Universitat Autònoma de Barcelona

EVALUATION OF PATELLOFEMORAL JOINT CONTACT PRESSURE BEFORE AND AFTER MEDIAL PATELLOFEMORAL LIGAMENT RECONSTRUCTION USING A PARAMETRIC FINITE ELEMENT MODEL

Erik Montesinos Berry

Universitat Autònoma de Barcelona

FACULTAT DE MEDICINA
Departament de Cirurgia

EVALUATION OF PATELLOFEMORAL JOINT CONTACT PRESSURE BEFORE AND AFTER MEDIAL PATELLOFEMORAL LIGAMENT RECONSTRUCTION USING A PARAMETRIC FINITE ELEMENT MODEL.

TESIS DOCTORAL:

Erik Montesinos Berry

Barcelona 2018

Directores

Dr. Joan Carles Monllau

Dr. Vicente Sanchis Alfonso

Tutor

Dr. Joan Carles Monllau

La tesis doctoral titulada:

EVALUATION OF PATELLOFEMORAL JOINT CONTACT PRESSURE BEFORE AND AFTER MEDIAL PATELLOFEMORAL LIGAMENT RECONSTRUCTION USING A PARAMETRIC FINITE ELEMENT MODEL.

y presentada por el doctorando:

ERIK MONTESINOS BERRY

Está realizada bajo el modelo de compendio de publicaciones cumpliendo la normativa de la Universitat Autónoma de Barcelona para este tipo de tesis doctorales.

Referencia bibliográfica de los artículos incluidos:

Sanchis-Alfonso V, Ramirez-Fuentes C, **Montesinos-Berry E**, Domenech J, Martí-Bonmatí L. Femoral insertion site of the graft used to replace the medial patellofemoral ligament influences the ligament dynamic changes during knee flexion and the clinical outcome. Knee Surg Sports Traumatol Arthrosc. 2017 Aug;25(8):2433-2441.

Sanchis-Alfonso V, Ramírez-Fuentes C, **Montesinos-Berry E**, Elía I, Martí-Bonmatí L. Radiographic Location Does Not Ensure a Precise Anatomic Location of the Femoral Fixation Site in Medial Patellofemoral Ligament Reconstruction. Orthop J Sports Med. 2017 Nov 21;5(11):2325967117739252.

I wish to thank Dr. Sanchis and Dr. Monllau for being my mentors in the fascinating world of knee surgery, and for guiding me through the scientific research method. This has enabled me to treat my patients better.

INDEX

1. Introduction...1

2. Preliminary Published Studies..7

3. Hypothesis and Goals...10

4. Medial Patellofemoral Anatomy...12

5. Medial Patellofemoral Ligament: Surgical Techniques..........16

6. Material and Methods...20

7. Results...28

8. Discussion...38

9. Conclusions..43

Bibliography...45

Published articles...54

1. INTRODUCTION

In the last two decades the treatment of lateral patellar instability has seen many changes. The classical approach to this condition being distal and proximal realignment techniques, in the early nineties medial patellofemoral reconstruction techniques started gaining popularity.

Why is the reconstruction of the medial patellofemoral ligament becoming so important within the Orthopaedic Surgeon' s arsenal of surgical techniques? It is interesting to note the more than half of subjects with a first time patella dislocation will have some form of disability if left untreated [1,2]. This disability will be in the form of patellar instability, recurrent dislocations, anterior knee pain, anterior knee pain and patellofemoral arthrosis. The reconstruction of the medial patellofemoral femoral has become the most widely used surgical technique to treat this dislocation, associated or not to other techniques depending on the anatomical structural characteristics of the knee, such as trochlear dysplasia, increased TT-TG (Tibial tubercle, trocheal groove) distance, and patella alta.

We will describe the anatomy of the medial patellofemoral ligament and the different techniques used to reconstruct it. These techniques can be divided into static techniques, where the plasty is connected to bone of the patellar and the femoral side, and dynamic techniques where one the sides of the plasty is connected to soft tissues.

When reconstructing the medial patellofemoral ligament care must be taken not to overtighten the plasty, since this could lead to a pressure increase in the patellofemoral joint which can cause an early osteoarthritis. This could be a devastating consequence in a young active patient.

There are different techniques available to perform a medial patellofemoral ligament reconstruction, and measuring the patellofemoral contact pressure before and after the reconstruction would allow us to determine if a specific procedure is safe from a patellofemoral contact pressure standpoint.

The use of finite element methods is becoming more widely used in medicine. It is a complex methodology used by engineers, initially developed for large structures that were too large and complex structurally speaking to be able to measure pressures and forces. In a very simplistic description, a finite element methodology divides the structure into hundreds of small parts (elements), each of which is analyzed and measured individually and then correlated to the rest of the elements.

We have applied the finite element methodology to the knee patellofemoral joint with its special anatomic characteristics and the properties of its cartilage.

2. PRELIMINARY PUBLISHED STUDIES

We have developed a finite element methodology to analyze the patellofemoral pressures before and after different reconstruction techniques of the patellofemoral ligament reconstruction, based of the ligament length changes of the different techniques to calculate the ligament tension, and its consequences on patellofemoral joint pressure.
We analyze 3 different techniques. An anatomic technique, with an anatomic femoral fixation point, a non anatomic technique with a physiometric behavior, and a non anatomic technique and non physiometric behavior of the ligament plasty.

This methodology has been developed after 2 preliminary published studies.

- Femoral insertion site of the graft used to replace the medial patellofemoral ligament influences the ligament dynamic changes during knee flexion and the clinical outcome.

-Radiographic Location Does Not Ensure a Precise Anatomic Location of the Femoral Fixation Site in Medial Patellofemoral Ligament Reconstruction

The first preliminary study's purpose was to investigate how an ideal anatomic femoral attachment affects the dynamic length change pattern of a virtual medial patellofemoral ligament (MPFL) from an extended to a highly flexed knee position; to determine the relative length and length change pattern of a surgically reconstructed MPFL; and to correlate femoral attachment positioning, length change pattern, and relative graft length with the clinical outcome.

We found that the femoral attachment point significantly influences the relative length and the dynamic length change of the grafts during knee flexion–extension and graft isometry. Moreover, it influences the long-term outcome of the MPFL reconstructive surgery. A nonanatomic femoral fixation point should not be considered the cause of persistent pain and instability after MPFL reconstruction in all cases.

These length changes of the medial patellofemoral plasty enabled our engineering team to develop the patellofemoral finite element model used in our study.

Our second preliminary study enabled us to determine what we consider exactly an anatomic femoral fixation point, based on the 100 cases analyzed to determine the correlation between a radiographic and anatomic reference.

We evaluate the accuracy of the radiological method to locate the anatomic femoral fixation point in MPFL reconstruction surgery and (2) we determine the factors influencing the predictability of this method to obtain this objective.

We analyzed a total of 100 consecutive 3-dimensional computed tomography (3D CT) knee examinations were performed at 0° of extension in 87 patients treated for chronic lateral patellar instability. For each knee, 2 virtual 7 mm–diameter femoral tunnels were created: 1 using the adductor tubercle as a landmark (anatomic tunnel) and the other according to the radiological method described by Schoëttle et al (radiographic tunnel). We measured the percentage of overlap between both tunnels. Moreover, of the 100 included knees, 10 were randomly selected for a variability study.

The result of the study were, considering an overlap area greater than 50% as reasonable, the radiographic method achieved this in only 38 of the 100 knees. Intrarater and interrater reliability were excellent. There was a trend for female patients with severe trochlear dysplasia to have less overlap. This model accounted for 64.2% of the initial variability in the data.

Therefore an exact anatomic femoral tunnel placement could not be achieved with the radiographic method. Radiography provided only an approximation and should not be the sole basis for the femoral attachment location. Moreover, in female patients with severe trochlear dysplasia, the radiographic method was less accurate in determining the anatomic femoral fixation point, although differences were not statistically significant.

3. HYPOTHESIS AND GOALS

Currently, medial patellofemoral ligament (MPFL) reconstruction is the "gold standard" in chronic lateral patellar instability (CLPI) surgery, which is typically performed whenever there have been at least two previous episodes of lateral patellar dislocation [3,4]. Different surgical techniques have been described for MPFL reconstruction, with different attachment points, different types of grafts and different configurations for the, each with good short-term clinical results [3,4,5,6,7,8]. However, there is uncertainty regarding the long-term outcome of these MPFL reconstructions techniques. To classify a surgical technique for MPFL reconstruction as being effective, it is not enough for the instability and pain to disappear. For a surgical technique to be considered to be effective, new problems, such as chondropathy or patellofemoral osteoarthritis (PFOA), should never be caused. These problems might be the consequence of the increase in the patellofemoral contact pressure, secondary to an inadequate MPFL reconstruction [9,10,11], which is clinically relevant because surgery for lateral patellar instability is generally performed in young individuals, and the development of symptomatic PFOA in young persons does not have a good solution at this time. An effective way to evaluate the patellofemoral contact pressure throughout the range of motion of the knee after MPFL reconstruction is by using the finite element methodology (FEM) [9,12,13,14] . Moreover, this technology also enables us to evaluate the kinematic behaviour of the MPFL-graft and maximum MPFL-graft stress, that is, the tension that the graft can withstand before breaking, in all knee flexion-extension positions.

Generation of a patient-specific finite element model of the patellofemoral joint (PFJ) requires Computerized Tomography (CT) images to be processed, segmented and then converted into a

3D finite element model. This process is complex, expensive and very time-consuming, without offering direct clinical application. Segmentation is a process that requires manual correction to eliminate undesired tissues, and the computational burden makes the real model not suitable for clinical integration as a tool for MPFL reconstruction planning. Our purpose was the creation of a parametric model of the PFJ where the joint geometry is simplified and can be meshed by means of automatic mesh generation programs with suitable finite element aspect ratios for all meshes. Additionally, our parametric model enabled us to simulate different types of surgical techniques for MPFL reconstruction. We hypothesized that this model will allow us to evaluate the patellofemoral contact pressure and the maximum MPFL-graft stress in each specific reconstruction and at different flexion-extension angles of the knee. Our first objective was to determine the negative theoretical effects (patellofemoral contact pressure and the maximum MPFL-graft stress) on the PFJ in each type of MPFL reconstruction, which could be related to long-term deterioration of the PFJ. Since this is a novel method, we focused our attention on clinical validation. In this way, five clinical cases are presented to demonstrate the accuracy of our model and to show its versatility for predicting challenging clinical cases. An extrapolation of the computational results was performed to provide a qualitative comparison to the clinical outcomes. The contribution of our results is the introduction of FEM in daily clinical practice to optimize surgical procedures by using personalized treatments.

4. Medial Patellofemoral Anatomy

The medial patellofemoral ligament is the most important stabilizer of the patella [15,16,17]. The number of medial patellofemoral ligament reconstruction has increased significantly in the last 2 decades, and the anatomy of this ligament has come into focus, as the number of techniques increases.

The contribution of the medial patellofemoral ligament is only half of the total restraint to lateral patellar displacement [15,16,17,18,19,20]. The other structures that stabilize the patella medially are the medial patellotibial ligament (MPTL) and medial patellomeniscal ligament (MPML) [18,19,21,22].

Warren and Marshall [23] described the medial patellofemoral ligament as a condensation of fibers extending from the medial epicondyle to the superomedial patella. Conlan et al [15] identified the fibers that inserted on the undersurface of the distal quadriceps. These fibers have been identified in more recent studies about reconstructive techniques, and are now referred to as the as medial quadriceps tendon femoral ligament (MQTFL) [24,25,26,27]. The combination of all medial soft tissue restraints is often called the medial patellofemoral complex.

Proximal Soft Tissue Stabilizers

1. MPFL

The femoral origin of the medial patellofemoral ligament has been widely studied since an accurate anatomical tunnel placement is of outmost importance for a successful reconstruction. The origin is mostly described as in the region of the adductor tubercle and medial epicondyle [28]. Several anatomic studies of the medial patellofemoral ligament describe this ligament as having a small femoral origin and a wide, fan-shaped insertion on the patella and quadriceps tendon [15,16,18,24,25,27,29].

Some authors indicated that the femoral origin is more of a "cloud" and not a"point" [30].

2. MPFC

Since the patellar side attachment of the medial patellofemoral ligament occurs not only in the patella but in the quadriceps tendon some authors refer to this ligament as the medial patellofemoral complex [24].

Mochizuki et al [25] found that the proximal fibers of the medial patellofemoral ligament attached to the vastus intermedius and vastus medialis..

3. MQTFL

Tanaka [29] reported in a series of 28 cadaveric knees that most ligaments attached to the patella and quadriceps tendon, with a variability of the number of fibers attaching to each structure.

Fulkerson and Edgar have described the reconstruction technique of the MQTFL, recreating the proximal fibers to the quadriceps tendon.

Distal Soft Tissue Stabilizers

The 2 distal soft tissue stabilizers are the medial patello tibial ligament (MPTL), and the medial patello meniscal ligament (MPML), originating from the distal patella [15,16,18,21-27,31,32,33,34]. Both of these ligaments converge to insert on the same location on the inferomedial patella [22].

1. MPTL

The MPTL originated on the inferomedial patella 3,6mm proximal to the distal border of the patella inferior pole [15] and inserts 14 to 15mm distal from the joint line on the anteromedial tibia [35-42]. It is a thin ligament in Layer 2 that serves as a capsular reinforcement and condensation of the medial retinaculum that serves to resist lateral and anterolateral translation of the patella [15,17].

2. MPML

The MPML has a narrow origin of 3-5mm on the inferomedial patella, at a point described as 5.7mm proximal to the distal border of the patella [15,18,35]. It has a “close relation to the infrapatellar fat pad,” and a wide attachment to the anterior horn of the medial meniscus. Hinckel et al noted that this meniscal attachment was variable. In 7/9 cases the MPML attached to the anterior horn, while in 2 cases, it attached to the area between the anterior horn and body. Others have reported attachments distal to the coronary ligament on the tibia.

The role of reconstructing the distal soft tissue restraints that include the MPTL and MPML, and the indications for such, are still unclear. Biomechanical studies show that they function to reduce lateral patellar translation and tilt in greater angles of knee flexion than the MPFL, indicating a potential role for types of dislocation that occur in flexion rather than extension.

5. MEDIAL PATELLOFEMORAL LIGAMENT: SURGICAL TECHNIQUES

More than 100 surgical procedures have been described for treatment of patellar instability [43,44]. This indicates that no single technique is superior. We can classify these techniques in static techniques where the plasty is fixed on bone in the patellar and femoral side, and dynamic, where one of the fixations either patellar or femoral is a soft tissue fixation.

STATIC TECHNIQUES

Many different techniques for MPFL reconstruction have been described. All of them aim to provide tendinous tissue from the medial side of the patella to the anatomic insertion site of the natural MPFL at the adductor tubercle of the medial femoral condyle, in order to reconstruct the ligament.

Many sources of tendon have been described, gracilis and semitendinousus mainly, but also partial thickness quadriceps, vastus medialis retinaculum, allografts and artificial tendons.

The tendon can be fixed to the patella by means of bone anchors as described by Schoettle [45]. The plasty is then fixed to the medial femoral condyle with an interference screw.

A very important aspect of a medial patellofemoral reconstruction is achieving isometry. Identifying the anatomic insertion on the ligament in the femur allows the surgeon to find a good isometry consistently. The isometric point at the femoral condyle is usually located just distal to the adductor tubercle [46]. However an isometry test is always performed before drilling the femoral tunnel.

It is also important not to overtension the plasty as this will lead to osteoarthritis of the patellofemoral cartilage.

In general, static MPFL reconstructions have achieved very good patella stability and choice of graft and technique does not seem to influence the clinical results.

DYNAMIC TECHNIQUES

1. Soft tissue femoral fixation

This technique described by Monllau et al [47], uses the gracilis tendon. The tendon should measure at least 180mm. The tendon is fixed to the patella through a V shaped 4,5mm tunnel, 2 convergent tunnels are drilled with a cortical bridge of 10mm.

For the femoral fixation we use the adductor magnus tendon, located proximally to the medial femoral epicondyle. The incision is made in line with the medial intermuscular septum, and after incising the adductor fascia, the adductor magnus tendon is identified by finger palpation. The tendon is located in the posteromedial aspect of the femur and attached to the adductor tubercle. The adductor muscle and it hiatus are dissected as distally as possible to be as close the anatomic femoral attachment of the medial patellofemoral ligament.

The graft is passed by means of a looped suture, through the patella bone tunnels, then through the interval between layers 2 and 3 of the medial retinaculum, and the around the adductor tendon that acts as an elastic pulley, and back to the patella. Finally, both graft ends were sutured together at 30° of flexion with no. 0 high-resistance non absorbable sutures, paying special attention to not over tensioning the graft.

This technique is a simple soft tissue procedure, it is inexpensive since no hardware is needed. It is implant free. It can also be used in the pediatric or adolescent cases since no tunnels are drilled on the femoral side, that could injure the physis.

The limitations of this technique, is that it is not an anatomic technique, and there is a small risk of the patella bone bridge fracture.

2. Soft tissue patellar fixation

A potentially catastrophic complication of a patellar fixation, is a patella fracture [48]. These fixation methods can create a stress riser within the patella, leading to reported cases of iatrogenic patella fracture.

Fulkerson et al [49] developed a technique that reproduces the MQTFL, that was described in the anatomy. This attachment to the medial quadriceps is a distinct part of the ligament. The reconstruction graft is secured at the anatomic femoral origin of the MQTFL and brought under the vastus medialis such that it may be woven and attached to the deep distal medial quadriceps tendon to provide a secure, reliable reproduction of the MQTFL and excellent stabilization of the patellofemoral joint without risk of patella fracture. This technique offers an alternative procedure for the surgeon who wishes to avoid patella bone tunnels or intraosseous fixation.

The graft used for this technique is either a semitendinosus autograft or a posterior tibial tendon allograft.

A 5 cm incision is made for the proximal third of the medial patella border to the level of the quadriceps tendon. It is important to visualize the distal quadriceps and vastus medialis obliquus (VMO) tendons. A 1 cm incision is then placed in the vastus medialis tendon at the level of the proximal patella. Two parallel longitudinal 1.5 cm incisions are then made into the central third of the rectus/ intermedius portion of the quadriceps tendon.

A second 5cm incision is made just proximal to the adductor tubercle and extended distally to the epicondyle. The femoral fixation point is determined using the adductor magnus tendon as a key landmark. One then exposes the distal adductor tendon and the proximal medial collateral ligament to confirm the location, taking care to avoid risk of injury to the medial infrapatellar branch of the saphenous nerve and the more posteriorly located saphenous nerve.

An 8-mm socket is then created, 2.5 cm deep. The whipstitched end of the free tendon reconstruction graft is secured into the socket with an interference screw.

For graft passage, a hemostat is placed into the VMO tendon incision and then under the VMO until the tip comes out at the level of the bone socket, the graft is then passed deep to the vastus medialis tendon. The knee is then cycled several times and the draft is secured by drawing it into the slot created by the 2 parallel incisions in the distal quadriceps tendon. The tension is determined by the position of the patella seen under arthroscopy, the goal is to tension the graft in order for the patella to track centrally in the trochlea without any medial subluxation. The graft is marked at the desired position and non absorbable sutures are paced to lock the graft into the medialis and intermedius tendons.

Patella fracture is a serious complication of MPFL reconstruction. Therefore reconstruction of the MQTFL is a prudent alternative to MPFL reconstruction in patients with recurrent patella instability needing restoration of medial retinacular support.

6. MATERIAL AND METHODS

Parametric Finite Element Model of the Patellofemoral Joint

From a previous study [50], high spatial resolution CT data were available from 24 knees of patients with CLPI. Images were acquired with a 64-detector Multi-Detector CT system (Philips Medical Systems, Best, the Netherlands) at the highest spatial resolution, without slice interpolation (0.255x0.255x0.672 mm^3). An iterative thresholding scheme was used to extract bones from the imaging data, and triangulated surfaces were defined to describe the outer surfaces (MIMICS, Materialise NV, Leuven, Belgium). The main characteristics and dimensions considered for the parametric model were measured as a reference. The knee geometry was simplified to construct a 3D parametric model that achieved nearly anatomical geometry with variable parameters. The parameters were measured from CT scans both in the axial plane and using a multi-planar reformatting (MPR) technique. Certain patients were pathological; therefore, the parametric geometry also considered their particular geometry. The main parts of the PFJ parametric model were: the bones of the femur (femoral condyle) and patella as rigid parts as well as the femoral and patellar cartilages as hexahedral deformable components (Figure 1 A-D). As previously stated, each part was simplified to obtain nearly anatomical geometry with variable parameters. The patellar bone was modelled starting from a concave-revolution-solid shape, with the parametric radius and thickness. Several revolution cuts were performed on the solid part, and its final geometry was obtained (Figure 1B). The patellar cartilage was created following the same procedure, while maintaining the patellar dimensions (Figure 1A). The femoral bone was the most complex part of the model. It was defined as a discrete rigid part that had four main elements: a revolution shape that defined the bottom geometry, with a parametric width and radius; a solid loft for the irregular section, with different width and length parametric sections; a revolution shape in the posterior geometry, where the radius can be modified; and two revolution shapes, where the radius, thickness and relative position can be modified, that represent the femoral epicondyles (Figure 1C). The femoral cartilage was defined as deformable, and its generation was based on the femur geometry and consisted of a revolution shape for the bottom geometry and a combination of elements that defined the upper region (Figure 1D). The PFJ parametric model was developed using the software Abaqus/CAE v.6.14 (Dassault Systèmes, France).

From the 24 knees, a mean parametric model was generated. As cartilages cannot be reconstructed correctly from a CT, a fixed thickness of 3 mm was assumed. Tendons and ligaments were also included since they help to stabilize the patella and better distribute patellofemoral pressures (Figure 1E). The quadriceps tendon (QT), which consists of the vastus medialis (VM), vastus lateralis (VL), vastus intermedius (VI), and the rectus femoris (RF) tendons, and the patellar tendon (PT) were modelled as a group of four and two truss elements, respectively (Figure 1E), while the MPFL and the lateral retinaculum (LR) were defined as beam elements (B33) (Figure 1E). The QT was oriented from the insertion site on the patella to the muscle origin or the most distal wrapping point on the femur. The PT was oriented from the distal patella to the tibia [9,13,51]. The tendon and ligament properties were taken from previous studies [9,52,53] and are summarized in Table 1. A radius of 1 mm was assumed for the beam elements. A mesh convergence analysis was performed for the deformable parts, which determined that an element size should be 1 mm, so that the cartilages would have at least three elements along their thickness. Finally, the patellar cartilage was compounded by 5,756 nodes and 4,125 elements, while the femoral cartilage was defined by 24,918 nodes and 18,201 elements. The cartilages were modelled with an elastic modulus of 10 MPa and Poisson's ratio of 0.45 [2,12,27].

The parametric model consists of four surfaces: femoral bone, femoral cartilage, patellar bone and patellar cartilage. Bone-cartilage interactions, i.e., femoral bone with femoral cartilage and patellar bone with patellar cartilage, were defined as a tie constraint. The contact between both cartilage surfaces (femoral cartilage with patellar cartilage) was defined as a surface-to-surface standard contact with a contact adjustment of 0.1, a hard contact for the normal behaviour and a penalty friction formulation with a friction coefficient of 0.02 for the tangential behavior [54].

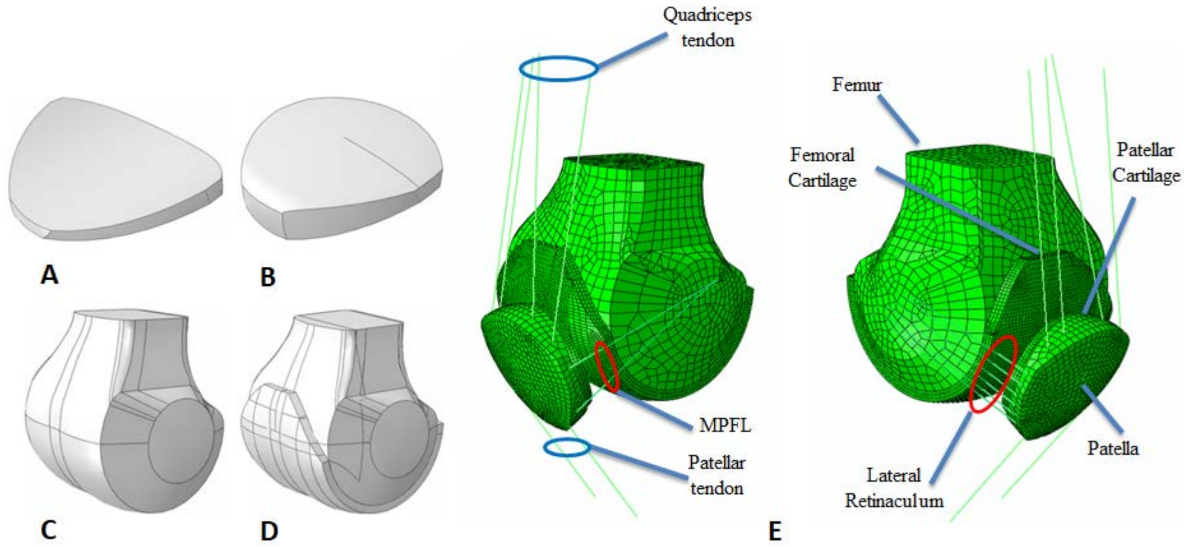


Figure 1. Parametric geometry of the four main parts of the PFJ model: A) Patellar cartilage; B) patellar bone; C) femoral bone; D) femoral cartilage; E) final model reconstruction including the joint ligaments and tendons.

Material Properties		
	Stiffness (N/mm)	Poisson Ratio
Quadriceps Tendon (QT)	1350	0,3
Patellar Tendon (PT)	2000	0,3
Lateral Retinaculum (LR)	2	0,3
Native Medial Patellofemoral Ligament (MPFL)	12	0,3
MPFL Reconstruction (Semitendinosus Graft)	100	0,3
MPFL Reconstruction (Gracilis Graft)	80	0,3
MPFL Reconstruction (Quadriceps Tendon Graft)	33.6	0,3

Table 1. Material properties considered for ligaments and tendons in the FEM simulation.

MPFL Reconstruction Techniques

Three types of MPFL double bundle semitendinosus reconstruction with patellar and femoral bony attachment were simulated based on a previous study [50]: anatomic reconstruction, meaning a reconstruction with a femoral anatomic fixation point (Figure 2A); non-anatomic but physiometric reconstruction, meaning the femoral fixation point is not anatomic, but behaves kinematically like a native MPFL (Figure 2B); and non-anatomic and non physiometric reconstruction (Figure 2C). For this last type of reconstruction, the femoral fixation point is too anterior, which means the ligament is too short and that it behaves kinematically in the opposite manner of a native ligament [50].

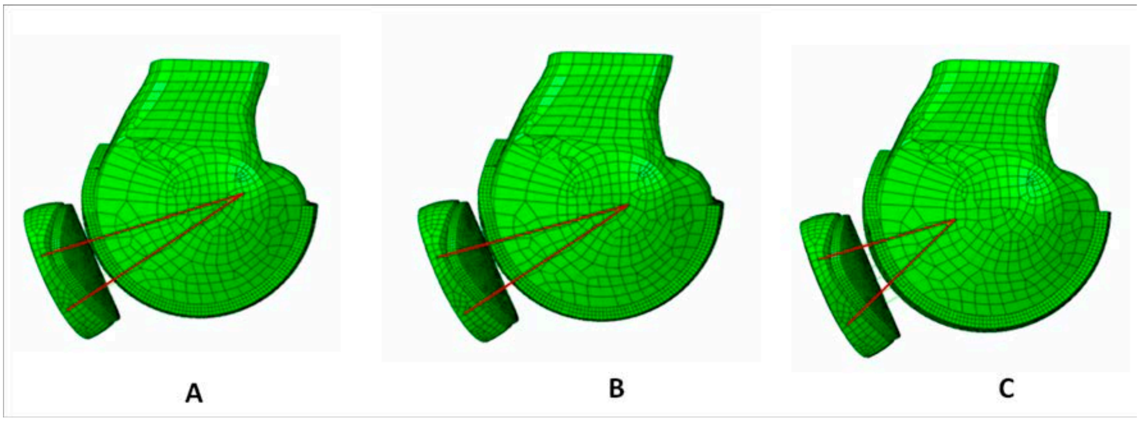


Figure 2. A) Reconstruction with a patellar bone fixation point and an anatomic femoral fixation point. B) Reconstruction with a patellar bone fixation point and a non-anatomic femoral fixation point that has physiometric behaviour. C) Reconstruction with a patellar bone fixation point and a femoral fixation point that is too far anterior and without physiometric behaviour.

Simulation of the Different Surgical Techniques

The three surgical techniques were analysed for 5 knee flexion positions: 0º, 30º, 60º, 90º and 120º, as in a previous dynamic CT scan study [50]. Initially, for all of the surgical techniques, the patellar group (bone and cartilage) was not in contact with the femoral group (bone and cartilage) to avoid non-desirable initial contact problems. The patella was initially aligned with the trochlear groove using the CT images. A perpendicular displacement (approximately 0.5 mm) to the femoral cartilage surface was imposed upon the patella. Once the contact between both cartilages was generated, the ligaments and tendons were included and the three surgical MPFL reconstruction techniques were analysed. The elements representing the QT and PT were then fixed so that the model was in equilibrium and no forces were applied through them. The initial contact pressures were removed to compare the different surgical techniques under the same conditions. Therefore, the results are presented in terms of relative contact pressures, which we subsequently refer to as the contact pressure. The femur position was fixed once every knee flexion position was simulated.

The data considered for the MPFL inclusion were taken from a previous study [50]. Table 2 summarizes the mean distance between the patella and femoral insertion points for the different MPFL reconstructions. Based on these data, the nodes of insertion for each technique and the elongation suffered by the ligaments were determined. The reference position, where the ligaments did not experience any strain, was considered at a knee flexion of 40º. The average MPFL lengths were considered in this part of the study and were the loading conditions incorporated into the model.

The average length of the MPFL for each surgical technique was analysed (Table 2), indicating that in some knee flexion positions, the distance between the femur and patella insertion points was smaller than the reference distance (40º), which means that the ligament is not experiencing any type of stress. Thus, analysis of certain positions was not necessary (Table 2, cases indicated by *). In the remaining positions, two different types of simulations were performed. First, in certain positions, the MPFL undergoes an elongation, which is simulated by applying a pretension force, $\Delta l * K$, where Δl is the length increment and K is the stiffness of the ligament (Table 2, cases indicated by $^{+}$). Second, several positions showed an MPFL length that was only possible if the cartilage was compressed because the relative position between the patella and femoral insertion point was further than the reference position (40º). As the ligaments were represented by only-tension elements, this relative position change was simulated with a temperature increment equal to $\Delta l / l_{0_{MPFL}} * \alpha_{MPFL}$, where Δl is the length increment, $l_{0_{MPFL}}$ is the initial length of the MPFL and α_{MPFL} is the assumed thermal dilatation coefficient of the MPFL (0.0005 ºC^{-1}). This type of simulation allows cartilages to be modelled in a compressed state that maintains the ligament stress. Equilibrium on both sides of the joint was preserved assuming the same Δl for the LR ligament and with the inclusion of the α_{LR} coefficient for the LR, calculated as $\Delta l/\Delta T * l_{0_{LR}}$ (Table 2, cases indicated by $^{\Diamond}$), because ΔT was the same for the entire model. This was an iterative process in which ΔT was recalculated until the desired length of the MPFL was achieved.

	Anatomic MPFL Reconstruction		Non-anatomic MPFL Reconstruction with Physiometric Behaviour		Non-Anatomic MPFL Reconstruction but Non-Physiometric	
Flexion Angle (º)	Length (mm)	SD (mm)	Length (mm)	SD (mm)	Length (mm)	SD (mm)
0	60,2^{+}	± 6,1	51,6^{+}	± 4,6	37,5^{+}	± 7,8
30	57,9^{+}	± 6,8	50,8^{+}	± 5,4	36,5^{+}	± 9,2
40	57,7	± 6,0	48,8	± 5,0	36,2$^{\Diamond}$	± 8,1
60	57,3*	± 6,4	44,9*	± 5,2	35,7$^{\Diamond}$	± 10,1
90	55,6*	± 5,7	38,3*	± 4,9	35,6$^{\Diamond}$	± 7,9
120	50,7*	± 4,9	33,7*	± 4,8	35,4$^{\Diamond}$	± 5,6

Table 2. Distance between the patellar and femoral insertion points for the analysed MPFL reconstruction techniques. (* No tension, $^{+}$Tension type 1, $^{\Diamond}$Tension type 2). The MPFL with a non-anatomical femoral attachment point with satisfactory results is always physiometric. The MPFL with a non-anatomical femoral attachment point with non-satisfactory results is always non-physiometric.

Clinical Validation of the Parametric Model

Five patient-specific cases were used for clinical validation of our parametric model. The PFJ parametric model was applied to simulate five patient-specific cases. The geometry of each patient was generated by modifying the main parameters of the parametric model. MPFL reconstruction was simulated depending on patient-specific data. The graft insertion points were based on each patient's geometry with the help of the corresponding CT data. Each patient underwent a different type of MPFL reconstruction. Each specific case was simulated taking into account the surgeon's MPFL measurements, as indicated in Table 3. Moreover, all five cases were clinically evaluated by one of the authors (V S-A).

		Measured length for each position (mm)					
Case	Graft Material Configuration	0º	30º	40º	60º	90º	120º
1 Non-Anatomic Femoral Attachment point with Non-Satisfactory Result	Semitendinosus SB	36,3*	35,9*	36,83	38,7^{+}	43,7^{+}	46,3^{+}
2 Non-Anatomic Femoral Attachment Point with Non-Satisfactory Result	Semitendinosus DB (Proximal)	23,1*	33,3*	36,33^{+}	42,4^{+}	46,6^{+}	48,6^{+}
	Semitendinosus DB (Distal)	25,4*	39,7*	42,77^{+}	48,9^{+}	54,3^{+}	54,8^{+}
3 Non-Anatomic Femoral Attachment Point with Non-Satisfactory Result	Quadriceps Tendon SB	56,2^{+}	46,8^{+}	43,03	35,5*	24,2*	22,4*
4 Anatomic Femoral Attachment Point with Satisfactory Result	Semitendinosus DB (Proximal)	52,2^{+}	51,1^{+}	50,17	48,3*	41,3*	35*
	Semitendinosus DB (Distal)	49,9^{+}	49,7^{+}	48,37	45,7*	39,7*	35,1*
5 Anatomic Femoral Attachment Point with Satisfactory Result	Semitendinosus DB (Proximal)	56,4^{+}	57^{+}	55,07	51,2*	46,9*	42,3*
	Semitendinosus DB (Distal)	55,1	56^{+}	54,17	50,5*	45,8*	41,9*

Table 3. Patient-specific data for the model validation. (* No tension, $^{+}$Tension type 1) (SB = Single Bundle, DB = Double Bundle). Cases # 1, 2 and 3 are non-anatomic and non-physiometric.

7. RESULTS

In a native knee, with an intact MPFL, that was used as a reference for the comparison among different reconstruction techniques, the maximum patellar cartilage contact pressures at 60, 90 and 120º were very low compared to the pressures at 0 and 30º. An increase in the patella contact pressure at 0° and 30° of knee flexion was observed after both anatomic and a non-anatomic MPFLr with physiometric behaviour. Finally, the non-anatomic MPFL reconstruction with non-physiometric behaviour predicted the contact pressures in all of the knee flexion positions. The maximum patellar cartilage contact pressures are displayed in Figure 3.

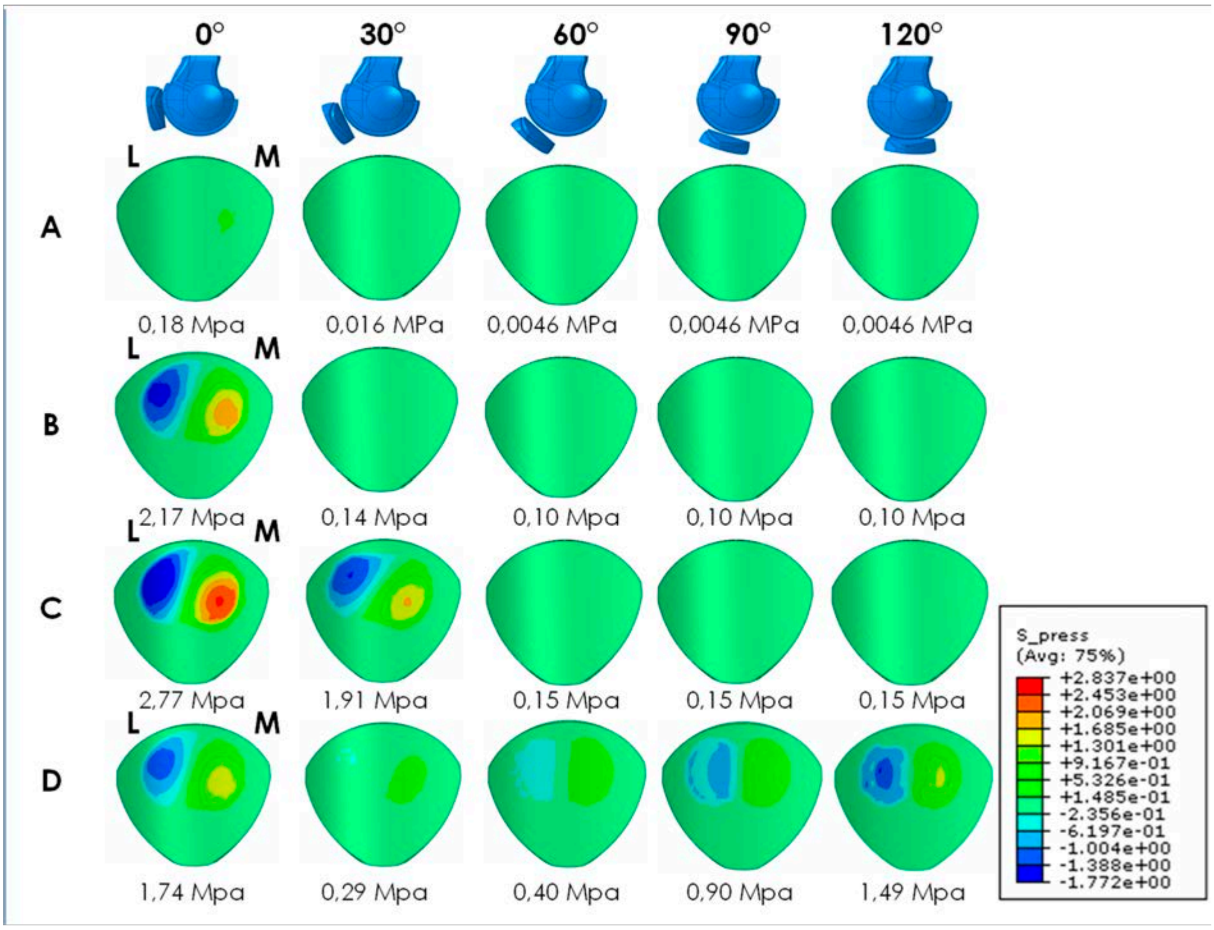


Figure 3. Patellar cartilage contact pressure (MPa): A) Native knee. B) Anatomic MPFL reconstruction. C) Non-anatomic MPFL reconstruction with physiometric behaviour. D) Non-anatomic MPFL reconstruction with a femoral fixation that is too far anterior and without physiometric behaviour (M-medial; L-Lateral).

In a native knee, both the MPFL and LR are under tension at 0º and 30º of knee flexion. At 60, 90 and 120º both the MPFL and LR were loose. In both the anatomic and a non-anatomic MPFLr with physiometric behaviour, the ligament was tense between 0° and 30° of knee flexion, but at 60, 90 and 120°, it had no tension. In the non-anatomic with non-physiometric behaviour reconstruction, the MPFL was tense at 60, 90 and 120° of knee flexion and was completely loose at 0 and 30° of knee flexion. The MPFL and LR maximum stresses are displayed in Table 4.

	Maximum MPFL Stress (MPa)					Maximun LR Stress (MPa)				
	0º	30º	60º	90º	120º	0º	30º	60º	90º	120º
A	8.85	0.78	0	0	0	1.52	0.15	0	0	0
B	74.72	6.55	0	0	0	1.51	0.14	0	0	0
C	97.02	69.60	0	0	0	1.66	1.10	0	0	0
D	63.44	14.74	46.71	77.57	92.70	0.78	0.17	1.24	2.09	2.51

Table 4. MPFL and LR stress. A) Native knee. B) Anatomic MPFL reconstruction with semitendinosus. C) Non-anatomic MPFL reconstruction with physiometric behaviour. D) Non-anatomic MPFL reconstruction with a femoral fixation that is too far anterior and without physiometric behaviour.

The following cases demonstrate the sensitivity and possible clinical implications of the use of a parametric model of the PFJ using FEM to evaluate MPFL reconstructions.

Case # 1 (Figure 4 and Table 5). A 17-year-old man was operated on for lateral patellar instability using a single semitendinosus bundle MPFL graft. The patient expressed persistent lateral patellar instability and severe pain. The simulation predicted a contact pressure on the patellar cartilage of 1.19MPa for 60º of knee flexion, 2.25 MPa for the 90º position, and an important contact pressure of 5.84 MPa for 120º of knee flexion (Figure 4). The maximum MPFL stress at 60º was 59.03 MPa; at 90º, it was 119.2 MPa and at 120º, it was of 252 MPa. At 0 and 30º, the MPFL was loose. The maximum lateral retinaculum (LR) stress at 60º was 1.62 MPa; at 90º, it was 5.38 MPa and at 120º, it was 7.06 MPa. At 0 and 30º, the LR was loose. From these data we predicted that the patient would develop patellar chondropathy, which was in fact seen during the arthroscopy performed during the MPFL revision surgery (Figure 4D). The tension pattern of the MPFL graft is typically seen in a non-anatomic femoral fixation point that is too far anterior in which the graft exhibits non-physiometric behaviour. This can be very clearly seen in the latest preoperative 3D CT (Figure 4C).

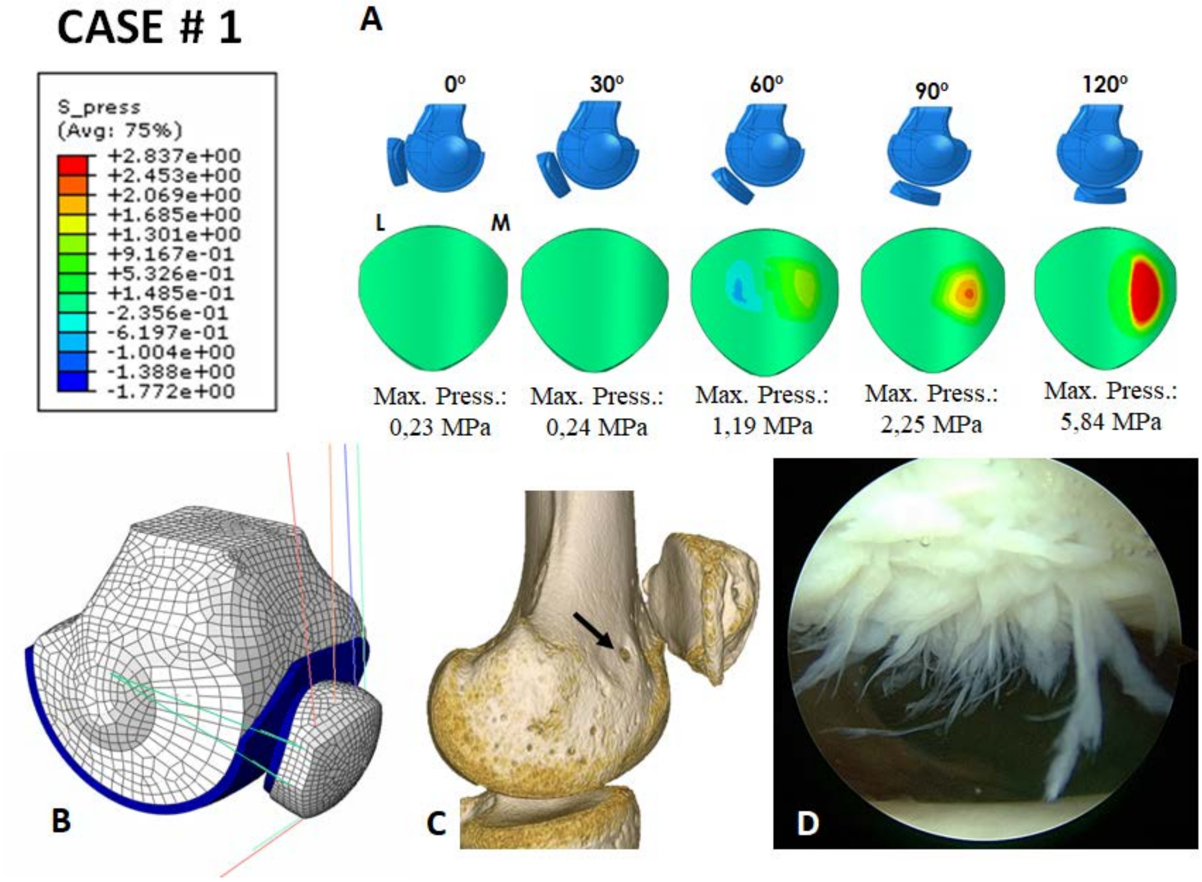


Figure 4. Case # 1 Surgical failure: A) Contact pressure (MPa) on the patellar cartilage. B) Parametric model of patient # 1. C) Femoral attachment point is too far anterior (black arrow). D) Visible patellar chondropathy during arthroscopy.

Case # 2 (Figure 5 and Table 5). A 28-year-old woman operated on for lateral patellar instability with a double bundle MPFL plasty, using the semitendinosus. The patient complained of severe pain and incapacitating lateral patellar instability. The simulation predicted higher contact pressures than in the previous simulation: 6.17 MPa for the 60º knee flexion position, 5.18 MPa for the 90º knee flexion position and 7.13 MPa for the 120º knee flexion position (Figure 5). The maximum MPFL stress at 60º was 19.51 MPa; at 90º, it was 29.52 MPa and at 120º, it was of 34.7 MPa. At 0 and 30º the MPFL was loose. The maximum LR stress at 60º was 4.56 MPa; at 90º, it was 7.54 MPa and at 120º, 8.37 MPa. At 0 and 30º, the LR was loose. The MPFL was tense at 60, 90 and 120° of knee flexion and was completely loose at 0 and 30° of knee flexion. Clinically, this tension pattern will lead to PFOA, which was in fact seen during surgery (Figure 5D). This tension pattern is typical of a non-anatomic femoral fixation point that is far too anterior, as clearly seen in the 3D CT in which the graft exhibits non-physiometric behaviour (Figure 5C).

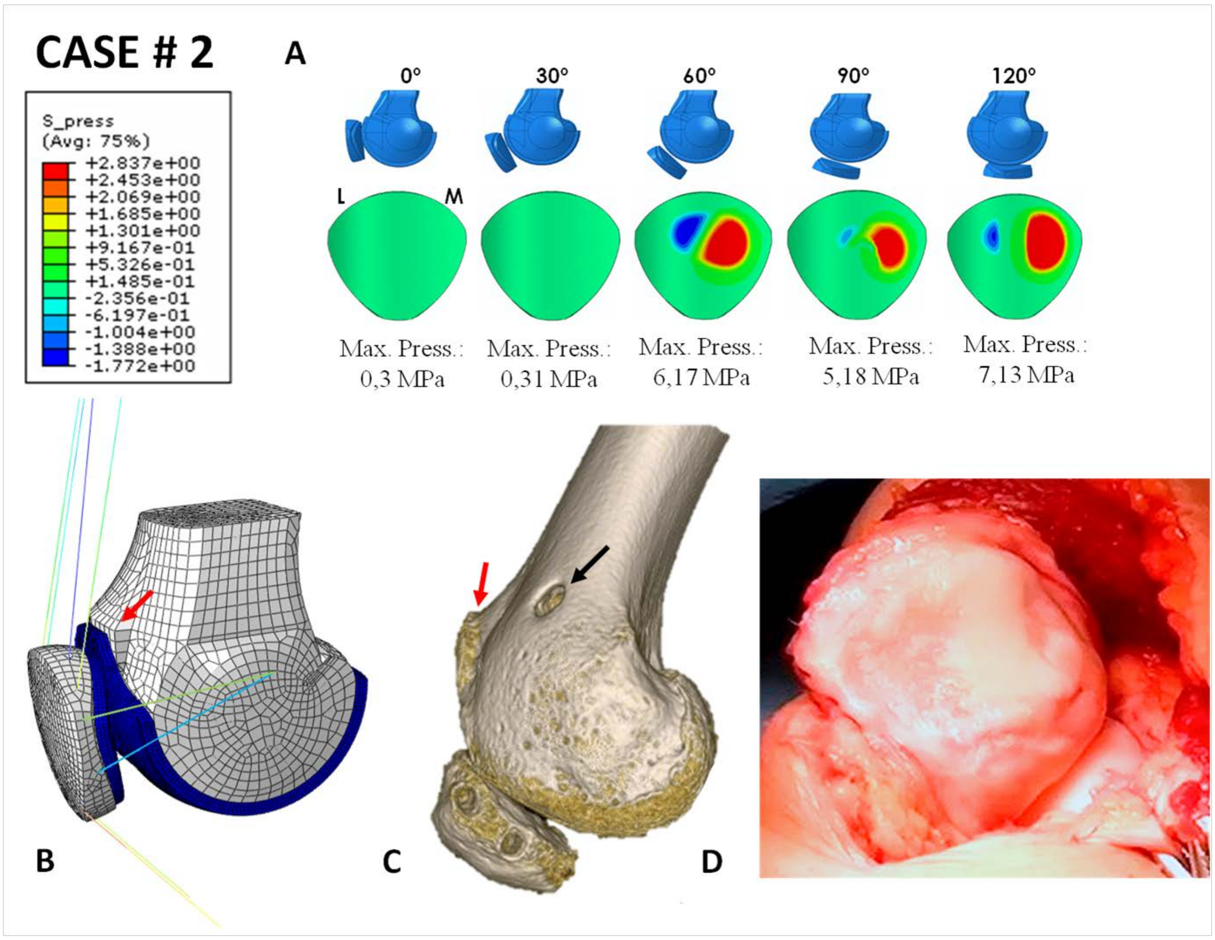


Figure 5. Case # 2 Surgical failure: A) Contact pressure (MPa) on the patellar cartilage. B) Parametric model of patient # 2. Trochlear dysplasia type D. C) Superior femoral attachment point is too far anterior (black arrow). D) Visible patellofemoral osteoarthritis.

Case # 3 (Figure 6 and Table 5). A 38-year-old woman was operated on for lateral patellar instability with an MPFL single bundle plasty using the quadriceps tendon. The patient complained of severe pain and incapacitating lateral patellar instability. The simulation performed with our FEM showed patellofemoral contact pressures far below those found in a native knee (Figure 6A). The maximum MPFL and LR stresses predicted for the 0º knee flexion position were 12.28 MPa and 8.22 MPa, respectively, and for 30º 3.93 MPa and 2.68 MPa, respectively. The prediction fulfils the requirements for an effective MPFL reconstruction: A tense graft at 0 and 30° of knee flexion with a clearly higher stress to failure than a native MPFL, but without increasing the patellofemoral pressure above the values that could cause symptomatic PFOA. In fact, no chondropathy was seen in this patient during the arthroscopy performed in the revision surgery (Figure 6D).

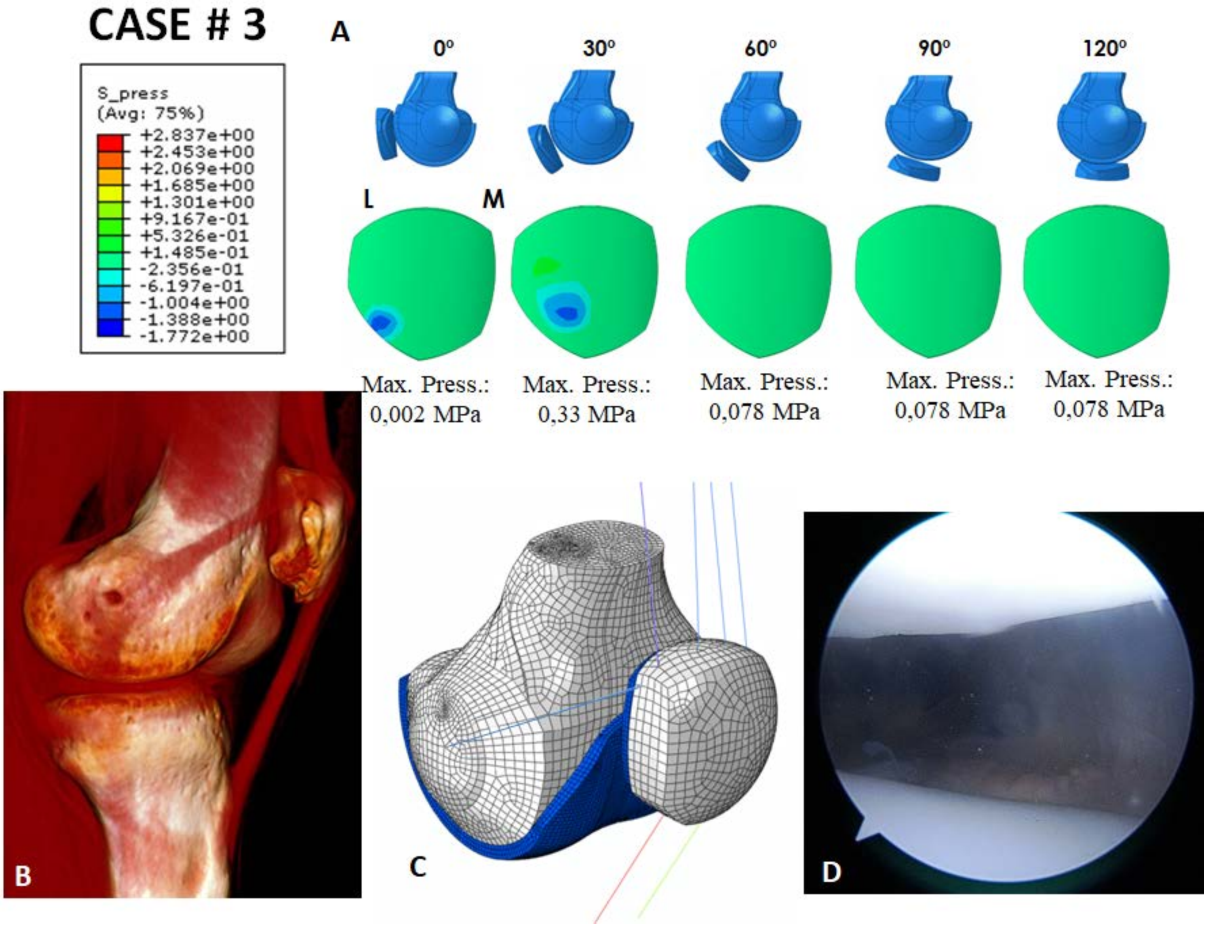


Figure 6. Case # 3 Surgical failure: A) Contact pressure (MPa) on the patellar cartilage. B) One can see that the graft is preserved; however, the orientation is too oblique and extremely vertical. C) Parametric model of patient # 3. D) Arthroscopy at the time of the revision surgery shows a normal patellofemoral cartilage.

Case # 4 (Figure 7 and Table 5). A 18-year-old woman was operated on for lateral patellar instability with an anatomic MPFL reconstruction using a double bundle semitendinosus autograft, with an excellent clinical result at 5 years of follow up. The simulation predicted a contact pressure of 0.2 MPa at 0º of knee flexion and 0.91 MPa at 30º of knee flexion. The maximum MPFL and LR stresses predicted for the 30º of knee flexion position were 29.47 MPa and 0.79 MPa, respectively, and for 0º of knee flexion, they were 60.02 MPa and 1.15 MPa, respectively. The prediction fulfils the requirements for an ideal MPFL reconstruction: A tense graft at 0 and 30° of knee flexion with a far higher stress to failure than a native ligament, but without increasing the patellofemoral pressure above the values that could cause symptomatic PFOA. This tension pattern is typical of an anatomic femoral fixation point as clearly is seen in the 3D CT (Figure 7C).

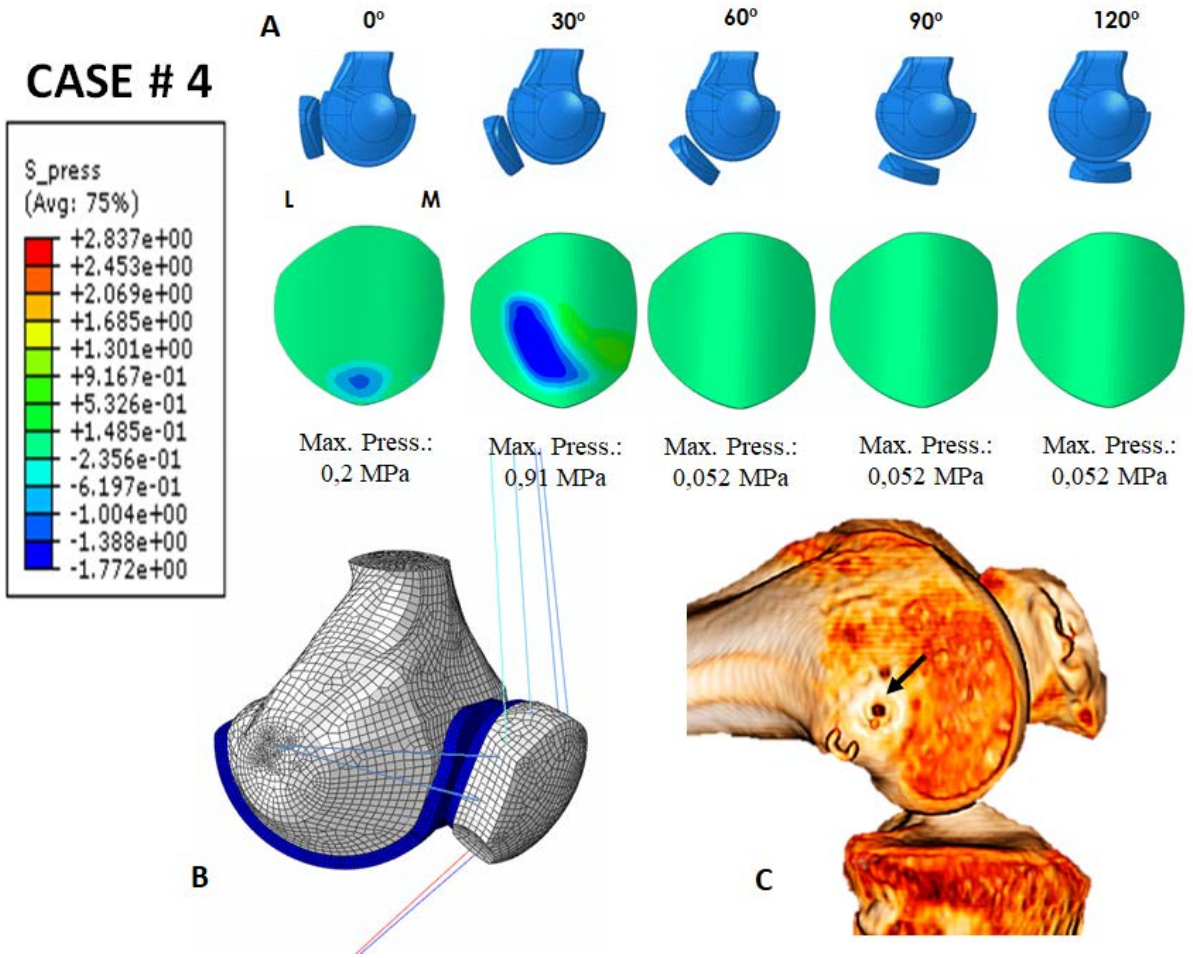


Figure 7. Case # 4 Primary surgery with an excellent result: A) Contact pressure (MPa) on the patellar cartilage. B) Parametric model of patient # 4. C) Anatomic femoral attachment point (black arrow).

Case # 5 (Figure 8 and Table 5). A 15-year-old woman was operated on for lateral patellar instability with an anatomic MPFL reconstruction using a double bundle semitendinosus autograft, with an excellent clinical result at 5 years of follow up. The simulation predicted a contact pressure of 1.57 MPa for 0º of knee flexion position and 1.63 MPa for 30º of knee flexion position. The maximum MPFL and LR stresses predicted for the 30º knee flexion position were 70.3 MPa and 1.27 MPa, respectively, and at 0º of knee flexion, they were 40.24 MPa and 0.53 MPa, respectively. The prediction fulfils the requirements for an ideal MPFL reconstruction: A tense graft at 0 and 30° of knee flexion with a far higher stress to failure than a native ligament, but without increasing the patellofemoral pressure above the values that could cause a symptomatic PFOA. This tension pattern is typical of an anatomic femoral fixation point as clearly is seen in the 3D CT (Figure 8C).

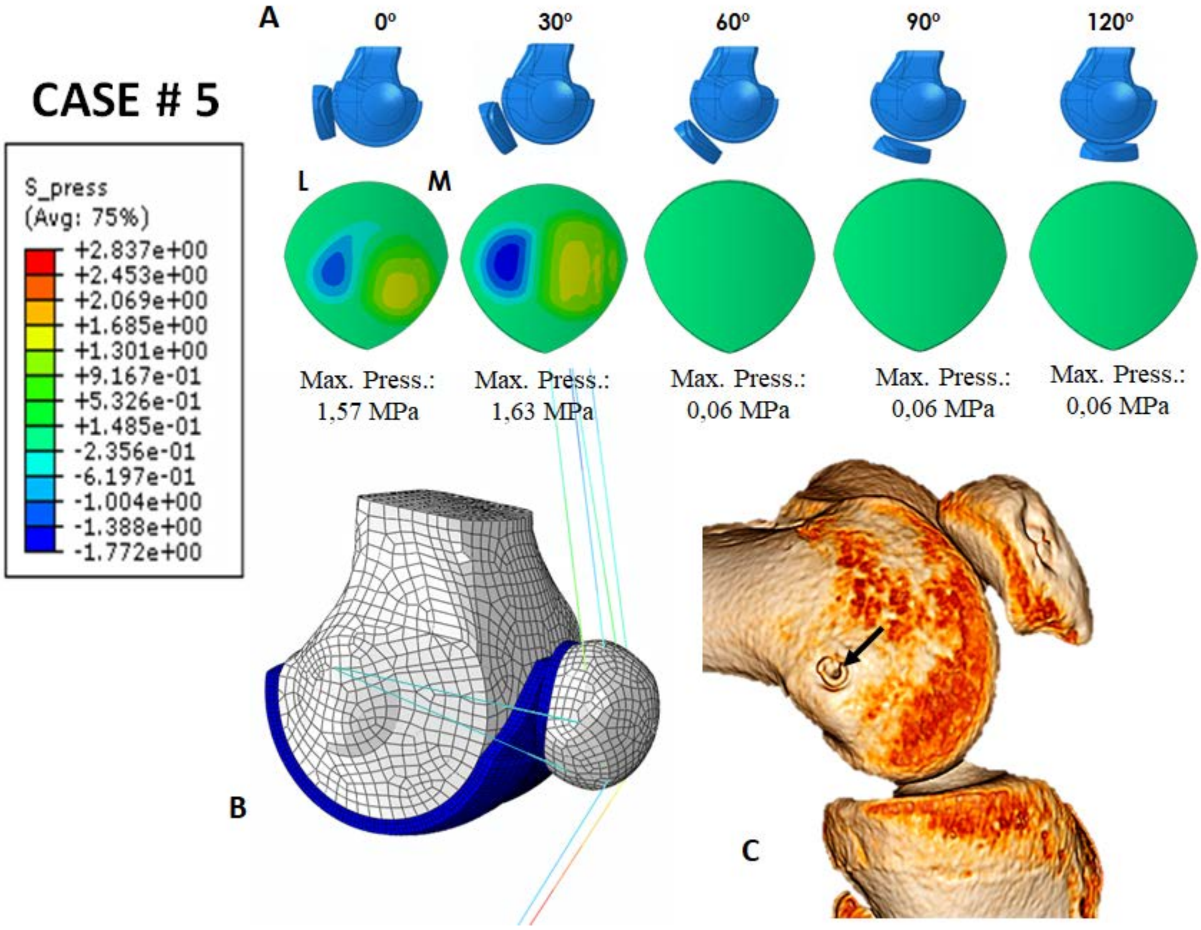


Figure 8. Case # 5 Primary surgery with an excellent result: A) Contact pressure (MPa) on the patella cartilage. B) Parametric model of patient # 5. C) Anatomic femoral attachment point (black arrow).

Our FEM was very accurate in cases 1, 2, 4 and 5, but not in case 3. Case 3 fulfilled the requirement for a correct plasty regarding the maximum stress and patellofemoral pressure. However, the patient had pain and instability after surgery. The instability could be explained by the single bundle plasty configuration, vertical direction of the plasty because of the nonanatomic femoral fixation point (Figure 6B), the patella alta, which makes this graft ineffective. All of these factors can contribute to instability and therefore to pain.

Case	Flexion Angle (º)	MPFL stress (MPa)	LR stress (MPa)
1	60	59,03	1,62
	90	119,20	5,38
	120	252,00	7,06
2	60	19,51	4,56
	90	29,52	7,54
	120	34,7	8,37
3	0	12,28	8,22
	30	3,93	2,68
4	0	60,02	1,15
	30	29,47	0,79
5	0	40,24	0,53
	30	70,30	1,27

Table 5. MPFL and LR ligaments stress obtained for each reconstruction and position analysed.

8. DISCUSSION

Our model is the first parametric 3D FEM of the PFJ analyses the effect of different MPFL reconstructions on the patella contact pressure as well as on the kinematic behaviour of the MPFL-graft and MPFL-graft stress along the total range of knee motion.

Our findings using the FEM are in agreement with those reported in previous studies and could have meaningful potential implications for clinicians performing MPFL reconstruction surgery [9,50,55,56,57,58]. Various authors have demonstrated that the changes in the length of a ligament that occur during joint flexion-extension show changes in the tension of that ligament [50,59,60,61,62]. Based on this observation, in a previous study using a dynamic CT scan, we concluded that the native MPFL was tense during the first 30º of knee flexion in all cases and after 30º was progressively not tense [50]. The explanation behind this affirmation lies in the fact that the attachment points of the MPFL are separated further during the first 30º of knee flexion and become progressively closer from 30º onwards. We called this the physiometric behaviour of the ligament. Our current study enabled us to directly confirm these findings. The ligament is tense between 0° and 30° of knee flexion, but at 60, 90 and 120°, it has no tension. This fact has clinical relevance as the MPFL is a structure that is only involved in the lateral stability of the patella during the first 30º of knee flexion. After 30º, the ligament loosens and the patellofemoral contact pressure, which also contributes somewhat to patellofemoral stability and is already low during the first 30º (0.23 MPa), decrease considerably (0.0046 MPa). This finding is in agreement with several anatomic and biomechanical studies that show that the MPFL is the most important restraint to lateral patellar displacement from 0º to 30º of knee flexion [55,56,57]. After 30º of knee flexion, the lateral patella stability depends on the femoral trochlea. Additionally, our study confirms previous findings that show that the location of the femoral attachment point is of utmost importance to obtain satisfactory clinical results [50]. The femoral attachment point is related to the patellofemoral contact pressure, tension of the MPFL-graft and physiometry of the reconstruction.

The ideal MPFL reconstruction technique must combine a precise balance between an optimal patellofemoral pressure with the maximum graft stress, which makes a new tear less likely. We must reproduce the patellofemoral contact pressure of a virgin knee and create a maximum MPFL-graft stress greater than that of the native MPFL with the intention of compensating for the anatomic factors (increased tibial tuberosity – trochlear groove (TT-TG) distance, patella alta and trochlear dysplasia) which predispose lateral patellar dislocation [3]. In fact, the maximum MPFL-graft stress in both anatomic and non-anatomic but physiometric reconstructions is much greater than that of a native MPFL. However, it is very important to not increase maximum MPFL-graft stress by increasing the patellofemoral pressure because in the short term, the technique will have a suitable result, but in the long term, it will not be effective for the joint. MPFL reconstruction evaluation by means of the FEM is more sensitive than evaluations using only clinical or radiological tests. The FEM is able to demonstrate the validity of a surgical technique in the long term since it enables one to determine whether a specific technique will lead to an increase in the patellofemoral pressure, which is closely related to future development of PFOA in the future. The elevated MPFL graft tension or an incorrect femoral tunnel position will increase the pressure applied to patellofemoral cartilage [63,64], and this increase of the PFJ contact pressure could result in joint degeneration [10,11]. Rood et al. [50] have shown that static MPFL reconstructions (i.e., reconstruction with both femoral and patellar osseous attachments) result in higher patellofemoral pressures compared with those in the intact situation and thus enhance the chance of PFOA in the long term.

The current tendency is to perform MPFL reconstructions with an anatomic femoral bone attachment and patellar bone attachment. In our study, we observed an increase in the patellofemoral contact pressure at 0° and 30° of knee flexion after an MPFL reconstruction (2.17 MPa at 0º and 0.14 MPa at 30º when using the semitendinosus as a graft) compared to the pressure found in a normal non-operated knee (0.18 MPa at 0º and 0.016 MPa at 30º). This leads us to consider the possible long-term effects from a slightly higher patellofemoral contact pressure. However, in theory, the patellofemoral contact pressures found in the anatomic reconstructions are not high enough to cause symptomatic PFOA since they are lower than those causing knee osteoarthritis [65]. The objective would be to not exceed the safety levels of patellofemoral pressure to induce patellofemoral chondropathy and ultimately PFOA. We should also remember that the increase in the patellofemoral contact pressure helps to stabilize the PFJ. Therefore, this factor would be beneficial in the classical anatomic reconstruction. Thus, a discrete increase in contact pressure, as we have observed, is desirable.

Currently, we are discussing the precise consequences of the clinical results of the non-anatomical techniques for the MPFL reconstruction in which the MPFL reconstruction behaves like a native MPFL (physiometric behaviour) from the physiological point of view. Servien et al. [58] found no negative clinical effects after two years when using these reconstructions. These findings also agree with our preivious findings [50], which could be due to the short follow-up in both cases. In this type of reconstruction, the FEM shows an increase in the patellofemoral contact pressure at 0 º and 30º of knee flexion in comparison to these pressures in the native knee (2.77 MPa at 0º and 1.91 MPa at 30º vs 0.18 MPa at 0º and 0.016 MPa at 30º). This pressure increase mainly occurs in the medial patellar facet. According to Jones et al. [66], the average contact stress at 30º is 1.7±0.6 MPa, with a peak of 3.2±0.6 at the surface of the patellar cartilage and of 2.8±0.7 at the deep. What we do not know is whether this pressure increase will result in chondropathy in the long-term and ultimately result in symptomatic PFOA. As far as we know, there is no study of the PFJ that has determined the contact stress threshold that is predictive of symptomatic PFOA. Segal et al. [65] observed that a threshold of 3.42 to 3.61 MPa had a 73.3% sensitivity with a specificity ranging from 46.7% to 66.7% for the prediction of symptomatic knee osteoarthritis. Obviously, these values cannot be extrapolated to the PFJ, which is the joint with the thickest cartilage in the human body. It is logical to think that the pressures causing symptomatic PFOA would be higher. In the non-anatomical MPFL reconstructions, the maximum patellofemoral contact pressures are in the order of 2.77 MPa, values that are considerably below the cut-off point mentioned above. Therefore, it is likely that a non-anatomical but physiometric reconstruction would not have long-term negative effects on the PFJ. Therefore, it would seem more important for the ligament to be "physiometric" rather than perfectly anatomical.

With the FEM, we are able to predict which MPFL reconstruction will cause severe patellofemoral chondropathy, resulting in symptomatic PFOA and requiring active treatment. In the cases in which PFOA occurred, it was because the MPFL-graft was loose, with knee flexion from 0º to 30º, and was tense from 60º onward. In these cases, the patellofemoral contact pressures were over 5 MPa from 60º onward. In all of these cases, the femoral attachment point was extremely non-anatomical (too far anterior) and the MPFL reconstruction was not physiometric. This predictive value of our parametric model of the PFJ has made the clinical validation of our model possible.

A limitation of this study is that the patellar and femoral cartilages had a constant thickness of approximately 3mm. The PFJ was reconstructed from CT data in which soft tissues are not clearly distinguished. However, the gap between both bones was approximately 6 mm ; therefore, the same thickness for both cartilages was assumed. Small differences would have been predicted if other thickness values had been considered. Additionally, the ligament material properties were taken from the literature [9,52,53]. In the future, patient-specific material properties could be considered. The inclusion of magnetic resonance (MR) data from the same patients and use of image registration techniques could combine MR and CT data, which would enable us not only to extract cartilage thickness accurately but also to determine patient-specific multi-variate matrix properties, such as the T1 or T2 relaxation times, which are related to proteoglycan and collagen matrix integrity, respectively [67]. Another important limitation of this study is the fact that we do not know the patellofemoral pressure values that predict the development of a symptomatic PFOA. We have extrapolated the well-known values that would lead to the development of a symptomatic tibiofemoral osteoarthrosis and hypothesized that the values necessary to develop a symptomatic PFOA should be higher than those for a symptomatic tibiofemoral osteoarthritis because the patellar cartilage is much thicker than that found on the tibia or in the femur [65]. Therefore, a higher pressure would be necessary to cause damage. Using the FEM enables us to reliably predict the clinical evolution of an MPFL-graft. Logically, in a condition with multifactorial etiopathogeny such as lateral patellar instability, in some cases, the model fails because there are additional factors (e.g., patella alta, increased tibial tubercle-trochlear groove distance and trochlear dysplasia) other than the tension of the MPFL-graft and patellofemoral contact pressures that could be responsible for the failed surgery. Although it has not been addressed in the present work, the conditions for which the graft would not prevent post-operative instability could be incorporated [3,57,68].

9. CONCLUSION

The main finding of this study is that the use of a parametric 3D finite element model of the PFJ enables us to evaluate different types of surgical techniques for MPFL reconstruction with regard to the effect on the patellofemoral contact pressure, as well as the kinematic behaviour of the MPFL-graft with flexion-extension of the knee and the maximum MPFL-graft stress. In this way, from diagnostic images, for example, a CT, we could simulate different surgical treatments and choose the best optimal technique for each patient. That is, we can customize treatment for individual patients.

BIBLIOGRAPHY

1. Hawkins R J, Bell R H, Anisette G. Acute patellar disloca- tions. The natural history. Am J Sports Med 1986; 14: 117-20.

2. Maenpaa H, Lehto M U. Patellar dislocation. The long-term results of nonoperative management in 100 patients. Am J Sports Med 1997; 25: 213-7.

3. Sanchis-Alfonso V (2014) Guidelines for medial patellofemoral ligament reconstruction in chronic lateral patellar instability. J Am Acad Orthop Surg 22:175-182

4. Segal NA, Anderson DD, Iyer KS (2009) Baseline articular contact stress levels predict incident symptomatic knee osteoarthritis development in the MOST cohort. J Orthop Res 27: 1562-1568

5. Fink C, Veselko M, Herbort M, Hoser C (2014) MPFL reconstruction using a quadriceps tendon graft: part 2: operative technique and short term clinical results. Knee 21:1175-9117

6. Fulkerson JP, Edgar C (2013) Medial quadriceps tendon-femoral ligament: surgical anatomy and reconstruction technique to prevent patella instability. Arthrosc Tech 12:e125-128

7. Teitge RA, Torga-Spak R (2004) Medial patellofemoral ligament reconstruction. Orthopedics 27:1037-1040

8. Weinberger JM, Fabricant PD, Taylor SA, Mei JY, Jones KJ (2017) Influence of graft source and configuration on revision rate and patient-reported outcomes after MPFL reconstruction: a systematic review and meta-analysis. Knee Surg Sports Traumatol Arthrosc 25: 2511-2519

9. Elias JJ, Cosgarea AJ (2006) Technical errors during medial patellofemoral ligament reconstruction could overload medial patellofemoral cartilage: A computational analysis. Am J Sports Med 34:1478–1485

10. Rood A, Hannink G, Lenting A, Groenen K, Koëter S, Verdonschot, N, van Kampen A (2015) Patellofemoral Pressure Changes After Static and Dynamic Medial Patellofemoral Ligament Reconstructions. Am J Sports Med 43: 2538-2544

11. Stephen JM, Kaider D, Lumpaopong P, Deehan DJ, Amis AA (2014) The effect of femoral tunnel position and graft tension on patellar contact mechanics and kinematics after medial patellofemoral ligament reconstruction. Am J Sports Med 42:364-372

12. DeVries WNA, Duchman KR, Bollier MJ (2015) A Finite element analysis of medial patellofemoral ligament reconstruction. Iowa Orthop J 35:13-19

13. Elías JJ, Cech JA, Weinstein DM, Cosgarea AJ (2005) Reducing the lateral force acting on the patella does not consistently decrease patellofemoral pressures. Am J Sports Med 32: 1202-1208

14. Shah KS, Saranathan A, Koya B, Elias JJ (2015) Finite element analysis to characterize how varying patellar loading influences pressure applied to cartilage: model evaluation. Comput Methods Biomech Biomed Engin 18:1509-1515

15. Conlan, W.P. Garth, Jr., J.E. Lemons, Evaluation of the medial soft-tissue restraints of the extensor mechanism of the knee, The Journal of bone and joint surgery. American volume 75(5) (1993) 682-93.

16. S.M. Desio, R.T. Burks, K.N. Bachus, Soft tissue restraints to lateral patellar translation in the human knee, The American journal of sports medicine 26(1) (1998) 59-65.

17. P.V. Hautamaa, D.C. Fithian, K.R. Kaufman, D.M. Daniel, A.M. Pohlmeyer, Medial soft tissue restraints in lateral patellar instability and repair, Clinical orthopaedics and related research (349) (1998) 174-82.

18. J.I. Tuxoe, M. Teir, S. Winge, P.L. Nielsen, The medial patellofemoral ligament: a dissection study, Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA 10(3) (2002) 138-40.

19. R. Philippot, B. Boyer, R. Testa, F. Farizon, B. Moyen, The role of the medial ligamentous structures on patellar tracking during knee flexion, Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA 20(2) (2012) 331-6.

20. A.A. Amis, P. Firer, J. Mountney, W. Senavongse, N.P. Thomas, Anatomy and biomechanics of the medial patellofemoral ligament, The Knee 10(3) (2003) 215-20.

21. B.B. Hinckel, R.G. Gobbi, C.C. Kaleka, G.L. Camanho, E.A. Arendt, Medial patellotibial ligament and medial patellomeniscal ligament: anatomy, imaging, biomechanics, and clinical review, Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA 26(3) (2018) 685-696.

22. B.M. Kruckeberg, J. Chahla, G. Moatshe, M.E. Cinque, K.J. Muckenhirn, J.A. Godin, T.J. Ridley, A.W. Brady, E.A. Arendt, R.F. LaPrade, Quantitative and Qualitative Analysis of the Medial Patellar Ligaments: An Anatomic and Radiographic Study, The American journal of sports medicine 46(1) (2018) 153-162.

23. L.F. Warren, J.L. Marshall, The supporting structures and layers on the medial side of the knee: an anatomical analysis, The Journal of bone and joint surgery. American volume 61(1) (1979) 56-62.

24. M.J. Tanaka, A. Voss, J.P. Fulkerson, The Anatomic Midpoint of the Attachment of the Medial Patellofemoral Complex, The Journal of bone and joint surgery. American volume 98(14) (2016) 1199-205.

25. T. Mochizuki, A. Nimura, T. Tateishi, K. Yamaguchi, T. Muneta, K. Akita, Anatomic study of the attachment of the medial patellofemoral ligament and its characteristic relationships to the

vastus intermedius, Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA 21(2) (2013) 305-10.

26. J.P. Fulkerson, C. Edgar, Medial quadriceps tendon-femoral ligament: surgical anatomy and reconstruction technique to prevent patella instability, Arthroscopy techniques 2(2) (2013) e125-8.

27. G. Placella, M.M. Tei, E. Sebastiani, G. Criscenti, A. Speziali, C. Mazzola, A. Georgoulis, G. Cerulli, Shape and size of the medial patellofemoral ligament for the best surgical reconstruction: a human cadaveric study, Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA 22(10) (2014) 2327-33.

28. J.A. Aragao, F.P. Reis, D.P. de Vasconcelos, V.L. Feitosa, M.A. Nunes, Metric measurements and attachment levels of the medial patellofemoral ligament: an anatomical study in cadavers, Clinics (Sao Paulo, Brazil) 63(4) (2008) 541-4.

29. M.J. Tanaka, Variability in the Patellar Attachment of the Medial Patellofemoral Ligament, Arthroscopy : the journal of arthroscopic & related surgery : official publication of the Arthroscopy Association of North America and the International Arthroscopy Association 32(8) (2016) 1667-70.

30. J.M. Stephen, P. Lumpaopong, D.J. Deehan, D. Kader, A.A. Amis, The medial patellofemoral ligament: location of femoral attachment and length change patterns resulting from anatomic and nonanatomic attachments, The American journal of sports medicine 40(8) (2012) 1871-9.

31. C. Smirk, H. Morris, The anatomy and reconstruction of the medial patellofemoral ligament, The Knee 10(3) (2003) 221-7.

32. H.J. Kang, F. Wang, B.C. Chen, Y.L. Su, Z.C. Zhang, C.B. Yan, Functional bundles of the medial patellofemoral ligament, Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA 18(11) (2010) 1511-6.

33. E. Panagiotopoulos, P. Strzelczyk, M. Herrmann, G. Scuderi, Cadaveric study on static medial patellar stabilizers: the dynamizing role of the vastus medialis obliquus on medial patellofemoral ligament, Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA 14(1) (2006) 7-12.

34. C.G. Ziegler, J.P. Fulkerson, C. Edgar, Radiographic Reference Points Are Inaccurate With and Without a True Lateral Radiograph: The Importance of Anatomy in Medial Patellofemoral Ligament Reconstruction, The American journal of sports medicine 44(1) (2016) 133-42.

35. B.B. Hinckel, R.G. Gobbi, M.K. Demange, C.A.M. Pereira, J.R. Pecora, R.J.M. Natalino, L. Miyahira, B.S. Kubota, G.L. Camanho, Medial Patellofemoral Ligament, Medial Patellotibial Ligament, and Medial Patellomeniscal Ligament: Anatomic, Histologic, Radiographic, and Biomechanical Study, Arthroscopy : the journal of arthroscopic & related surgery : official publication of the Arthroscopy Association of North America and the International Arthroscopy Association 33(10) (2017) 1862-1873.

36. C.C. Kaleka, L.J. Aihara, A. Rodrigues, S.F. de Medeiros, V.M. de Oliveira, R. de Paula Leite Cury, Cadaveric study of the secondary medial patellar restraints: patellotibial and patellomeniscal ligaments, Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA 25(1) (2017) 144-151.

37. H.J. Kang, J.H. Cao, S. Pan, X.J. Wang, D.H. Yu, Z.M. Zheng, The horizontal Y-shaped graft with respective graft tension angles in anatomical two-bundle medial patellofemoral

ligament reconstruction, Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA 22(10) (2014) 2445-51.

38. S. Lippacher, J. Dreyhaupt, S.R. Williams, H. Reichel, M. Nelitz, Reconstruction of the Medial Patellofemoral Ligament: Clinical Outcomes and Return to Sports, The American journal of sports medicine 42(7) (2014) 1661-8.

39. M. Nelitz, R.S. Williams, S. Lippacher, H. Reichel, D. Dornacher, Analysis of failure and clinical outcome after unsuccessful medial patellofemoral ligament reconstruction in young patients, International orthopaedics 38(11) (2014) 2265-72.

40. J.N. Shah, J.S. Howard, D.C. Flanigan, R.H. Brophy, J.L. Carey, C. Lattermann, A systematic review of complications and failures associated with medial patellofemoral ligament reconstruction for recurrent patellar dislocation, The American journal of sports medicine 40(8) (2012) 1916-23.

41. J.M. Stephen, D. Kaider, P. Lumpaopong, D.J. Deehan, A.A. Amis, The effect of femoral tunnel position and graft tension on patellar contact mechanics and kinematics after medial patellofemoral ligament reconstruction, The American journal of sports medicine 42(2) (2014) 364-72.

42. L.R. Slocum DB, James SL: Late reconstruction of ligamentous injuries of the medial compart- ment of the knee. Clin Orthop 100:23-55, 1974.

43. Hughston J C. Subluxation of the patella. J Bone Joint Surg (Am) 1968; 50: 1003-26.

44. Davis D K, Fithian D C. Techniques of medial retinacular repair and reconstruction. Clin Orthop 2002; (402): 38-52.

45. Schottle P B, Fucentese S F, Romero J. Clinical and radio- logical outcome of medial patellofemoral ligament recon- struction with a semitendinosus autograft for patella instability. Knee Surg Sports Traumatol Arthrosc 2005; 13: 516-21.

46. Nomura E, Horiuchi Y, Kihara M. A mid-term follow-up of medial patellofemoral ligament reconstruction using an artificial ligament for recurrent patellar dislocation. Knee 2000; 7: 211-5.

47. Monllau JC, Erquicia JI, Ibañez M. Reconstruction of the Medial Patellofemoral Ligament. Arthrosc Tech. 2017 Sep 4;6(5):e1471-e1476. doi: 10.1016/j.eats.2017.06.039. eCollection 2017 Oct.

48. Parikh SN, Wall EJ. Patellar fracture after medial patellofemoral ligament surgery: A report of five cases. J Bone Joint Surg Am 2011;93:e97(1-8).

49. Fulkerson JP, Edgar C. Medial quadriceps tendon-femoral ligament: surgical anatomy and reconstruction technique to prevent patella instability. Arthrosc Tech. 2013 Apr 12;2(2):e125-8. doi: 10.1016/j.eats.2013.01.002. Print 2013 May.

50. Sanchis-Alfonso V, Ramirez-Fuentes C, Montesinos-Berry E, Domenech J, Martí-Bonmati L (2017) Femoral insertion site of the graft used to replace the medial patellofemoral ligament influences the ligament dynamic changes during knee flexion and the clinical outcome. Knee Surg Sports Traumatol Arthrosc 25: 2433-2441

51. Elías JJ, Bratton DR, Weinstein DM, Cosgarea AJ (2006) Comparing two estimations of the quadriceps force distribution for use during patellofemoral simulation. J Biomech 39: 865-872

52. Ciccone WJ II, Bratton DR, Weinstein DM, Elias JJ (2006) Viscoelasticity and temperature variations decrease tension and stiffness of hamstring tendon grafts following anterior cruciate ligament reconstruction. J Bone Joint Surg Am 88:1071-1078

53. Drez DJr, Edwards TB, Williams CS (2001) Results of medial patellofemoral ligament reconstruction in the treatment of patellar dislocation. Arthroscopy 17: 298-306

54. Besier TF, Gold GE, Delp SL, Fredericson M, Beaupre GS (2008) The influence of femoral internal and external rotation on cartilage stresses within the patellofemoral joint. J Orthop Res 26: 1627-1635

55. Conlan T, Garth WP Jr, Lemons JE (1993) Evaluation of the medial soft-tissue restraint of the extensor mechanism of the knee. J Bone Joint Surg Am. 75: 682-693

56. Desio SM, Burks RT, Bachus KN (1998) Soft tissue restraints to lateral patellar translation in the human knee. Am J Sports Med. 26: 59-65

57. Hautamaa PV, Fithian DC, Kaufman KR, Daniel DM, Pohlmeyer AM (1998) Medial soft tissue restraints in lateral patellar instability and repair. Clin Orthop Relat Res 349:174-182

58. Servien E, Fritsch B, Lustig S (2011) In vivo positioning analysis of medial patellofemoral ligament reconstruction. Am J Sports Med 39:134-139

59. Good L (1995) In vitro correlation between tension and length change in an anterior cruciate ligament substitute. Clin Biomech (Bristol, Avon) 10:200–207

60. Moritomo H, Noda K, Goto A, Murase T, Yoshikawa H, Sugamoto K (2009) Interosseous membrane of the forearm: Length change of ligaments during forearm rotation. J Hand Surg Am 34: 685–691

61. Seo YJ, Song SY, Kim IS, Seo MJ, Kim YS, Yoo YS (2014) Graft tension of the posterior cruciate ligament using a finite element model. Knee Surg Sports Traumatol Arthrosc 22:2057–2063

62. Tan J, Xu J, Xie RG, Deng AD, Tang JB (2011) In vivo length and changes of ligaments stabilizing the thumb carpometacarpal joint. J Hand Surg Am 36:420–427

63. Stephen JM, Kaider D, Lumpaopong P, Deehan DJ, Amis AA (2014) The effect of femoral tunnel position and graft tension on patellar contact mechanics and kinematics after medial patellofemoral ligament reconstruction. Am J Sports Med 42:364-372

64. Stephen JM, Kittl C, Williams A, Zaffagnini S, Marcheggiani GM, Fink C, Amis AA (2016) Effect of Medial Patellofemoral Ligament Reconstruction Method on Patellofemoral Contact Pressures and Kinematics. Am J Sports Med 44: 1186-1194

65. Segal NA, Anderson DD, Iyer KS (2009) Baseline articular contact stress levels predict incident symptomatic knee osteoarthritis development in the MOST cohort. J Orthop Res 27: 1562-1568

66. Jones B, Hung CT, Ateshian G (2016) Biphasic Analysis of Cartilage Stresses in the Patellofemoral Joint. J Knee Surg 29:92-98

67. Martí-Bonmatí L, Sanz-Requena R, Alberich-Bayarri A (2008) Pharmacokinetic MR analysis of the cartilage is influenced by field strength. Eur J Radiol 67: 448-452

68. Farahmand F, Senevongse W, Amis A (1998) Quantitative study of the quadriceps muscles and trochlear groove geometry related to instability of the patellofemoral joint. J Orthop Res 16: 136-143

Knee Surg Sports Traumatol Arthrosc
DOI 10.1007/s00167-015-3905-0

Femoral insertion site of the graft used to replace the medial patellofemoral ligament influences the ligament dynamic changes during knee flexion and the clinical outcome

Vicente Sanchis-Alfonso[1,2] · Cristina Ramirez-Fuentes[3] · Erik Montesinos-Berry[4] · Julio Domenech[2] · Luis Martí-Bonmatí[3]

Received: 24 April 2015 / Accepted: 26 November 2015

Abstract
Purpose This study's purpose was to investigate how an ideal anatomic femoral attachment affects the dynamic length change pattern of a virtual medial patellofemoral ligament (MPFL) from an extended to a highly flexed knee position; to determine the relative length and length change pattern of a surgically reconstructed MPFL; and to correlate femoral attachment positioning, length change pattern, and relative graft length with the clinical outcome.
Methods Twenty-four knees with isolated nonanatomic MPFL reconstruction were analysed by three-dimensional computed tomography at 0°, 30°, 60°, 90°, and 120° of knee flexion. The lengths of the MPFL graft and a virtual anatomic MPFL were measured. The pattern of length change was considered isometric if the length distance changed <5 mm through the entire dynamic range of motion.
Results Knee flexion significantly affected the path lengths between the femoral and patellar attachments. The length of the anatomic virtual MPFL decreased significantly from 60° to 120°. Its maximal length was 56.4 ± 6.8 mm at 30°. It was isometric between 0° and 60°. The length of the nonanatomic MPFL with a satisfactory clinical result decreased during flexion from 0° to 120°. Its maximal length was 51.6 ± 4.6 mm at 0° of knee flexion. The lengths measured at 0° and 30° were isometric and statistically greater than the lengths measured at higher flexion degrees. The failed nonanatomic MPFL reconstructions were isometric throughout the dynamic range, being significantly shorter (27.1 ± 13.3 %) than anatomic ligaments.
Conclusion The femoral attachment point significantly influences the relative length and the dynamic length change of the grafts during knee flexion–extension and graft isometry. Moreover, it influences the long-term outcome of the MPFL reconstructive surgery. A nonanatomic femoral fixation point should not be considered the cause of persistent pain and instability after MPFL reconstruction in all cases.
Level of evidence III.

Keywords Patella · Medial patellofemoral ligament · Femoral attachment · Anatomic reconstruction · 3D-CT

Introduction

Currently, medial patellofemoral ligament (MPFL) reconstruction is the procedure of first choice for treating patients with chronic lateral patellar instability and at least two documented patellar dislocations [22]. Many surgical techniques with various femoral graft fixation sites have been described for the reconstruction of the MPFL, with generally good short- and mid-term clinical outcomes [22].

Interest in anatomic ligament reconstructions began with the anterior cruciate ligament (ACL) and now includes the MPFL, for which femoral anatomic attachment of grafts is increasingly favoured. Anything that is not completely anatomic seems to be perceived as incorrect, but high-level evidence to support that perception is lacking. Moreover, the normal anatomic location of the

✉ Vicente Sanchis-Alfonso
vicente.sanchis.alfonso@gmail.com

1 Hospital 9 de Octubre, Valencia, Spain

2 Hospital Arnau de Vilanova, Valencia, Spain

3 Department of Radiology, Hospital Universitario y Politécnico La Fe and GIBI230 IIS La Fe Research Group, Valencia, Spain

4 Agoriaz Orthopedic Center, Riaz, Switzerland

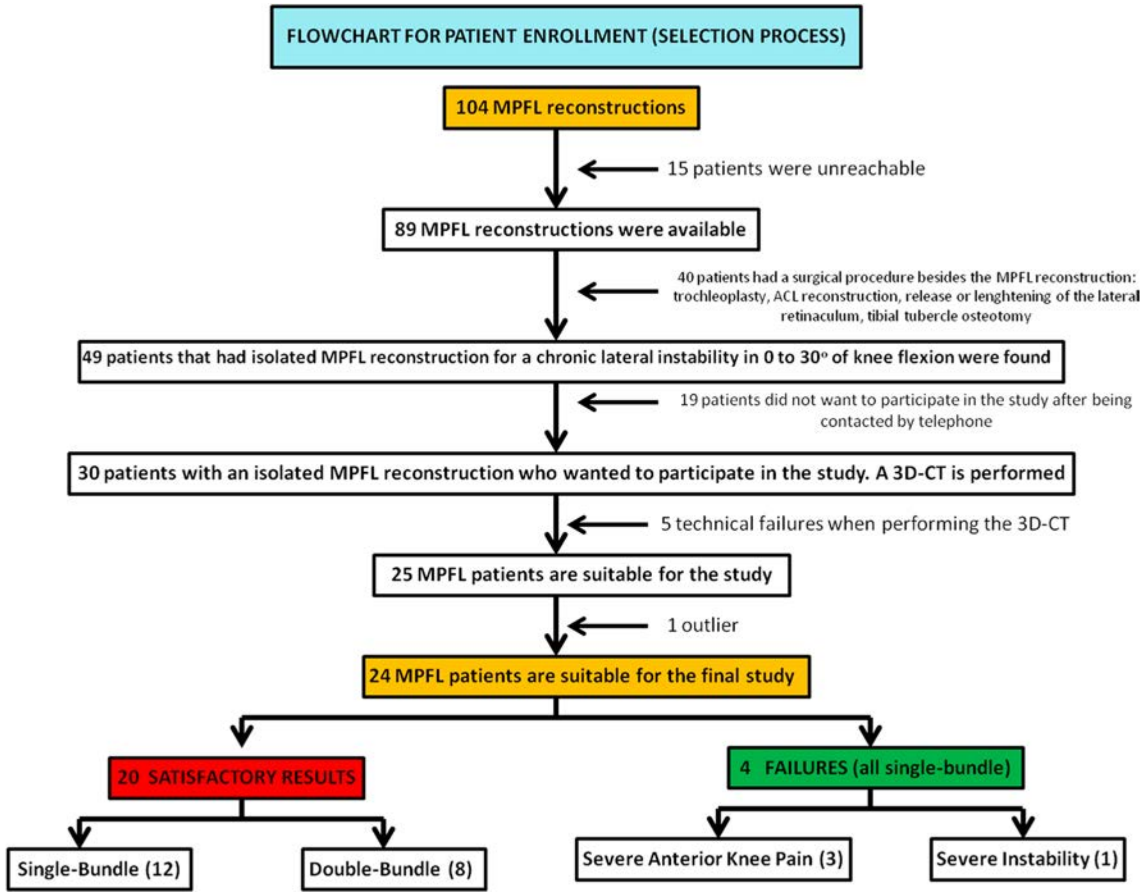


Fig. 1 Flow chart for patient enrolment (selection process)

femoral MPFL attachment is not as well defined as for other knee ligaments [15, 27], and no definitive studies have analysed the effects of nonanatomic femoral fixation point on the outcome. Therefore, very little information exists about the best femoral attachment site of the graft, and controversy continues about the importance of an anatomic MPFL reconstruction.

As in ACL reconstruction surgery [12], changes in the femoral attachment site have been hypothesized to have a considerable effect on the relative length of the reconstructed MPFL as well as on the length change pattern of the graft throughout the dynamic range of knee motion. All these items will have an impact on failed surgeries.

Our study was designed to (1) investigate the effect of an ideal anatomic femoral attachment site on the dynamic length change pattern of a virtual MPFL graft from an extended knee to a highly flexed position with three-dimensional computed tomography (3D-CT) reconstructions; (2) determine the in vivo relative length and the length change pattern of the reconstructed MPFL; and (3) correlate femoral attachment positioning, length change pattern, and relative graft length with failed surgery as a clinical outcome. The final objective of the study was to demonstrate that a nonanatomic femoral fixation point should not be considered the cause of all cases of persistent pain and instability after an MPFL reconstruction.

Materials and methods

Between 2002 and 2012, 101 consecutive patients (104 knees) with chronic lateral patellar instability with at least two documented patellar dislocations underwent MPFL reconstruction at our institution. Of these 104 knees, 30 were available for evaluation, but only 24 were included in this study (see flow chart for patient enrolment, Fig. 1).

The study group consisted of 24 patients (17 females and seven males) with a mean age at the time of surgery of 23 years (range 16–38). Patients were evaluated at a mean of 5 years (range 2–10) after surgery. The MPFL reconstruction was performed using one-bundle reconstruction (partial-thickness quadriceps or semitendinosus tendon graft) in 16 cases and double-bundle reconstruction with semitendinosus tendon autograft in eight cases.

To control for confounding variables, all cases were preoperatively evaluated for trochlear dysplasia according to the Dejour [4] classification, either severe (grade C or D) or nonsevere (grade A or B), because a correlation between severe trochlear dysplasia and MPFL reconstruction failure has been observed [13, 16]. Other major factors that contribute to chronic lateral patellar instability that could also be confounding variables are less important than trochlear dysplasia, and therefore, we did not consider them in our study [17, 35].

At the final follow-up, 20 patients had satisfactory results, while four had nonsatisfactory results defined as failed surgery. MPFL reconstruction surgery was considered to have failed when the instability, anterior knee pain, or both recurred to the extent that a new surgical reconstruction of the MPFL was required. Results were considered satisfactory when the patient had no pain (excepting sporadic discomfort) or instability; performed the same physical activities, including sports, as before the injury; and was subjectively satisfied with the surgical procedure.

CT acquisition

The operated knee was scanned with a high-spatial-resolution dynamic 256-detector row Brilliance iCT scanner (Philips Medical Systems, Eindhoven, the Netherlands) at five different knee flexion angles (0°, 30°, 60°, 90°, and 120°). Subjects were asked to be in a lateral position and to be relaxed. The flexion angle was determined by using a goniometer. The raw data sets were acquired under 64 × 0.6 mm collimation, rotation time 0.5 s, pitch 0.5, 120 kV, and automated mAs control. Lead aprons were used for all patients to shield their gonads. Images were reconstructed with 0.9 mm slice thickness, and a 3D high-resolution bone surface rendering for knee volumetric reconstruction was obtained at each knee angle.

Image analysis

The 3D surface rendering for knee reconstruction at 0° of knee flexion was chosen as a reference. To minimize technical errors in measurement, the femoral model at 0° of flexion was superimposed on each femoral model at 30°, 60°, 90°, and 120° of flexion using the surface-to-surface matching method [36]. The centre of the femoral and patellar tunnels was established (Fig. 2). The ideal femoral anatomic attachment point was determined by the method described by Fujino et al. [7] (Fig. 2). Sanchis-Alfonso et al. [23] have shown that the widely used method described by Schoettle et al. [24] to identify the femoral fixation point in MPFL reconstruction surgery is only an approximation and should not be the sole basis for identifying the femoral attachment location. The only way we can be sure of an anatomic femoral placement of the graft is to make an incision that is large enough to unequivocally identify the most important anatomic landmark, the adductor tubercle [23]. The method described by Fujino et al. [7] uses the adductor tubercle as a landmark to identify the femoral attachment of the MPFL. We believe that this method is the most accurate of the described methods, from an anatomic point of view. According to Fujino et al. [7], the femoral attachment of the MPFL is distal to the apex of the adductor tubercle and parallel to the long axis of the femur. In this study, the mean linear distance between the two points was 10.6 mm, and the position of the insertion site was consistent in all knees. In our study, the malposition of the femoral attachment was defined in relation to the ideal anatomic femoral attachment.

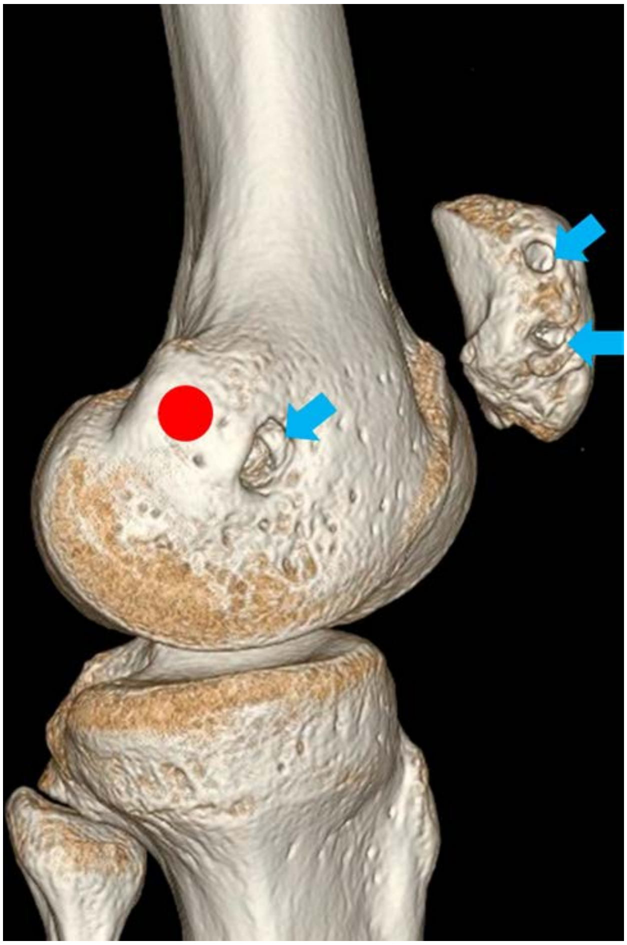


Fig. 2 Anatomic femoral attachment (*red circle*) according to the method described by Fujino et al. [7]. Patellar attachments and nonanatomic femoral attachment performed during surgery (*blue arrows*). We defined the malposition of the femoral attachment in relation to the ideal anatomic femoral attachment

The length of the MPFL graft/virtual anatomic MPFL was defined as the linear distance between the centre of the femoral attachment site and the centre of the

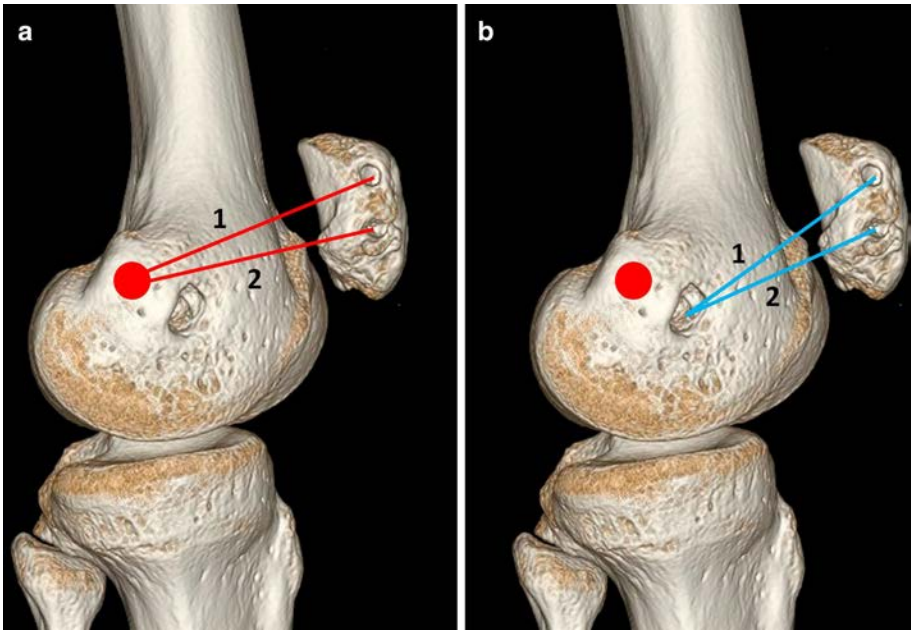


Fig. 3 **a** A virtual anatomic MPFL (*red lines*) was created on the three-dimensional model. The length of the graft was defined as the linear distance between the centre of the femoral attachment site (*red circle*) and the centre of the patellar attachment site. **b** MPFL graft (*blue lines*) in a case with a double-bundle reconstruction with hamstring tendon autograft. Note that although we use a 3D model, the measurement is in 2D. (*1*) Proximal bundle, (*2*) distal bundle

patellar attachment site (Fig. 3). Tateishi et al. [32] have demonstrated that the centre of the femoral drill hole position determines the graft length change pattern in patients with patellar instability. In the cases in which a patellar tunnel was not performed (four cases), a point that was 30 % of the distance from the superior pole of the patella [19] was marked, using the technique described by Yoo et al. [36]. Moreover, the length of the virtual native MPFL was calculated as the distance between the theoretical ideal anatomic femoral point and the centre of the patellar attachment performed during surgery (Fig. 3). The distance measured from the ideal anatomic femoral point to the patellar point served as a reference for calculating the relative length of the reconstructed MPFL. The length of the MPFL graft and the virtual native MPFL was measured at five different knee flexion angles. According to Smirk and Morris [27], length pattern changes are isometric when there is <5 mm of length change throughout the range of motion.

Our study was approved by the Institutional Review Board at our institution (Hospital Universitario y Politécnico La Fe, Valencia, Spain, ID # 2013/0341), and informed consent was obtained from all patients.

Statistical analysis

All values were expressed as the mean ± SD. The differences in length among the different knee flexion positions in both virtual native and operated MPFL were analysed using a paired Student's t test. The level of significance was set at $p < 0.05$ in all instances. All statistical analyses were performed using SPSS software, version 17 Institute (Cary, NC, USA).

Results

3D-CT reconstructions corroborated a nonanatomic MPFL femoral attachment site in all 24 MPFL reconstructed knees. In 4 of the 24 cases (17 %), the clinical result at the final follow-up was considered a failed surgery: three cases due to severe anterior knee pain and one case with recurrence of lateral patellar instability. Of the failed cases due to pain, two had a grade A trochlear dysplasia and one had a grade B dysplasia. No correlation existed between the severity of trochlear dysplasia and the failure of MPFL surgery due to pain. In the case that failed because of persistent instability, the trochlear dysplasia was a grade C, and the malposition of the femoral fixation point was very noticeable (Fig. 4).

Knee flexion had a significant effect on the length of the path between the femoral and patellar attachments of the MPFL. The measurements of the lengths of the anatomic virtual MPFL, the nonanatomic MPFL with a satisfactory result, and the nonanatomic MPFL with a nonsatisfactory result (severe pain) at 0°, 30°, 60°, 90°, and 120° of knee flexion are summarized in Table 1.

The length of the anatomic virtual MPFL increased during flexion from 0° to 30°, decreased nonsignificantly from 30° to 60°, and decreased significantly from 60° to 120°. Its maximum length was 56.4 ± 6.8 mm at 30° of knee flexion and was not statistically greater than the length measured at 0° (n.s.) or 60° (n.s.) of knee flexion. However, the lengths at 0°, 30°, and 60° were statistically greater than at 90° and 120° ($p < 0.001$) of knee flexion (Table 1; Fig. 5). This pattern was considered as the in vivo MPFL standard dynamic length change. We

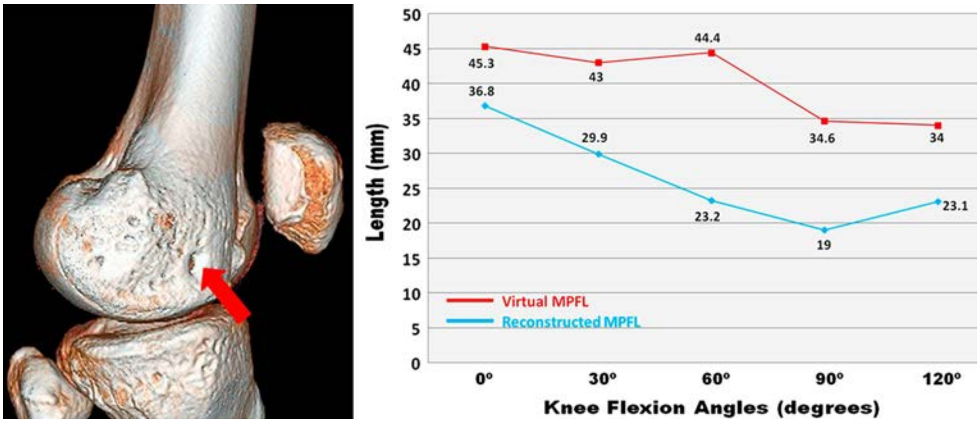


Fig. 4 Curves representing the length with different knee flexion angles (0°, 30°, 60°, 90°, and 120°) of the virtual anatomic MPFL and the failed reconstructed MPFL due to instability. The malposition of the femoral fixation point (*arrow*) is very noticeable

Table 1 Length of an anatomic virtual MPFL, a nonanatomic MPFL with satisfactory result, and a nonanatomic MPFL with nonsatisfactory result due to severe anterior knee pain at the different knee flexion angles

Knee flexion angle (°)	Anatomic virtual MPFL reconstruction ($n = 24$)	Nonanatomic reconstructed MPFL with satisfactory result ($n = 20$)	Nonanatomic reconstructed MPFL with severe anterior knee pain ($n = 3$)
0	54.6 ± 6.1	51.6 ± 4.6	37.5 ± 7.8
30	56.4 ± 6.8	50.8 ± 5.4	36.5 ± 9.2
60	53.3 ± 6.4	44.9 ± 5.2	35.7 ± 10.1
90	47.0 ± 5.7	38.3 ± 4.9	35.6 ± 7.9
120	41.2 ± 4.9	33.7 ± 4.8	35.4 ± 5.6

The data are presented as mean ± SD (mm)

observed a graft length change from 0° to 30° of knee flexion of 2.8 ± 1.6 mm. The length change at 60° of knee flexion was 3.7 ± 2.5 mm; at 90°, it was 10.0 ± 3.6 mm; and at 120°, it was 16.1 ± 4.9 mm, always compared with its maximum length. The anatomic virtual MPFL was isometric between 0° and 30° in all cases. In 20 cases (83 %), the ligament was isometric from 0° to 60° of knee flexion. Beyond 60° of knee flexion, the graft became progressively lax, and the isometry was lost.

The length of the nonanatomic reconstructed MPFL with a satisfactory result was decreased during flexion from 0° to 120°. Its maximum length was 51.6 ± 4.6 mm at 0° of knee flexion, but it was not statistically greater than the length measured at 30° (n.s.) of flexion. However, the lengths at 0° and 30° were statistically greater than those at 60°, 90°, and 120° ($p < 0.01$) of knee flexion (Table 1; Fig. 5). We observed a graft length change from 0° to 30° of knee flexion of 2.4 ± 1.5 mm. The length change at 60° was 7.5 ± 2.9 mm; at 90°, it was 14.2 ± 5.2 mm; and at 120°, it was 18.7 ± 6.1 mm, always compared with its maximum length. The nonanatomic MPFL reconstruction with satisfactory results was isometric between 0° and 30° in all cases. Only in four cases (20 %) was the ligament isometric from 0° to 60° of knee flexion. However, beyond 60° of knee flexion, the graft became progressively lax and the isometry was lost.

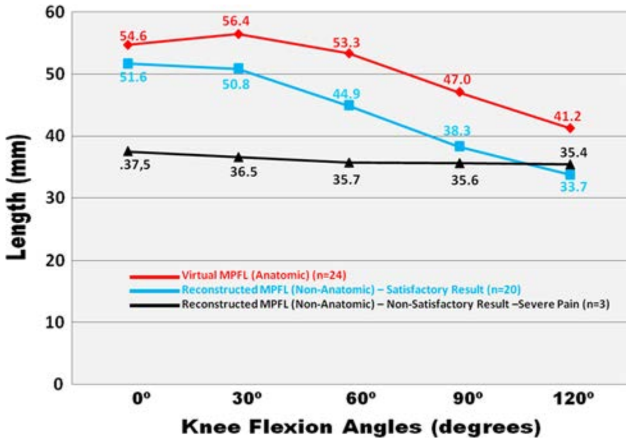


Fig. 5 Curves representing the mean length with different knee flexion angles (0°, 30°, 60°, 90°, and 120°) of the virtual anatomic MPFL, a nonanatomic MPFL reconstruction with satisfactory result, and a nonanatomic MPFL reconstruction with a nonsatisfactory result (severe anterior knee pain). Note the length change pattern of the anatomic virtual MPFL (*red line*), the nonanatomic MPFL reconstruction with satisfactory result (*blue line*), and the nonanatomic MPFL reconstruction with severe anterior knee pain (*black line*)

A nonanatomic MPFL with a satisfactory result was always shorter than an anatomic ligament (8.5 ± 6.3 %). A failed MPFL reconstruction was significantly shorter than

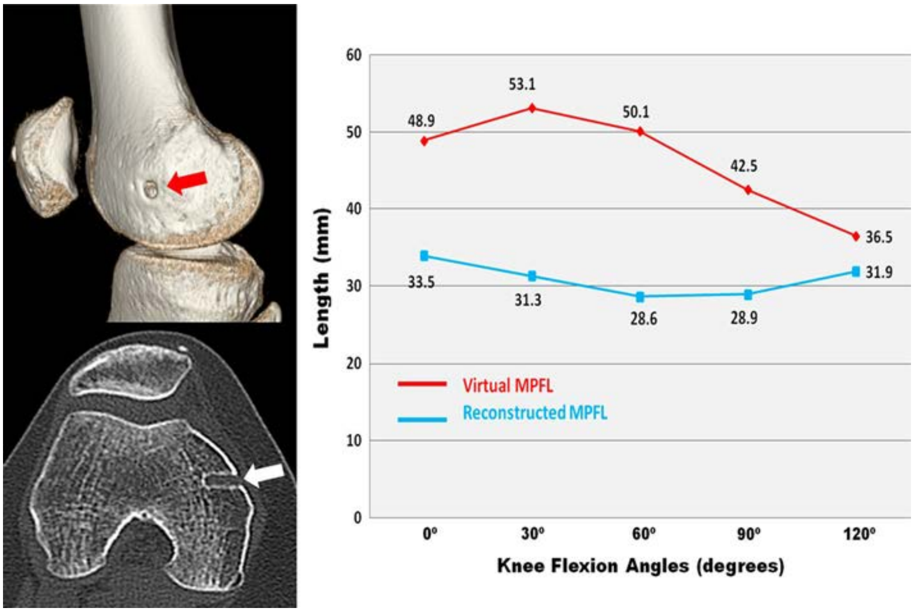


Fig. 6 Curves representing the length with different knee flexion angles (0°, 30°, 60°, 90°, and 120°) of the virtual anatomic MPFL and the failed reconstructed MPFL due to severe anterior knee pain. The malposition of the femoral fixation point (*arrow*) is very noticeable

an anatomic ligament (27.1 ± 13.3 %) (Table 1; Fig. 6). In the three cases of a failed MPFL reconstruction due to severe pain, the reconstruction was isometric from 0° to 120° of knee flexion (Figs. 5, 6).

The measurements of the length of the proximal and distal bundles of the anatomic virtual MPFL double-bundle reconstruction and the nonanatomic MPFL double-bundle reconstruction with a clinical satisfactory result at 0°, 30°, 60°, 90°, and 120° of knee flexion are summarized in Tables 2 and 3. No significant differences were found between the two patellar attachment sites in the length change pattern or in the ligament isometry for the double-bundle MPFL reconstruction (Figs. 7, 8).

Table 2 Length of anatomic virtual proximal and distal bundles in a double-bundle MPFL reconstruction at different knee flexion angles

Knee flexion angle (°)	Anatomic virtual proximal bundle ($n = 8$)	Anatomic virtual distal bundle ($n = 8$)
0	53.8 ± 2.5	52.1 ± 2.3
30	56.5 ± 3.0	54.7 ± 2.5
60	53.0 ± 3.2	51.4 ± 2.9
90	46.6 ± 3.0	45.1 ± 3.2
120	41.1 ± 3.3	40.4 ± 3.5

The data are presented as mean ± SD (mm)

Table 3 Length of nonanatomic proximal and distal bundles in a double-bundle MPFL reconstruction with a satisfactory result at different knee flexion angles

Knee flexion angle (°)	Nonanatomic reconstructed MPFL proximal bundle with satisfactory result ($n = 8$)	Nonanatomic reconstructed MPFL distal bundle with satisfactory result ($n = 8$)
0	52.4 ± 2.7	48.5 ± 4.0
30	51.0 ± 4.5	47.9 ± 5.3
60	45.0 ± 5.4	42.8 ± 6.1
90	38.3 ± 6.3	37.3 ± 6.3
120	33.9 ± 5.3	34.4 ± 5.2

The data are presented as mean ± SD (mm)

Discussion

The most important finding of the present study was that the femoral attachment point is of utmost importance for MPFL graft length change during knee flexion and for relative graft length. Both factors will influence the long-term success and the failure rate of the MPFL reconstructive surgery.

To the best of our knowledge, only five studies evaluating the in vivo MPFL kinematics have been published [9, 11, 21, 30, 36]. However, all of them were performed in anatomically normal knees by 3D-CT [9, 21, 30, 36] or open MRI [11]. 3D-CT has also been used previously to noninvasively measure in vivo cruciate ligament length at different flexion angles [14, 20, 37]. Our study is the first to evaluate MPFL kinematics in patients with chronic lateral patellar instability. We evaluated both the kinematics of the graft used to reconstruct the MPFL as well as the virtual native anatomic MPFL kinematics. Regarding the length change pattern of the anatomic ligament during knee flexion, we found the greatest distance between attachment points at

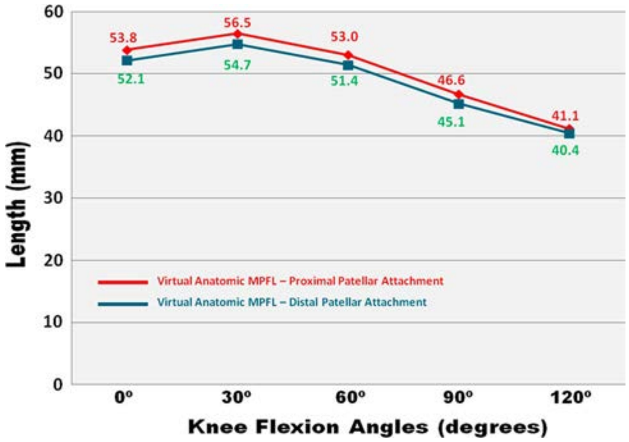


Fig. 7 Length change pattern of the graft in the eight cases of virtual anatomic double-bundle MPFL reconstruction. In all of these cases, the femoral fixation point is the virtual anatomic point determined using Fujino's method. The two patellar fixation points are those made during the surgical procedure

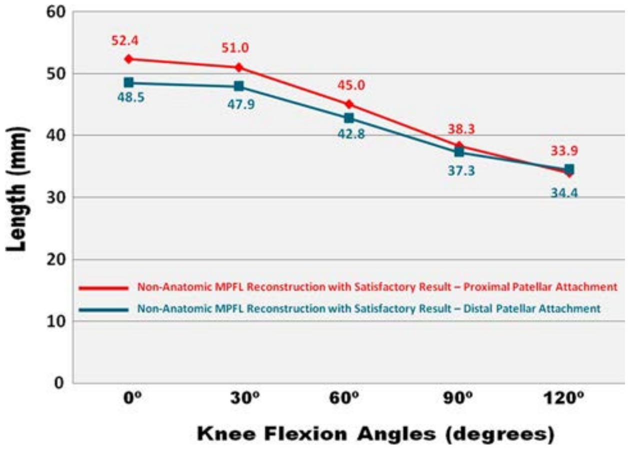


Fig. 8 Length change pattern of the graft in the eight cases of a nonanatomic double-bundle MPFL reconstruction with satisfactory result. In these cases, the femoral fixation point is the initial one made during the surgical procedure. The two patellar fixation points are also the ones made during the surgical procedure

30° of knee flexion, in accordance with previous studies [30, 36], and a significant approximation among the attachment points when the knee was flexed over 60°, in agreement with other authors [11, 36]. 3D-CT scan reconstruction offered an excellent definition of the bony anatomy, allowing for an accurate location of the MPFL femoral fixation site. Moreover, the wide gantry of the CT scan permitted higher angles of the knee than with MRI and facilitated scanning of tall patients. Finally, CT scan produced fewer postsurgical and metal artefacts than MRI. Although a disadvantage of CT is its use of ionizing radiation, no critical organs were within the scanning region; however, the risk of radiation-induced bone cancer is uncertain.

Although the ligament tension was not measured, several authors have demonstrated that a change in the ligament length reflects tension changes in this particular ligament [8, 18, 25, 31]. Therefore, we can infer that the native anatomic ligament is more tense during the first 30° of knee flexion and then loses a considerable amount of tension with higher degrees of knee flexion. As shown by previous studies [1, 3, 5, 10], this pattern shows that the MPFL contribution to resisting lateral patellar dislocation is greatest during the first 30° of knee flexion. Precisely after 30° of knee flexion, lateral patella stability depends more on the femoral trochlea than on the MPFL [5, 10]. A similar pattern in length change, in which the greatest separation of the attachment points occurs during the first 30° of flexion and a significant approximation of the femoral and patellar attachment points is seen at more than 30° of flexion, was found in MPFL grafts with nonanatomic femoral attachment points and a good clinical outcome. In contrast, this length change pattern is lost in reconstructive MPFL surgeries with nonanatomic femoral attachment points that have poor clinical results. In our cases with double-bundle reconstruction, no significant differences were seen between the two patellar attachment points in the length changes of the MPFL. This finding is in agreement with the results obtained by Yoo et al. [36] and with the study by Tateishi et al. [32], who found that the MPFL length changes depend on the femoral attachment site more than on the patellar attachment site. Therefore, the choice of the femoral attachment point is much more crucial for the success of the MPFL reconstructive surgery than the patellar attachment.

Another key element for obtaining a good clinical result in MPFL reconstruction is the correct graft length, which is closely linked to the location of the femoral attachment point. We have observed that a very short graft is associated with a poor clinical result. In this way, experimental studies [6] have shown that a short graft increases its tension with knee flexion, and this will eventually cause patellofemoral osteoarthritis.

Another controversial subject in MPFL surgery that is clinically relevant is the knee flexion angle at which the graft is fixed [22]. Theoretically, the graft should be fixed in the flexion angle at which its length is greatest. Our data suggest that the best flexion angle for fixation should be 30° in the cases with an anatomic femoral fixation point because this flexion angle is where the graft is longest.

Most authors consider that isometry does not exist during the entire flexion extension range [27, 28, 34], which is in agreement with the findings of our clinical series. However, in a recently published paper by Stephen et al. [29], the authors found that the MPFL was isometric from 0° to 110°. In our virtual anatomic MPFL reconstructions, we observed that the isometry was maintained from 0° to 60°, following the isometry criteria defined by Smirk and Morris [27]. As previously mentioned, the patella is most vulnerable to dislocation in the first 30° of knee flexion. Therefore, if the graft remains isometric from 0° to 30°, the patella will be protected from lateral dislocations [27]; it does not matter whether the graft loses tension with higher degrees of knee flexion. In our nonanatomic reconstructions with satisfactory clinical results, isometry was achieved from 0° to 30°, and the graft length was at least similar to the anatomic virtual ligament. In the cases in which surgery failed, this normal pattern of isometry was lost.

There is currently debate about the exact consequences of a nonanatomic MPFL reconstruction for the clinical results. There are only two papers that correlate the femoral fixation point during MPFL reconstruction surgery with clinical results. Servien et al. [26] found no negative effects of a nonanatomic femoral fixation point on the clinical results after a 2-year follow-up. A possible reason for this might be that the femoral fixation point was close enough to its ideal position to avoid having a negative effect. In our series, we found negative clinical consequences only with fixation points that were too anterior. Servien et al. [26] might also not have found a correlation between the nonanatomic femoral fixation point and the clinical result because of the short follow-up of their patients (2 years). This is particularly relevant with regard to the risk of developing osteoarthritis. A nonanatomic fixation point is a risk factor for surgery failure, as shown by Camp et al. [2], who observed that 80 % of patients had a new patella dislocation 4 years after surgery. In contrast, in our 5 or more years of follow-up of cases with nonanatomic femoral fixation points, no cases of new patellar dislocations were found.

Potentially meaningful clinical implications may be drawn from our findings in the context of MPFL reconstruction surgery. In a knee with a chronic lateral patellar instability, some degree of chondropathy of the medial facet of the patella is frequently found. If the graft we use to replace the MPFL in such a knee is more robust and rigid than the native MPFL, maintaining isometry during the entire range of motion of the knee would likely produce greater patellofemoral compression in a joint, causing the pre-existing medial patellar chondropathy to worsen. Therefore, in a knee with chronic lateral patellar instability, having ligament isometry just from 0° to 30° would be desirable. Thaunat and Erasmus [33] referred to this as "favourable anisometry", which our goal of stabilizing the patella in the 0°–30° range would achieve.

One of the strongest points of our study is that it was conducted in vivo, preserving the effect that soft tissues and surrounding muscle forces have on the patellofemoral alignment. Also, in our study, the knees are from young patients, with anatomic stigmas of a knee with a chronic lateral patellar instability.

However, the study has several limitations. First, a relatively small cohort was analysed. Secondly, despite attempts to limit potential confounding factors, it is not always possible to control some individual factors. Thirdly, grafts were analysed in non-weight-bearing conditions, and the effects of weight on the dynamics of the patellofemoral joint could therefore not be ascertained. The fourth weakness is that even though the study model was a 3D-CT knee, the measurements were in 2D and a ligament is not a strictly linear structure, but rather curvilinear. Fifth, the in vivo knee joint kinematics were only acquired in five flexion positions due to time and ionizing radiation exposure constraints. Moreover, if excessive tension was applied on the graft, the measured distance between the femoral and the patella fixation points could have been artificially shortened, which could have biased the final results. Finally, as far as we know, very few authors have used this methodology to evaluate the MPFL. Therefore, more studies will be necessary to validate this evaluation method and to confirm our results.

This study shows that a nonanatomic femoral fixation point is not always clinically responsible for persistent pain and instability after MPFL reconstruction.

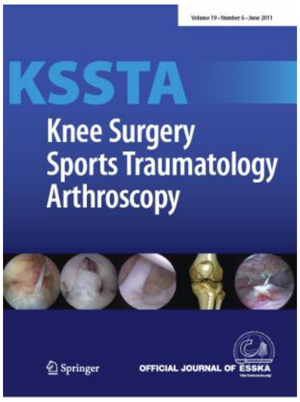
Conclusion

Establishing an anatomic femoral fixation point during MPFL reconstruction is an easy and reproducible way to achieve an optimal pattern of change in graft length, isometry, and an ideal graft length. However, a nonanatomic reconstruction that reproduces isometry, the pattern for the change in length, and the length of a native MPFL will provide a satisfactory clinical result.

References

1. Amis AA, Firer P, Mountney J, Senavongse W, Thomas NP (2003) Anatomy and biomechanics of the medial patellofemoral ligament. Knee 10(3):215–220
2. Camp CL, Krych AJ, Dahm DL, Levy BA, Stuart MJ (2010) Medial patellofemoral ligament repair for recurrent patellar dislocation. Am J Sports Med 38(11):2248–2254
3. Conlan T, Garth WP Jr, Lemons JE (1993) Evaluation of the medial soft-tissue restraints of the extensor mechanism of the knee. J Bone Joint Surg Am 75(5):682–693
4. Dejour D, Le Coultre B (2007) Osteotomies in patellofemoral instabilities. Sports Med Arthrosc 15:39–46
5. Desio SM, Burks RT, Bachus KN (1998) Soft tissue restraints to lateral patellar translation in the human knee. Am J Sports Med 26(1):59–65
6. Elias JJ, Cosgarea AJ (2006) Technical errors during medial patellofemoral ligament reconstruction could overload medial patellofemoral cartilage: a computational analysis. Am J Sports Med 34:1478–1485
7. Fujino K, Tajima G, Yan J, Kamei Y, Maruyama M, Takeda S, Kikuchi S, Shimamura T (2015) Morphology of the femoral

insertion site of the medial patellofemoral ligament. Knee Surg Sports Traumatol Arthrosc 23(4):998–1003
8. Good L (1995) In vitro correlation between tension and length change in an anterior cruciate ligament substitute. Clin Biomech (Bristol, Avon) 10(4):200–207
9. Graf M, Diether S, Vlachopoulos L, Fucentese S, Fürnstahl P (2014) Automatic string generation for estimating in vivo length changes of the medial patellofemoral ligament during knee flexion. Med Biol Eng Comput 52(6):511–520
10. Hautamaa PV, Fithian DC, Kaufman KR, Daniel DM, Pohlmeyer AM (1998) Medial soft tissue restraints in lateral patellar instability and repair. Clin Orthop Relat Res 349:174–182
11. Higuchi T, Arai Y, Takamiya H, Miyamoto T, Tokunaga D, Kubo T (2010) An analysis of the medial patellofemoral ligament length change pattern using open-MRI. Knee Surg Sports Traumatol Arthrosc 18:1470–1475
12. Hirschmann MT, Mathis D, Rasch H, Amsler F, Friederich NF, Arnold MP (2013) SPECT/CT tracer uptake is influenced by tunnel orientation and position of the femoral and tibial ACL graft insertion site. Int Orthop 37(2):301–309
13. Hopper GP, Leach WJ, Rooney BP, Walker CR, Blyth MJ (2014) Does degree of trochlear dysplasia and position of femoral tunnel influence outcome after medial patellofemoral ligament reconstruction? Am J Sports Med 42(3):716–722
14. Jeong WS, Yoo YS, Kim DY, Shetty NS, Smolinski P, Logishetty K, Ranawat A (2010) An analysis of the posterior cruciate ligament isometric position using an in vivo 3-dimensional computed tomography-based knee joint model. Arthroscopy 26(10):1333–1339
15. Kang HJ, Wang F, Chen BC, Su YL, Zhang ZC, Yan CB (2010) Functional bundles of the medial patellofemoral ligament. Knee Surg Sports Traumatol Arthrosc 18:1511–1516
16. Kita K, Tanaka Y, Toritsuka Y, Amano H, Uchida R, Takao R, Horibe S (2015) Factors affecting the outcomes of double-bundle medial patellofemoral ligament reconstruction for recurrent patellar dislocations evaluated by multivariate analysis. Am J Sports Med. doi: 10.1177/0363546515606102
17. Matsushita T, Kuroda R, Oka S, Matsumoto T, Takayama K, Kurosaka M (2014) Clinical outcomes of medial patellofemoral ligament reconstruction in patients with an increased tibial tuberosity-trochlear groove distance. Knee Surg Sports Traumatol Arthrosc 22(10):2438–2444
18. Moritomo H, Noda K, Goto A, Murase T, Yoshikawa H, Sugamoto K (2009) Interosseous membrane of the forearm: length change of ligaments during forearm rotation. J Hand Surg Am 34(4):685–691
19. Nomura E, Inoue M, Osada N (2005) Anatomical analysis of the medial patellofemoral ligament of the knee, especially the femoral attachment. Knee Surg Sports Traumatol Arthrosc 13(7):510–515
20. Nishimori M, Deie M, Adachi N, Nakamae A, Ishifuro M, Ochi M (2014) Simulated anterior cruciate ligament reconstruction using preoperative three-dimensional computed tomography. Knee Surg Sports Traumatol Arthrosc 22(5):1175–1181
21. Oka S, Matsushita T, Kubo S, Matsumoto T, Tajimi H, Kurosaka M, Kuroda R (2014) Simulation of the optimal femoral insertion site in medial patellofemoral ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. doi:10.1007/s00167-014-3192-1
22. Sanchis-Alfonso V (2014) Guidelines for medial patellofemoral ligament reconstruction in chronic lateral patellar instability. J Am Acad Orthop Surg 22:175–182
23. Sanchis-Alfonso V, Ramirez-Fuentes C, Montesinos-Berry E, Aparisi-Rodriguez F, Martí-Bonmatí L (2015) Does radiographic location ensure precise location of the femoral fixation site in medial patellofemoral ligament surgery? Knee Surg Sports Traumatol Arthrosc. doi:10.1007/s00167-015-3523-x
24. Schoettle PB, Schmeling A, Rosenstiel N, Weiler A (2007) Radiographic landmarks for femoral tunnel placement in medial patellofemoral ligament reconstruction. Am J Sports Med 35:801–804
25. Seo YJ, Song SY, Kim IS, Seo MJ, Kim YS, Yoo YS (2014) Graft tension of the posterior cruciate ligament using a finite element model. Knee Surg Sports Traumatol Arthrosc 22(9):2057–2063
26. Servien E, Fritsch B, Lustig S, Demey G, Debarge R, Lapra C, Neyret P (2011) In vivo positioning analysis of medial patellofemoral ligament reconstruction. Am J Sports Med 39:134–139
27. Smirk C, Morris H (2003) The anatomy and reconstruction of the medial patellofemoral ligament. Knee 10:221–227
28. Steensen RN, Dopirak RM, McDonald WG 3rd (2004) The anatomy and isometry of the medial patellofemoral ligament: implications for reconstruction. Am J Sports Med 32:1509–1513
29. Stephen JM, Lumpaopong P, Deehan DJ, Kader D, Amis AA (2012) The medial patellofemoral ligament: location of femoral attachment and length change patterns resulting from anatomic and nonanatomic attachments. Am J Sports Med 40(8):1871–1879
30. Song SY, Pang CH, Kim CH, Kim J, Choi ML, Seo YJ (2015) Length change behavior of virtual medial patellofemoral ligament fibers during in vivo knee flexion. Am J Sports Med 43(5):1165–1171
31. Tan J, Xu J, Xie RG, Deng AD, Tang JB (2011) In vivo length and changes of ligaments stabilizing the thumb carpometacarpal joint. J Hand Surg Am 36(3):420–427
32. Tateishi T, Tsuchiya M, Motosugi N, Asahina S, Ikeda H, Cho S, Muneta T (2011) Graft length change and radiographic assessment of femoral drill hole position for medial patellofemoral ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 19:400–407
33. Thaunat M, Erasmus PJ (2007) The favourable anisometry: an original concept for medial patellofemoral ligament reconstruction. Knee 14:424–428
34. Victor J, Wong P, Witvrouw E, Sloten JV, Bellemans J (2009) How isometric are the medial patellofemoral, superficial medial collateral, and lateral collateral ligaments of the knee? Am J Sports Med 37:2028–2036
35. Wagner D, Pfalzer F, Hingelbaum S, Huth J, Mauch F, Bauer G (2013) The influence of risk factors on clinical outcomes following anatomical medial patellofemoral ligament (MPFL) reconstruction using the gracilis tendon. Knee Surg Sports Traumatol Arthrosc 21(2):318–324
36. Yoo YS, Chang HG, Seo YJ, Byun JC, Lee GK, Im H, Song SY (2012) Changes in the length of the medial patellofemoral ligament: an in vivo analysis using 3-Dimensional computed tomography. Am J Sports Med 40(9):2142–2148
37. Yoo YS, Jeong WS, Shetty NS, Ingham SJ, Smolinski P, Fu F (2010) Changes in ACL length at different knee flexion angles: an in vivo biomechanical study. Knee Surg Sports Traumatol Arthrosc 18(3):292–297



Editorial Office:
Runeeta RAI
email: kssta@esska.org
Centre Médical - FNM
76, rue d'Eich
L-1460 Luxembourg
Phone: (+352) 4411-7036

Luxembourg, 24 October 2018

To whom it may concern

The affiliation of the article's co-author, Dr. Erik Montesinos-Berry, for the article published in KSSTA:

Sanchis-Alfonso, V., Ramirez-Fuentes, C., Montesinos-Berry, E., Domenech, J., & Martí-Bonmatí, L. (2015). Femoral insertion site of the graft used to replace the medial patellofemoral ligament influences the ligament dynamic changes during knee flexion and the clinical outcome. Knee Surgery, Sports Traumatology, Arthroscopy, 25(8), 2433–2441. doi:10.1007/s00167-015-3905-0

is being modified by means of an addendum to:

Erik Montesinos-Berry MD, Orthopaedic Surgeon, Agoriaz Orthopaedic Center, Riaz, Switzerland. PhD Candidate Universitat Autònoma de Barcelona (UAB).

Jon Karlsson
Editor-in-Chief

Original Research

Radiographic Location Does Not Ensure a Precise Anatomic Location of the Femoral Fixation Site in Medial Patellofemoral Ligament Reconstruction

Vicente Sanchis-Alfonso,*†‡ MD, PhD, Cristina Ramírez-Fuentes,§ MD, PhD,
Erik Montesinos-Berry,‖¶# MD, Isabel Elía,§ MD and Luis Martí-Bonmatí,§ MD, PhD

Investigation performed at the Department of Radiology, Hospital Universitario y Politécnico La Fe, Valencia, Spain

---

Background: A frequently used method to determine the anatomic femoral fixation point in the operating room during medial patellofemoral ligament (MPFL) reconstruction is the radiographic method. However, the ability of this radiological method to establish an anatomic femoral attachment point might not be as accurate as expected.

Purpose: (1) To evaluate the accuracy of the radiological method to locate the anatomic femoral fixation point in MPFL reconstruction surgery and (2) to determine the factors influencing the predictability of this method to obtain this objective.

Study Design: Cohort study (diagnosis); Level of evidence, 2.

Methods: A total of 100 consecutive 3-dimensional computed tomography (3D CT) knee examinations were performed at 0° of extension in 87 patients treated for chronic lateral patellar instability. For each knee, 2 virtual 7 mm–diameter femoral tunnels were created: 1 using the adductor tubercle as a landmark (anatomic tunnel) and the other according to the radiological method described by Schöttle et al (radiographic tunnel). We measured the percentage of overlap between both tunnels. Moreover, of the 100 included knees, 10 were randomly selected for a variability study.

Results: Considering an overlap area greater than 50% as reasonable, the radiographic method achieved this in only 38 of the 100 knees. Intrarater and interrater reliability were excellent. There was a trend for female patients with severe trochlear dysplasia to have less overlap. This model accounted for 64.2% of the initial variability in the data.

Conclusion: An exact anatomic femoral tunnel placement could not be achieved with the radiographic method. Radiography provided only an approximation and should not be the sole basis for the femoral attachment location. Moreover, in female patients with severe trochlear dysplasia, the radiographic method was less accurate in determining the anatomic femoral fixation point, although differences were not statistically significant.

Keywords: medial patellofemoral ligament; femoral attachment; MPFL anatomic reconstruction; 3D CT

Medial patellofemoral ligament (MPFL) reconstruction as a treatment for chronic lateral patellar instability is becoming more popular around the world.[8] One of the key factors for the success of this surgical procedure is the correct choice of the femoral attachment point.[8] The selected femoral attachment point is of utmost importance for MPFL graft length changes during knee flexion and relative graft length.[11] Both factors influence the long-term success and failure rates of MPFL reconstruction surgery.[11] Establishing an anatomic femoral fixation point during MPFL reconstruction is an easy and reproducible way to achieve an optimal change in the length pattern of the graft, correct isometry, an ideal graft length, and graft stress as well as good long-term clinical results.[11] Proper femoral placement restores physiological kinematics and patellofemoral

---

*Address correspondence to Vicente Sanchis-Alfonso, MD, PhD, Avd Cardenal Benlloch 36, 23, 46021 Valencia, Spain (email: vicente.sanchis.alfonso@gmail.com).

†Hospital 9 de Octubre, Valencia, Spain.

‡Hospital Arnau de Vilanova, Valencia, Spain.

§Hospital Universitario y Politécnico La Fe and Biomedical Imaging Research Group (GIBI230), Instituto de Investigación Sanitaria La Fe, Valencia, Spain.

‖Agoriaz Orthopaedic Center, Riaz, Switzerland.

¶Clinique CIC, Montreux, Switzerland.

#Universidad Autónoma de Barcelona, Barcelona, Spain.

The authors declared that they have no conflicts of interest in the authorship and publication of this contribution.

Ethical approval for this study was obtained from the Instituto de Investigación Sanitaria La Fe (registration No. 2013/0341).

The Orthopaedic Journal of Sports Medicine, 5(11), 2325967117739252
DOI: 10.1177/2325967117739252

pressure postoperatively.[11] To determine the anatomic femoral fixation point in the operating room, the radiographic method described by Schöttle et al[12] in 2007 is frequently used. This radiographic method simplifies the operative procedure and allows for a very small skin incision at the femoral side of the knee. However, the precision of this radiological method to establish an anatomic femoral attachment point might not be as accurate as expected.

It has been shown that this radiographic method provides only an approximation and should not be the sole basis for the anatomic femoral attachment location.[10] The main limitation of this previous study was that the number of patients in the series was relatively small.[10] Another important limitation was the fact that all the different measurements were taken by the same radiologist, and therefore the reproducibility of the method used to determine the femoral attachment location was not evaluated, which could lead to important errors and biases.[10]

The objectives of this study were (1) to evaluate the radiographic method described by Schöttle et al[12] regarding the accuracy of the anatomic location for the femoral fixation point of the MPFL and (2) to determine the factors influencing the predictability of this method to establish an anatomic femoral fixation point. Our main hypothesis was that in most patients with chronic lateral patellar instability, the Schöttle method would not ensure a precise fixation point from an anatomic standpoint in MPFL reconstruction surgery. Our secondary hypothesis was that in a group of female patients with severe dysplasia, which is more surgically demanding, the radiological method would have more failures.

METHODS

Patients

Enrolled in this study were 87 patients (65 female, 22 male) treated for chronic lateral patellar instability with at least 2 documented patellar dislocations (Table 1). In 13 patients, the contralateral knee also underwent MPFL reconstruction because of chronic lateral patellar instability with at least 2 documented patellar dislocations. Therefore, the total number of knees analyzed was 100. All knees were preoperatively evaluated for patella alta (Caton-Deschamps index ≥1.2 on lateral knee radiography), tibial tuberosity–trochlear groove (TT-TG) distance on CT, and trochlear dysplasia according to the 4 types of the Dejour[1,2] classification on CT. This study was approved by the hospital's institutional review board (Hospital Universitario y Politécnico La Fe; No. 2013/0341). All patients gave their informed consent.

TABLE 1

Patient Characteristics[a]

Age, mean (range), y	24 (14-48)
Sex, n	
Male	22
Female	65
Patella alta, No. of knees	45
Pathological TT-TG distance (>20 mm), No. of knees	39
TT-TG distance, mean (range), mm	19.12 (4-33)
Trochlear dysplasia, No. of knees	77
Type A	12
Type B	11
Type C	19
Type D	35

[a] TT-TG, tibial tuberosity–trochlear groove.

Computed Tomography

A total of 100 consecutive 3-dimensional computed tomography (3D CT) knee examinations were performed. All the knees were imaged with a high–spatial resolution 256–detector row CT scanner (Brilliance iCT; Philips) at 0° of extension. The raw data sets were acquired under 64 × 0.625–mm collimation, rotation time of 0.5 seconds, slice reconstruction thickness of 0.9 mm, pitch of 0.45, 120 kV, and automated mAs control. All patients had the gonads shielded by the placement of a lead apron. Images were reconstructed and transmitted to a picture archiving and communication system (Impax; AGFA HealthCare). A 3D bone surface–rendering knee image was obtained in all of the cases.

Imaging Analysis

For each knee, 2 virtual 7 mm–diameter femoral tunnels were created "in silico" on the surface-rendering images. One of the tunnels was created using the adductor tubercle as a landmark because it is a well-defined anatomic point of reference and because the relationship between the adductor tubercle and the femoral insertion of the MPFL is constant ($\sim$1 cm).[4,15,17,18] This was considered as the *anatomic tunnel* (Figure 1A). The other was created according the radiological method described by Schöttle et al[12] (Figure 1B). This was considered as the *radiographic tunnel*. We used 7 mm as a fixed standardized diameter because it is the tunnel width normally used in our daily surgical practice. The percentage of the anatomic tunnel covered by the tunnel created according to the Schöttle method was calculated. A simple spatial overlap index, termed the *overlap coefficient*, was set at 50% to define the minimum overlap to be considered as similar, as the value ranges from 0 (no spatial overlap between the 2 locations) to 1 (complete overlap). The 50% overlap was arbitrarily established to minimize spurious results and maximize clinical similarity in a similar way to the kappa statistic. To measure the percentage of overlap, open-access software (GeoGebra 4.4; https://www.geogebra.org/download) was used according to the technique described previously.[10]

Recent studies have shown that the femoral insertion of the MPFL is located distal to the adductor tubercle at the midpoint between the medial femoral epicondyle and the adductor tubercle.[5,7,15-18] According to Fujino et al,[4] the femoral attachment of the MPFL is distal to the apex of the adductor tubercle and parallel to the long axis of the femur;

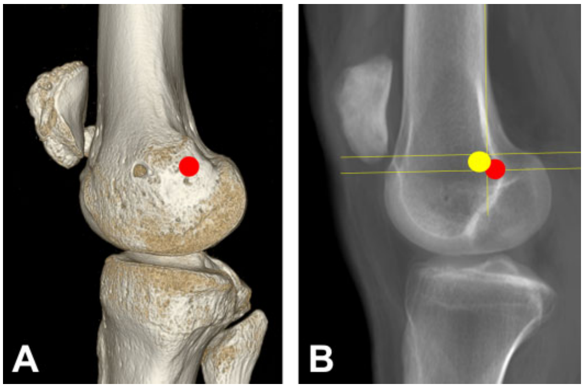


Figure 1. Using software analysis, the point calculated on 3-dimensional computed tomography was translated to a 2-dimensional fluoroscopy image. (A) Tunnel created using the adductor tubercle as a landmark (anatomic tunnel) (red circle). (B) Tunnel created according to the radiological method described by Schöttle et al[12] (yellow circle).

the mean linear distance between the 2 points was 10.6 mm, and the position of the insertion site was consistent in all knees. The great variability in the location of the adductor tubercle explains the variability in the location of the femoral insertion of the MPFL. Therefore, the MPFL must be considered unique for every person. That is, the optimal femoral position is patient specific and must be precisely defined before surgery. Volumetric 3D CT provides the opportunity to locate the adductor tubercle and therefore the location of the femoral attachment point of the MPFL based on the location of the adductor tubercle. According to Schöttle et al,[12] the radiographic site of the anatomic MPFL femoral attachment is located, on a true lateral radiograph, 1.3 mm anterior to the tangent line to the posterior femoral cortex, 2.5 mm distal to the perpendicular line drawn through the top of the medial femoral condyle, and proximal to the perpendicular line drawn through the most posterior part of the Blumensaat line. In our study, 3D CT was used to define the Schöttle area by determining the Blumensaat line in the distal femur's surface-rendering 3D reconstruction after eliminating the contralateral condyle in the image.

Of the 100 included knees, 10 were randomly selected for the variability study. Two radiologists with more than 5 years of experience in musculoskeletal radiology (C.R.-F. and I.E.) performed the measurements. Both radiologists independently measured all 10 of the knees 5 times with a time interval of at least 1 week between each measurement. Both observers were blinded to any additional data. Before performing the measurements, the 2 observers agreed on the precise definitions of the landmarks to be used, according to the anatomic method described by Fujino et al[4] and the radiological method described by Schöttle et al.[12]

Statistical Analysis

All values were expressed as the mean ± SD. A P value of $<.05$ was considered significant. Interclass and intraclass correlation coefficients (ICCs) were obtained in the 10 randomly chosen knees in the variablilty study. The chi-square test was used to analyze the relationships between an overlap greater than 50% and the major factors of instability (trochlear dysplasia, TT-TG distance >20 mm, and patella alta). Moreover, a multivariate statistical technique (correspondence analysis) was used to analyze the relationship between the categories of variables. To compare the 3 qualitative variables (percentage of overlap, trochlear dysplasia, and sex), contrasts of proportions were used. All statistical analyses were performed using SPSS software version 17 (IBM).

RESULTS

The mean percentage of the overlap area of the femoral tunnel using the radiographic method and the anatomic landmarks was 38.97% ± 23.58% (range, 0%-93%). Considering an overlap area greater than 50% as reasonable, the radiographic method achieved it in only 38 of the 100 knees (38%). The point identified with the radiographic method was located in 92% of the knees anterior and proximal to the point that we considered as anatomic.

The mean percentage of overlap obtained by the 2 observers was 47.1% ± 26.9% and 47.2% ± 31.1%, respectively. The intrarater reliability for the measurement of the percentage of the anatomic tunnel area covered by the femoral tunnel created using the radiographic method was similar for both radiologists: observer 1 ICC = 0.866 (95% CI, 0.716-0.959); observer 2 ICC = 0.862 (95% CI, 0.709-0.957) (Figure 2). With regard to interrater reliability, the ICC was 0.943 (95% CI, 0.800-0.985) (Figure 3).

Evaluating the influence of dysplasia on the results, 37% of knees with dysplasia had an overlap area greater than 50% compared with 39% of knees without dysplasia, with the differences being nonsignificant ($\chi^2 = 0.016$, $P = .898$). The percentage was lower (31%) in knees with severe trochlear dysplasia compared with 47% of knees that did not have severe dysplasia. However, these differences were also not statistically significant ($\chi^2 = 2.608$, $P = .1063$).

The influence of patient sex was also statistically nonsignificant. The overlap area was greater than 50% in 44% of male patients compared with 36% of female patients ($\chi^2 = 0.652$, $P = .419$). The area of overlap was greater than 50% in 36% of knees with patella alta compared with 40% of knees that did not have patella alta. However, the differences were not statistically significant ($\chi^2 = 0.126$, $P = .723$).

An area of overlap greater than 50% was observed in only 33% of knees with an increased TT-TG distance (>20 mm) compared with 41% of knees that did not present a pathological TT-TG distance. These differences were also not significant ($\chi^2 = 0.591$, $P = .442$).

Finally, an overlap of more than 50% of the anatomic femoral tunnel was obtained using the radiographic method in only 30% (12/40) of female patients with severe trochlear dysplasia (type C and D) compared with 67% (7/12) of male patients without severe trochlear dysplasia ($Z = -1.774$, $P = .076$). The differences were not statistically

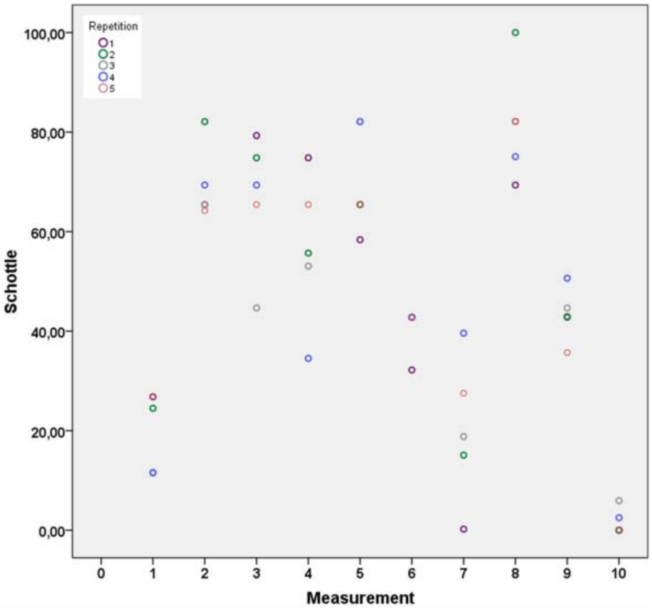


Figure 2. Bland-Altman plot of intrarater reliability.

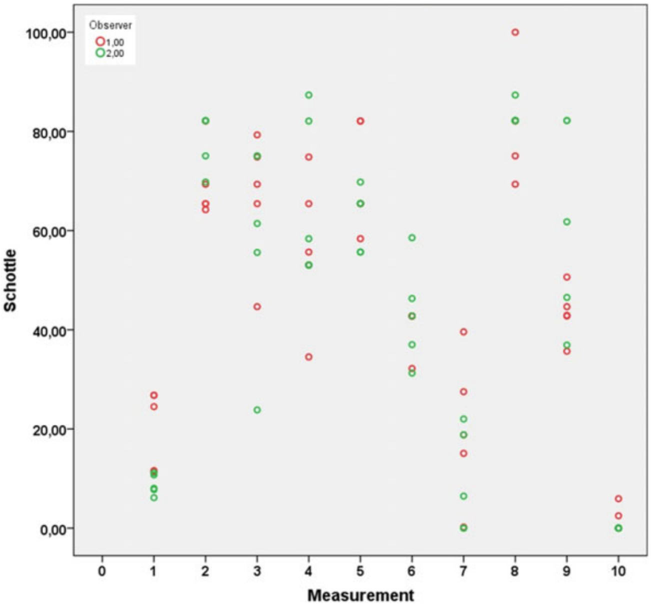


Figure 3. Bland-Altman plot of interrater reliability.

TABLE 2
Severe Trochlear Dysplasia by Sex

	Tunnel Overlap >50%, %	
	No	Yes
No		
Male	41.67	58.33
Female	57.58	42.42
Yes		
Male	66.67	33.33
Female	70.00	30.00

significant, but a tendency toward significance could be observed (Table 2).

In the multivariate statistical analysis, none of the analyzed factors (patella alta, TT-TG distance >20 mm, or trochlear dysplasia) had a significant effect on the percentage of overlap greater than 50% of the anatomic femoral tunnel using the radiographic method. Only severe trochlear dysplasia might predict nonoverlapping, although the association was not statistically significant ($P = .069$). Only severe trochlear dysplasia correlated with no overlaps greater than 50%. This regression model used to analyze the relationship between categories of variables predicting accurate (overlapping) tunnels accounted for 64.2% of the initial variability in the data.

DISCUSSION

Our study confirms that the radiographic method described by Schöttle et al[12] did not ensure a precise location, from an anatomic standpoint, of the femoral fixation point in MPFL reconstruction surgery in patients with chronic lateral patellar instability. In most cases, 2-dimensional (2D) radiological methods do not allow for a proper anatomic femoral placement.[10] Compared with that study,[10] our current investigation has important strengths. First, the number of evaluated knees is larger (30 vs 100, respectively), with the results being more generalizable. Also, an analysis of the interobserver and intraobserver variability of the 2 methods used to identify the femoral fixation point of the MPFL was performed to validate previous results.

Interobserver and intraobserver variability could affect the reliability of the volumetric 3D CT scan analysis to assess the femoral attachment location. Accuracy and reproducibility in radiological results are important because many crucial surgical decisions are often based on the assumption that they represent the truth. Radiologist-dependent factors, among others, might contribute to measurement inconsistencies. In our series, high intraobserver and interobserver consistency was shown. Our findings validate previous results.[10] Moreover, our study is in agreement with that of Ziegler et al,[19] who demonstrated that even using a pure lateral radiological view as recommended by Schöttle et al,[12] the radiological method is not a precise method to determine the anatomic femoral fixation point of the MPFL. In our study, we also used a strict lateral view. In this ideal situation, the authors found a mean distance of 4.1 mm from the anatomic MPFL attachment.[19] If the lateral radiograph is not strictly lateral, the error is even greater. Just a small 5° rotation will have a significant effect in determining the anatomic femoral fixation point (7.5-9.2 mm).[19]

Our study has clinical implications in MPFL reconstruction surgery. The 2D method will frequently produce a nonanatomic femoral tunnel placement. A malpositioned femoral tunnel occurs in between 31% and 64% of MPFL reconstructions.[6,13] The determination of the femoral attachment point location in MPFL reconstruction surgery is of major importance because it determines the length change behavior of the graft and therefore the graft tension and patellofemoral compression force at different angles of knee flexion.[11] Mistakes in the femoral attachment point have resulted in increased patellofemoral contact pressure, increased rates of MPFL reconstruction failure, and loss of graft isometry.[3,9] In the present study, it was observed that certain patients may have had more errors with the 2D method (female patients with trochlear dysplasia), but this was not a significant finding. The clinical relevance of this finding lies in the fact that lateral patellar instability is more frequent in female patients with severe trochlear dysplasia. Moreover, this is the most surgically demanding group and therefore requires a more precise anatomic technique. The reason is simple: the MPFL graft must compensate for the harmful effects of the associated anatomic factors that favor patellar instability.

Fluoroscopy is an ingenious real-time radiographic method that can be most helpful for surgeons who perform this type of surgery very occasionally to avoid gross failures at the time of determining the femoral attachment point in MPFL reconstruction surgery. Although fluoroscopy is extremely variable and prone to errors, it seems to work to some extent when combined with isometry testing. Without advanced 3D imaging, the only accurate way to be sure of an anatomic femoral placement of the graft and to perform accurate MPFL reconstruction is to make a large enough incision to unequivocally identify the most important anatomic landmark: the adductor tubercle.

The femoral insertion of the MPFL is located between the adductor tubercle and the medial epicondyle. It has been observed that the distance between the adductor tubercle and the femoral insertion of the MPFL has lower variations than that between the medial femoral epicondyle and the femoral insertion of the MPFL.[17] That is the reason why some authors advocate the use of the adductor tubercle as a landmark for MPFL reconstruction instead of the medial femoral epicondyle.[17] Moreover, the adductor tubercle is a well-defined anatomic landmark and therefore easier to identify than the medial femoral epicondyle.[17] According to Viste et al,[17] the relationship between the adductor tubercle and the femoral insertion of the MPFL is constant (10 mm below). Smirk and Morris[15] also found that the femoral insertion of the MPFL is most frequently located 1 cm distal to the adductor tubercle. According to Wijdicks et al,[18] the attachment of the MPFL is 8.9 ± 2.0 mm from the adductor tubercle. These findings are in accordance with those observed by Fujino et al,[4] who found that the anatomic MPFL femoral attachment point is located 10.6 mm distal to the apex of the adductor tubercle and was also consistent between knees. These are the reasons why the adductor tubercle has been considered the landmark to identify the femoral fixation point of the MPFL in our study.

Fujino et al[4] used the adductor tubercle as a landmark to identify the femoral fixation point of the MPFL. Yet, these authors used 3D CT reconstructions of the distal femur. The bone surface anatomy of the medial side of the distal femur is easily detected with 3D CT–reconstructed images. As small-incision surgery is preferred by patients over large-incision surgery, an attractive option would be to use 3D CT technology to locate the anatomic femoral attachment point. With the 3D CT method, we can determine exactly where the adductor tubercle is. 3D CT provides an image similar to what we would find with a surgical dissection of that anatomic area.

As previously mentioned, there is consensus among studies regarding the fact that the distance between the adductor tubercle and the MPFL femoral fixation point, estimated at 1 cm, is constant and uniform between different knees.[4,15,17,18] Based on this finding, 3D CT allows us to determine the femoral fixation point of the MPFL for each specific knee. 3D CT allows one to locate the femoral attachment point of the MPFL based on the location of the adductor tubercle. This point that can be exactly determined on 3D CT can be easily extrapolated, through specific software, to a 2D image (see Figure 1). It would be a similar image to what we can obtain with fluoroscopy in the operating room. Therefore, using radioscopy in the operating room, with a strict lateral view, we can identify this fixation point that the radiologist has extrapolated into a 2D image. We would not need a large incision to identify the femoral insertion point; a 1- to 1.5-cm incision would be enough for femoral fixation of the graft. This surgical technique would practically be a percutaneous technique. Thus, 3D CT allows us to perform tailor-made surgery, determining the femoral attachment point location based on anatomy. Our findings are in accordance with those of Siebold and Borbon,[14] who recommended individualizing the femoral fixation site, as it varies in each patient.

One limitation of our study is that the test used of contrasts of proportions is only applicable to large sample sizes ($n > 30$), and the sample size of male patients without severe dysplasia was smaller ($n = 12$). Therefore, the number of patients, especially male patients without severe dysplasia, should be increased, although the difficulty is that the prevalence of the disease in this group of patients is low.

CONCLUSION

An exact anatomic femoral tunnel placement could not be achieved with the Schöttle method. Radiographic 2D identification of the femoral graft placement site only provided an approximation and should not be the sole basis for the femoral attachment location. The femoral attachment point must be determined during surgical exposure based on knowledge of the anatomy, and 3D imaging may aid in identifying the appropriate location.

REFERENCES

1. Dejour D, Le Coultre B. Osteotomies in patellofemoral instabilities. *Sports Med Arthrosc*. 2007;15:39-46.
2. Dejour H, Walch G, Nove-Josserand L, Guier C. Factors of patellar instability: an anatomic radiographic study. *Knee Surg Sports Traumatol Arthrosc*. 1994;2(1):19-26.
3. Elias JJ, Cosgarea AJ. Technical errors during medial patellofemoral ligament reconstruction could overload medial patellofemoral

cartilage: a computational analysis. *Am J Sports Med*. 2006;34(9): 1478-1485.

4. Fujino K, Tajima G, Yan J, et al. Morphology of the femoral insertion site of the medial patellofemoral ligament. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(4):998-1003.
5. LaPrade MD, Kennedy MI, Wijdicks CA, LaPrade RF. Anatomy and biomechanics of the medial side of the knee and their surgical implications. *Sports Med Arthrosc*. 2015;23(2):63-70.
6. McCarthy M, Ridley TJ, Bollier M, Wolf B, Albright J, Amendola A. Femoral tunnel placement in medial patellofemoral ligament reconstruction. *Iowa Orthop J*. 2013;33:58-63.
7. Nomura E, Horiuchi Y, Kihara M. Medial patellofemoral ligament restraint in lateral patellar translation and reconstruction. *Knee*. 2000;7(2):121-127.
8. Sanchis-Alfonso V. Guidelines for medial patellofemoral ligament reconstruction in chronic lateral patellar instability. *J Am Acad Orthop Surg*. 2014;22:175-182.
9. Sanchis-Alfonso V, Montesinos-Berry E, Ramirez-Fuentes C, Leal-Blanquet J, Gelber PE, Monllau JC. Failed medial patellofemoral ligament reconstruction: causes and surgical strategies. *World J Orthop*. 2017;8(2):115-129.
10. Sanchis-Alfonso V, Ramirez-Fuentes C, Montesinos-Berry E, Aparisi-Rodriguez F, Martí-Bonmatí L. Does radiographic location ensure precise location of the femoral fixation site in medial patellofemoral ligament surgery? *Knee Surg Sports Traumatol Arthrosc*. 2016;24(9): 2838-2844.
11. Sanchis-Alfonso V, Ramirez-Fuentes C, Montesinos-Berry E, Domenech J, Martí-Bonmati L. Femoral insertion site of the graft used to replace the medial patellofemoral ligament influences the ligament dynamic changes during knee flexion and the clinical outcome. *Knee Surg Sports Traumatol Arthrosc*. 2017;25(8): 2433-2441.
12. Schöttle PB, Schmeling A, Rosenstiel N, Weiler A. Radiographic landmarks for femoral tunnel placement in medial patellofemoral ligament reconstruction. *Am J Sports Med*. 2007;35(5):801-804.
13. Servien E, Fritsch B, Lustig S, et al. In vivo positioning analysis of medial patellofemoral ligament reconstruction. *Am J Sports Med*. 2011;39(1):134-139.
14. Siebold R, Borbon CA. Arthroscopic extraarticular reconstruction of the medial patellofemoral ligament with gracilis tendon autograft: surgical technique. *Knee Surg Sports Traumatol Arthrosc*. 2012;20(7): 1245-1251.
15. Smirk C, Morris H. The anatomy and reconstruction of the medial patellofemoral ligament. *Knee*. 2003;10(3):221-227.
16. Steensen RN, Dopirak RM, McDonald WG 3rd. The anatomy and isometry of the medial patellofemoral ligament: implications for reconstruction. *Am J Sports Med*. 2004;32(6):1509-1513.
17. Viste A, Chatelet F, Desmarchelier R, Fessy MH. Anatomical study of the medial patello-femoral ligament: landmarks for its surgical reconstruction. *Surg Radiol Anat*. 2014;36(8):733-739.
18. Wijdicks CA, Griffith CJ, LaPrade RF, et al. Radiographic identification of the primary medial knee structures. *J Bone Joint Surg Am*. 2009; 91(3):521-529.
19. Ziegler CG, Fulkerson JP, Edgar C. Radiographic reference points are inaccurate with and without a true lateral radiograph: the importance of anatomy in medial patellofemoral ligament reconstruction. *Am J Sports Med*. 2016;44(1):133-142.