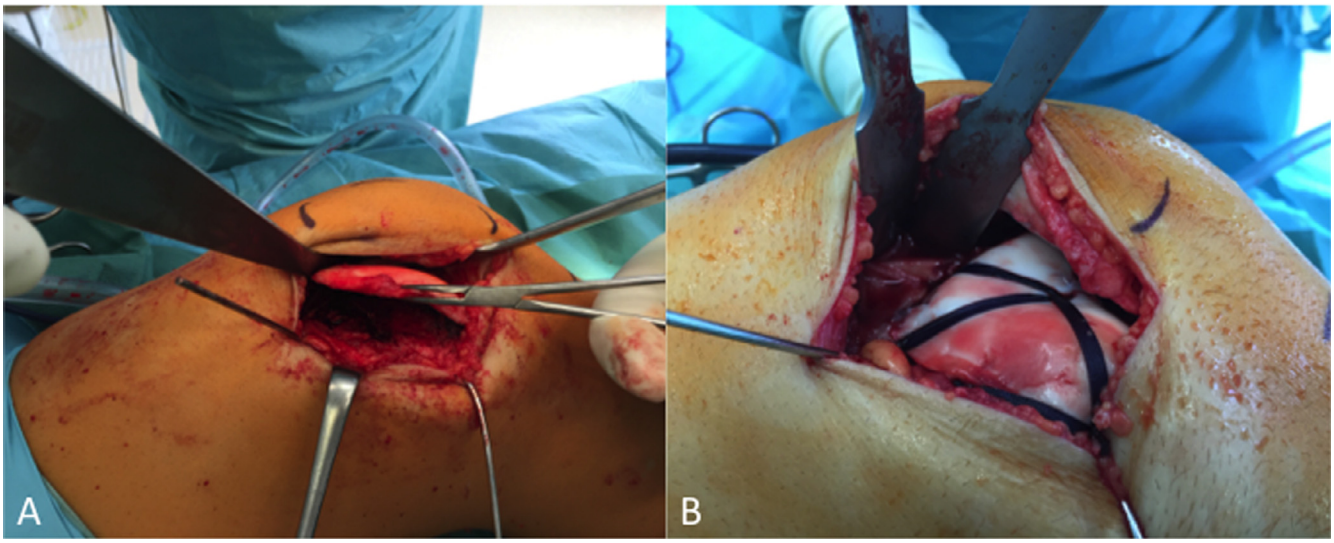

Figure 9 (A) Intraoperative view of right knee with the thin flap raised. (B) A new groove has been created, and the thin flap has been secured with Vicryl tape. (Courtesy of Prof. Phillip Schöttle, MD, PhD, Munich, Germany).

anteriorly to exit the anterior patellar cortex in the proximal half of the patella. The gracilis tendon is then passed in a looped fashion through the patellar tunnels. If is quite helpful to "bulletize" the ends of the graft utilizing the Vicryl suture and, if the passage is difficult, sterile mineral oil can be used to assist in passage. The plane between Layers 2 and 3 of the medial retinacular structures is developed and the graft is passed between these layers using a suture shuttle. The exit point is just anterior to the adductor tubercle. Intraoperative fluoroscopy is used to obtain a perfect lateral view and identify Schöttle's point.[39] A radiolucent triangle (Innomed, Savannah, GA) is very helpful during this step. This represents perhaps the key step in MPFL reconstruction as femoral tunnel placement is critical. A 3/32" beath pin is then placed at this point and advanced in an anterior and proximal direction in order to avoid the previously placed suture anchors used to fix the trochleoplasty. The graft ends are looped around the pin and the graft is checked for isometry during flexion and extension. A 7 mm cannulated acorn reamer is then used over the pin to create the blind femoral socket. It is important to measure the tendon graft length and ensure the femoral socket is long enough to avoid "bottoming-out" and having inadequate tension. A nitinol guidewire is placed into the tunnel at this point, and the graft suture ends are then shuttled, exiting through the lateral skin. With the knee at roughly 45° of flexion on a radiolucent triangle, the MPFL graft ends are ensured to be fully introduced into the tunnel, tensioned at roughly 0.5 lbs of force, and fixed with a 7 mm biocomposite interference screw inserted over the nitinol guidewire. As the screw is tightened, the graft "creeps" or shortens into the socket during the final turns. This effectively overtightens the graft beyond the desired limit. The screwdriver is turned counterclockwise one-half turn which returns the tension to the desired set limit. Patellar tracking and translation are once again assessed, with the goal of a 1-2 quadrant glide laterally with the knee straight.

Z-Lengthening and Closure

Following completion of the MPFL reconstruction, a Z-lengthening is performed as needed in the presence of an overly tight lateral retinaculum. It is important not to overlengthen then lateral structures and create an iatrogenic medial instability. We prefer the Z-lengthening and have found it to be more precise when compared to a simple release. It may also be associated with greater quadriceps strength and less pain.[40] The superficial layer of the lateral retinaculum is incised vertically with Bovie electrocautery and allowed to reflect laterally. Dissection is then carried laterally between the superficial layer and deep layer. A vertical incision through the deep retinacular layer is then made roughly 1.5-2 cm posterior (or laterally) to the initial incision though the superficial layer. Frequently we observe a visible "pop" and improved resting position of the patella. This deep-layer release is carried distally to the level just above the lateral meniscus and proximal to the most distal extent of the vastus lateralis muscle. The superficial layer laterally is then reapproximated to the deep layer medially with #0 Vicryl suture. This effectively lengthens the lateral retinaculum in a controlled manner in a "Z" fashion.

The wound is thoroughly irrigated with copious normal saline. A #1 Vicryl suture is used to close the medial parapatellar arthrotomy, taking great care not to inadvertently capture the MPFL graft. The remainder of the wound is closed in a layered fashion and a sterile dressing is applied. The knee is then placed in a hinged knee brace with range of motion allowed between 0° and 70°.

Surgical Technique for Thin-Flap Technique

The "thin-flap" technique initially described by Bereiter and Gautier is similar to the "thick-shell" technique described above. The key distinguishing feature is that a 2-3 mm

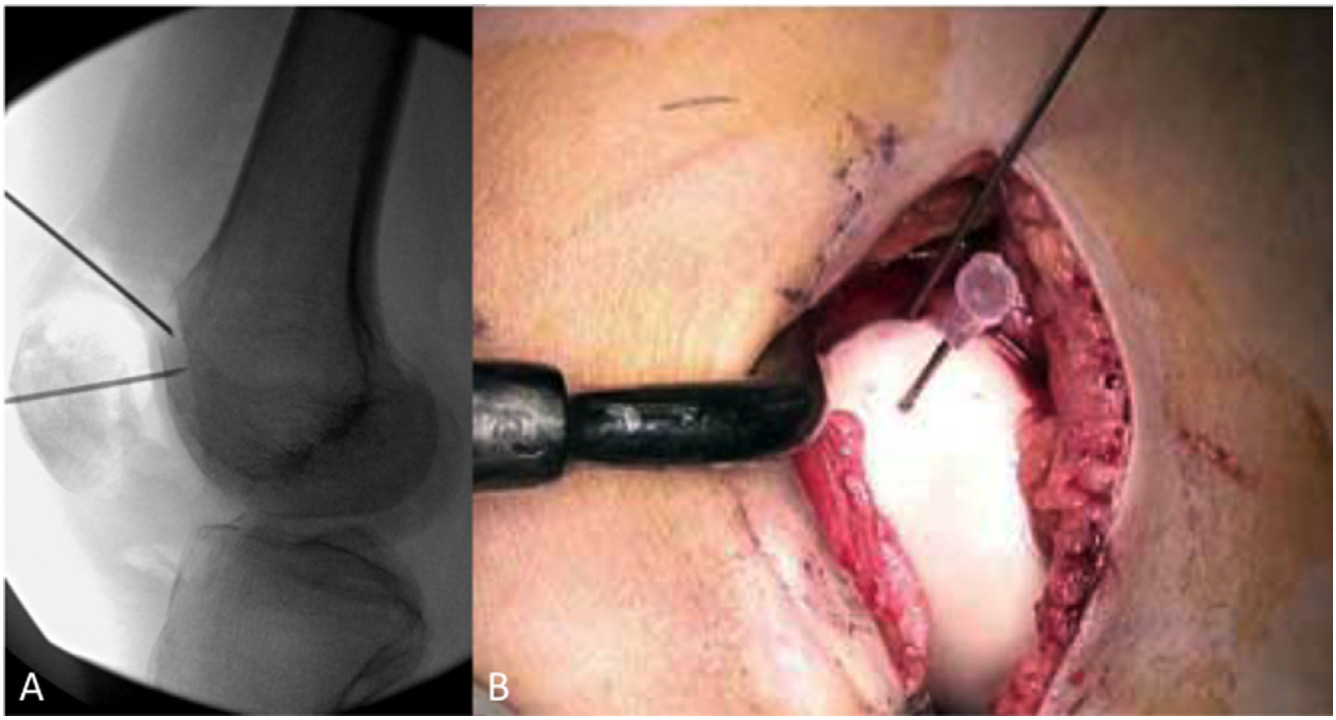

Figure 10 (A) Intraoperative fluoroscopic image. The proximal K-wire is placed at the proximal extent of the cartilage. The distal needle is placed at the crossing sign. (B) Intraoperative view of same patient demonstrating placement of wire and needle.

osteochondral flap comprising the medial and lateral condyles and trochlea is elevated en bloc as compared to the 5 mm thick shell utilized in the Lyon or "thick-shell" technique.

A lateral parapatellar approach with the knee fully extended is made. The trochlear cartilage flap with 1-2 mm of underlying subchondral bone is carefully elevated as 1 piece from the lateral and medial femoral condyles utilizing osteotomes (Fig. 9). The subchondral bone can also be "thinned" with the previously described commercial guide. In contrast to the "thick-shell" technique where the 5 mm offset guide is used, a 3 mm guide is used for the "thin-flap" technique. The subchondral TG is then recontoured and deepened with a high-speed burr, curettes, or osteotomes. The "thin-flap" is then molded into the deepened groove. Unlike the Lyon "thick-shell" technique, no central osteotomy is required as the thin-flap is quite malleable. Similar to the "thick-shell" technique, the "thin-flap" is secured utilizing PushLock anchors (Arthrex, Naples, FL) and no. 2 Vicryl (Ethicon, Cornelia, GA) sutures, although one suture is directed along the new groove and the other laterally toward the highest point of the lateral femoral condyle (Fig. 9). The margin of the osteochondral flap is reattached to the synovium and periosteum with absorbable sutures.

Surgical Technique for Proximal Entrance Grooveplasty

A medial or lateral parapatellar approach can be utilized and the trochlea is fully exposed. If a TTO is planned, performing this first facilitates exposure. The synovium superior to the trochlea is incised sharply with a scalpel or electrocautery and then undermined exposing the entire bony prominence.

Intraoperative assessment and intraoperative fluoroscopy are used to determine the amount of resection. The goal is to remove the bone proximal to the sulcus, which is defined by the crossing sign (Fig. 10). The amount of resection generally requires the removal of approximately 10 mm of proximal trochlea. The resection is completed with osteotomes or a high-speed burr until the area is level with the distal femur, with a slight slope toward the more distal trochlea and the proximal opening more lateral-facing.

Synovium or fat is advanced onto the exposed bony surface and sutured back to the cartilage/bone edge using a suture anchor (Fig. 11). Care should be taken not to put the synovium on stretch, as this can lead to shortening of the suprapatellar pouch and potential restriction of postoperative motion.

Postoperative Rehabilitation

Patients are placed in a long leg hinged knee brace and restricted to 50% weight bearing on the operative limb for 6 weeks. At the present time, there is a paucity of literature regarding specific postoperative rehabilitation protocols in the setting of trochleoplasty. As with any intraarticular knee procedure, arthrofibrosis is a risk with prolonged immobilization. Physical therapy is started early in the first week as stiffness and scar formation occur quickly if there is a delay in initiation of motion. The brace is set for motion from 0° to 70° for the first 2 weeks, 0° to 90° from weeks 2 to 4, and

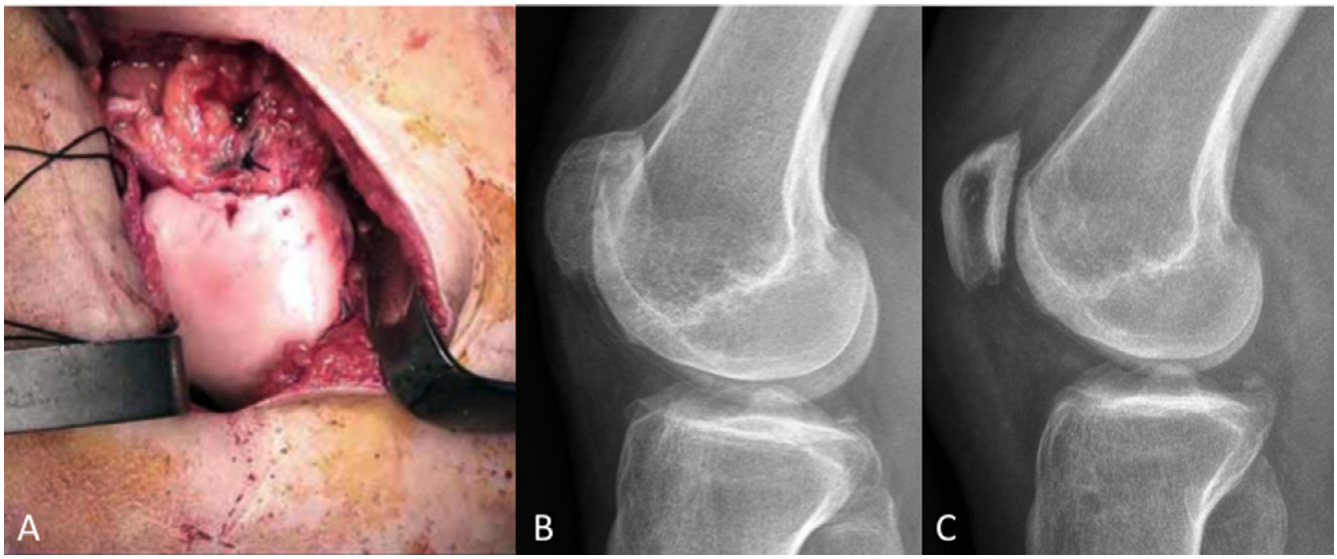

Figure 11 (A) Intraoperative view after resection of proximal portion of the groove with suprapatellar synovium placed over the resected bone. (B) Pre- and (C) postoperative sagittal images of a patient treated with grooveplasty and MPFL reconstruction.

then unrestricted thereafter. The physical therapist can assist with flexion 15° beyond each brace setting and instruct the patient to do the same with heel slides with the brace removed at home. Short arc quadriceps activation, isometrics, and electrical stimulation are added with a progression toward stationary bike, elliptical and leg press between weeks 6 and 12. A return to jogging is allowed after week 12, assuming adequate muscle control and absence of an effusion. The importance of adequate quadriceps reconditioning cannot be overemphasized. A graduated return to sport-specific reconditioning is then allowed with a goal of return to sport by 5-6 months postoperatively.

Results

Groove-Deepening Trochleoplasty Results

Within the literature, trochleoplasty has been performed in a complicated and heterogeneous patient population, which introduces some variability in published results. There is a great deal of variability in surgical indications, surgical techniques, and the addition of concomitant procedures. Outcomes, however, have been generally positive following the procedure. There are currently no Level 1 randomized clinical trials including trochleoplasty, thus the available studies are smaller case series with short- and mid-term follow-up. Several key trends have emerged in the literature that serve to guide practice and lay a foundation for future investigation.

McNamara et al presented the results of a modified "thick-shell" or Dejour technique in 90 patients (107 knees).[41] These patients were noted to have severe dysplasia. It should also be noted that only 14 (13.1%) of patients had a MPFL reconstruction at the time of trochleoplasty. Eighty-three percent of patients reported that they were satisfied with their outcome. At 6-year follow-up, Kujala scores improved significantly from a mean of 63-84 postoperatively ($P< 0.05$). Sports participation rose from 40% to 67% at final follow-up. It was observed that 21 knees (19.6%) required revision for recurrent instability including 10 MPFL reconstructions.

Dejour et al noted no instability events in 22 patients (24 knees) treated with the "thick-shell" technique at a mean follow-up of 66 months.[42] They also noted postoperative improvements in Kujala scores from 44 to 81. Seventy-two percent of patients reported that pain had decreased and 75% of patients had a negative apprehension sign. No patients exhibited radiographic evidence of progressive osteoarthritis during the 66-month study period.

Ntagiopoulous et al presented mid-term results (mean follow-up of 7 years) of 27 patients (31 knees) treated with combined "thick-shell" trochleoplasty and bony or soft tissue stabilization for high-grade dysplasia (Dejour B and D).[43] They demonstrated substantial improvements in Kujala and International Knee Documentation Committee (IKDC) scores. There were no postoperative patellar dislocations reported although a patellar apprehension sign was found on exam in 6 knees.

At our own institution, a total of 64 patients (71 knees) with severe trochlear dysplasia treated between 2011 and 2017 were enrolled in a prospective study. All patients underwent "thick-shell" sulcus-deepening trochleoplasty technique along with other concomitant stabilizing procedures. MPFL reconstructions were performed in all patients along with lateral release or lengthening (50.7%), TTO (32.8 %), and some type of cartilage procedure (41.8%) to include shaving chondroplasty (38.8%), chondral allograft (10.4%), microfracture (7.5%), and/or removal of loose body (22.4%). The mean age of patients was 19.6 ± 6.8 years and a majority of patients were female (81.6%). The mean follow-up was 27.7 months (range 12-78.4 months). All knees were classified as either Dejour B (81.3%) or D (18.8%) and had a mean CDI of 1.20. Mean spur height preoperatively was 7.41 mm (± 1.84 mm).

In our cohort, there were no episodes of recurrent dislocation. One patient was found to have a recurrent J sign at terminal extension and patellar apprehension on exam postoperatively requiring a distal femoral osteotomy for genu valgum. All patients reported clinically significant improvements compared with baseline preoperative outcome scores. The mean preoperative Kujala score improved from 55.88 to 85.80 ($P<$ 0.001), and the mean preoperative IKDC score improved from 49.99 to 79.86 ($P<$ 0.001). All but 1 patient (96.9%) returned to work while 88.2% of patients were able to return to sport. Patients reported high satisfaction rates (mean 9.5 ± 1.6 of 10). Ten knees (20.4%) developed stiffness and required manipulation under anesthesia, with 8 undergoing arthroscopic lysis of adhesions as well. These were during our early experience with a more conservative rehab progression. We have experience only 1 patient with arthrofibrosis requiring manipulation since instituting the current protocol of immediate motion. No patients had progression of arthritis or fixation failure noted on annual X-rays.

Fucentese et al assessed CT scans before and after performing the "thin-flap" sulcus-deepening trochleoplasty in 14 patients (17 knees) and demonstrated improvement in key radiographic measures.[44] The TG was lateralized by a mean of 6.1 mm proximally and 2.5 mm distally while the patella was medialized 5 mm. The depth of the groove also improved, increasing by 5.9 mm proximally and 2.8 mm distally. Other investigators have examined the pre- and postoperative sulcus angle measurements and noted correction ranging from 12° to 39° after trochleoplasty.[42,43,45]

Metcalfe et al published the largest study to date on the Bereiter or "thin-flap" trochleoplasty.[46] This study included 173 patients (199 knees) treated over a 12-year time period. The mean follow-up time was 4.4 years (range 1-12). IKDC scores increased from 44.3 to 71.3 and Kujala scores increased from 51.5 to 82.5. Ninety percent of patients reported resolution of symptoms. Eighty-eight percent of patients were satisfied with their outcomes. Almost 74% of patients returned to sport. Sixteen patients (8.3%) experienced a recurrent patellar instability. Twenty-seven patients (14%) underwent revision procedures, of which 9 were MPFL reconstructions. The authors discussed that during the course of the trial, they began to more consistently augment trochleoplasty with soft tissue balancing procedure, which resulted in a changing incidence of revision surgery with subsequent MPFL reconstructions. Ten percent of the initial 40 patients required subsequent MPFL reconstruction, compared to 3% of the next 174.

Proximal Entrance Grooveplasty Results

The results of the open proximal grooveplasty were described by Peterson et al in 1988 in 25 knees.[8] All patients had recurrent patellar dislocation and trochlea dysplasia, and 17 had failed other patellar realignment procedures. Lateral retinacular release and medial plication were performed in conjunction with open proximal grooveplasty. The mean follow-up was 6 years (range 1-14 years). One patient had a redislocation. Excellent or good results were obtained in 17 and 5 knees, respectively. The fair and poor results were associated with PF pain and apprehension without frank dislocation. The authors did not describe anatomic risk factors or trochlear dysplasia in their patient cohort.

This 1988 paper stands as the only published paper using this technique, despite increasing use of the grooveplasty technique, particularly with concomitant patella cartilage restoration surgeries.[47] In part, the high incidence of concomitant surgeries makes comparison studies difficult. Despite a paucity of published outcomes of this procedure, the Peterson grooveplasty has a potential role in the treatment of trochlear dysplasia and associated patellar instability with less morbidity and potential complications and a less steep learning curve than conventional trochleoplasties. This operation is suitable for knees with a large proximal convexity and more normal concave distal trochlea with no significant patella alta.

Complications

There are many technical challenges in performing trochleoplasty that lead to a steep learning curve and risks for complications. It cannot be overstated that correct patient selection is critical in minimizing complication. Song et al conducted a systematic review of trochleoplasty results in patients with severe dysplasia. This review included both sulcus-deepening trochleoplasty and Goutallier wedge-recession trochleoplasty.[22] They noted an overall complication rate of 13.4%. Notably, the pooled rate of redislocation was 1% (3 of 329 patients). Four percent of patients had difficulty with range of motion or arthrofibrosis and 9% had an increase in PF pain. Among the studies that evaluated for PF arthrosis, 8% developed this finding at final follow-up.

A frequently cited complication after trochleoplasty is stiffness or arthrofibrosis, which has been reported in up to 46% of knees.[11,22,41,48] Recent studies, however, have shown an incidence between 0% and 20%, which is more in line with our experience.[43,48,49] Manipulation under anesthesia and/or arthroscopic lysis of adhesions (LOA) are effective tools for treating patients with stiffness should this develop. Several authors have demonstrated satisfactory return to function after LOA/manipulation under anesthesia.[48,49] It has been proposed that early passive range of motion exercises may help to minimize the periarticular scar formation that can be seen arthroscopically during LOA.[50]

Subchondral collapse is a concerning risk of trochleoplasty. Articular cartilage can be directly damaged while osteotomizing the osteochondral shell, but it can also be indirectly damaged while using the burr to remove subchondral bone secondary to thermal injury or over-resection. The use of a measured offset guide may minimize this potential complication and add an additional degree of reproducibility.

In many cases, patients have a high burden of existing chondral damage as a result of multiple previously sustained patella dislocations. This can lead to PF pain despite correction.[45] This complication has been observed in up to 14% of patients.[51] Even after improving joint mechanics and reducing instability, it is possible that trochleoplasty may not be protective against progression of osteoarthritis. While osteoarthritis rates have been reported as low as 0%-7%, the lack

of long-term results of the contemporary techniques leaves this question unresolved.[42,46,51]

Complications related to the proximal grooveplasty technique also include persistent or recurrent instability and pain. One potential complication is continuation of abnormal patella tracking, and potentially a persistent J sign, due to lack of deepening the TG. The consequences of resection of cartilage in the abnormal proximal aspect of the trochlea are unknown. However, the natural history of the underlying high-grade trochlea dysplasia, with or without patellar instability, is that of PF arthritis.[52-55]

Conclusion

Trochlear dysplasia plays a dominant role as an anatomic risk factor in patients with patellar instability. Patients with a Dejour type B or D trochlear dysplasia, persistent symptomatic patellar instability, a J sign, and a spur height of >5-7 mm may be candidates for groove-deepening trochleoplasty. Additionally, entrance grooveplasty may be indicated in patients with dysplasia restricted to the proximal trochlea or those with focal arthrosis of the proximal trochlea where conventional groove-deepening trochleoplasty would not be indicated. It must be emphasized that trochleoplasty is not indicated in all cases of trochlear dysplasia and a complete understanding of trochlear morphology is paramount. An MPFL reconstruction should be included with any trochleoplasty procedure, and it is important to also consider concomitant TTO and lateral retinacular z-lengthening as necessary.

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