Universitat Autònoma de Barcelona

Estudio experimental de la repercusión sobre la articulación femoropatelar de la rodilla de un tipo de reconstrucción no isométrica del ligamento patelofemoral medial

Gerardo José Ginovart Galiana

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$$\boldsymbol{A}\,\boldsymbol{x}=\boldsymbol{y},$$

$$x_i=\frac{1}{L^{\mathrm{T}}_{i,i}}\left(z_i-\sum_{k=i+1}^{n}L^{\mathrm{T}}_{i,k}\,x_k\right).$$

$$z_i=\frac{1}{L_{i,i}}\left(y_i-\sum_{k=1}^{i-1}L_{i,k}\,z_k\right)$$

$$L_{ij}=\frac{1}{L_{jj}}\left(A_{ij}-\sum_{k=1}^{i-1}L_{ik}\,L_{jk}\right),\ \text{para } i>j$$

$$L_{ii}=\sqrt{A_{ii}-\sum_{k=1}^{i-1}L_{ik}^{2}}.$$

Estudio experimental de la repercusión sobre la articulación femoropatelar de la rodilla de un tipo de reconstrucción no isométrica del ligamento patelofemoral medial

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Tesis doctoral
Gerardo José Ginovart Galiana

UAB
Universitat Autònoma
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TESIS DOCTORAL

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TUTOR DE LA TESIS

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CIRUGIA Y CIENCIAS MORFOLOGICAS

CIRUGIA ORTOPÉDICA Y TRAUMATOLOGIA

2021

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CERTIFICAN:

Que el trabajo de investigación titulado:

Estudio experimental de la repercusión sobre la articulación femoropatelar de la rodilla de un tipo de reconstrucción no isométrica del ligamento patelofemoral medial.

Ha sido realizado bajo nuestra dirección y esta en condiciones de ser presentado para lectura y defensa ante el tribunal correspondiente para obtener el titulo de Doctor.

Y para que así conste a los efectos oportunos, firmamos el presente documento en Barcelona a Julio de 2020

Prof. Dr. Joan Carles Monllau

Dr. Vicente Sanchis Alfonso

La tesis doctoral con titulo: Estudio experimental de la repercusión sobre la articulación femoropatelar de la rodilla de un tipo de reconstrucción no isométrica del ligamento patelofemoral medial y presentada por el doctorando Gerardo Jose Ginovart Galiana ha sido realizada como compendio de publicaciones siguiendo la normativa de la Universidad Autónoma de Barcelona para este tipo de tesis doctoral.

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Clinical and radiological outcomes after a quasi-anatomical reconstruction of medial patellofemoral ligament with gracilis tendon autograft. Monllau JC, Masferrer-Pino A, Ginovart G, Perez-Prieto D, Gelber P, Sanchis-Alfonso V. Knee Surg Sports Traumatol Arthrosc. 2017; 25:2453-59

Parametric Finite Element Model of medial patellofemoral ligament Reconstruction.Model development and clinical validation. Sanchis-Alfonso V, Alastruey-lopez D, Ginovart G, Montesinos-Berry E, Garcia-Castro F, Ramirez-Fuentes C, Monllau JC, Alberich-Bayarri A, Perez-Anson MA. Journal of Experimental Orthopaedics. 2019; 6(1): 32.

Evaluation of Patellar Contact Pressure Changes after Static versus Dynamic Medial Patellofemoral Ligament Reconstructions Using a Finite Element Model. Vicente Santis Alfonso, Gerard Ginovart, Diego Alastruey lopez, Erik Montesinos Berry, Joan Carles Monllau, Angel Alberich Bayarri, Maria Angeles Perez. Journal of Clinical Medicine. 2019 Dec 1; 8(12): 2093.

I*solated reconstruction of medial patellofemoral ligament with an elastic femoral fixation leads to excellent clinical results.* Vincent Marot, Vicente Sanchis Alfonso, Simone Perelli, Pablo Eduardo Gelber, Christian Javier Sanchez Rabago, Gerard Ginovart, Juan Carlos Monllau. Knee Surg Sports Traumatol Arthrosc. 2020 [Epub ahead of print]

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Muchas gracias a todos.

“ES MEJOR ENCENDER UNA VELA

QUE MALDECIR LA OSCURIDAD.”

-CONFUCIO- .

INDICE

1. FUNDAMENTOS DE LA TESIS

La inestabilidad femoropatelar (FP) es un síndrome clínico debido a anomalías morfológicas en la articulación que favorecen que la patela se disloque lateralmente. La inestabilidad FP debe entenderse como una disfunción multifactorial que esta influenciada y determinada por un conjunto de factores anatómicos, ligamentosos, óseos y neuromusculares que condicionan la orientación espacial y biomecánica de esta articulación.

El cartílago articular juega aquí un papel fundamental en la distribución de cargas, puesto que la articulación FP esta sujeta a fuerzas mecánicas de gran magnitud durante actividades cotidianas como caminar, correr, subir y bajar escaleras, etc. Cualquier cambio en la biomecánica FP puede llevar a alteraciones, tanto en la superficie del cartílago como en el hueso subcondral subyacente, y acabar afectando la fisiología y aún, en los individuos en crecimiento, la morfología de la articulación.

La inestabilidad FP supone la presencia de un defecto en la cinética y engranaje de la articulación que en caso de luxación representa la pérdida total de contacto entre las superficies articulares afectas, y, sistemáticamente, una lesión del ligamento patelofemoral medial (LPFM). La compleja biomecánica y el delicado equilibrio entre los estabilizadores estáticos y dinámicos de la articulación condiciona que la resolución quirúrgica de la inestabilidad sea compleja y que existan diversas técnicas para corregirla.

En los últimos 25 años, la reconstrucción del LPFM ha adquirido gran popularidad debido a que se ha reconocido su papel fundamental en el control de la estabilidad lateral de la rótula. Multitud de técnicas han sido descritas para la reconstrucción del LPFM. Sin embargo, la falta de definición precisa de los puntos de anclaje del LPFM, hasta muy recientemente, su vecindad con la línea de crecimiento femoral distal y la posible repercusión que inserciones inadecuadas del LPFM pudieran acarrear para el cartílago FP, motivaron el desarrollo de una técnica de reconstrucción alternativa, que se denominó cuasi-anatómica. Los buenos resultados obtenidos en niños y adolescentes con inestabilidad FP, expandieron su uso en la edad adulta, con resultados igualmente buenos y pocas complicaciones.

La frecuencia de la lesión, el prurito científico de conocer mejor el porqué de los resultados obtenidos, el interés personal por esta patología y los factores que la desencadenan (Fig 1) fueron los motivos principales de esta tesis.

Fig 1. Inestabilidad FP. Monumento funerario Georgio Meisellio, Ciudad del Vaticano. Con la autorización de Mons. Hans-Peter Fisher, Rettore Pontificio Collegio Teutonico.

El proyecto se concibió como un análisis exhaustivo de la técnica quirúrgica cuasi-anatómica desde tres vertientes diferentes: la anatómica, la clínica y la biomecánica. Las dos primeros aspectos pudieron estudiarse con relativa facilidad, a través de modelos cadavéricos y de una serie clínica, respectivamente. Para la tercera, mas compleja, se desarrolló una metodología mas sofisticada, basada en un modelo paramétrico de elementos finitos, a fin de poder cuantificar de manera mas objetiva las subsecuentes variaciones en la tensión del neoligamento y en las presiones de contacto que se generaban sobre el cartílago articular FP. Por último, de nuevo en la vertiente clínica, se pudo comprobar la bondad de la técnica mediante un estudio clínico comparativo con la técnica anatómica estándar, considerada el patrón oro de la reconstrucción del LPFM.

La relevancia clínica del proyecto global ha sido recientemente galardonada con el primer premio a la mejor comunicación en investigación en cirugía ortopédica, en el 13º Congreso Nacional INVESCOT (Valencia 29/02/2020).

2. INTRODUCCIÓN

La inestabilidad FP responde a un problema multifactorial en relación con el alineamiento de la extremidad inferior, la anatomía y congruencia trocleo-patelar, la forma e integridad de los tejidos blandos restrictores y la función de la musculatura circundante. Así pues, el diagnóstico de inestabilidad FP estará basado en la historia clínica y referencias del paciente, la exploración física y el estudio por imagen de la extremidad inferior y de la articulación en si misma.

Las causas de inestabilidad FP son múltiples, aunque no siempre están todas presentes, y es importante diferenciar las anomalías morfológicas de los factores dinámicos. Entre las anomalías morfológicas la mas importante es, sin lugar a dudas, la displasia de la tróclea femoral. Otros factores relevantes son: la altura rotuliana (rótula supera o alta), la lateralización excesiva de la tuberosidad tibial anterior y la displasia del músculo cuádriceps femoral. Existen además en la extremidad inferior, unos factores de inestabilidad secundarios como son: anomalías de torsión (anteversión femoral y rotación externa de tibia) y anomalías de alineación, en los planos frontal (genuvalgo) y sagital (genu recurvatum).

En general, la inestabilidad FP es una patología considerada poco frecuente, que afecta entre un 5.8 y un 77.4 de cada 100.000 individuos[1]. Después de un primer episodio de luxación, la posibilidad de recidiva se sitúa en torno a un 17%, aunque en pacientes con historia de inestabilidad previa la posibilidad de un nuevo episodio aumenta hasta un 49%[2] y en el caso de adolescentes, con fisis abiertas y displasia troclear, alcanza hasta un 69%[3].

A pesar de que el tratamiento conservador es el habitual en el primer episodio de luxación FP, la reconstrucción del LPFM, ya sea aislada o combinada con otros procedimientos, es actualmente recomendada como el tratamiento de elección en las recidivas.

El LPFM (Fig 2) es una estructura fibrosa, situada en la segunda capa anatómica de la cara medial de la rodilla, que conecta los dos tercios superomediales de la patela con el epicóndilo medial del fémur. Pese a que durante mucho tiempo se le prestó

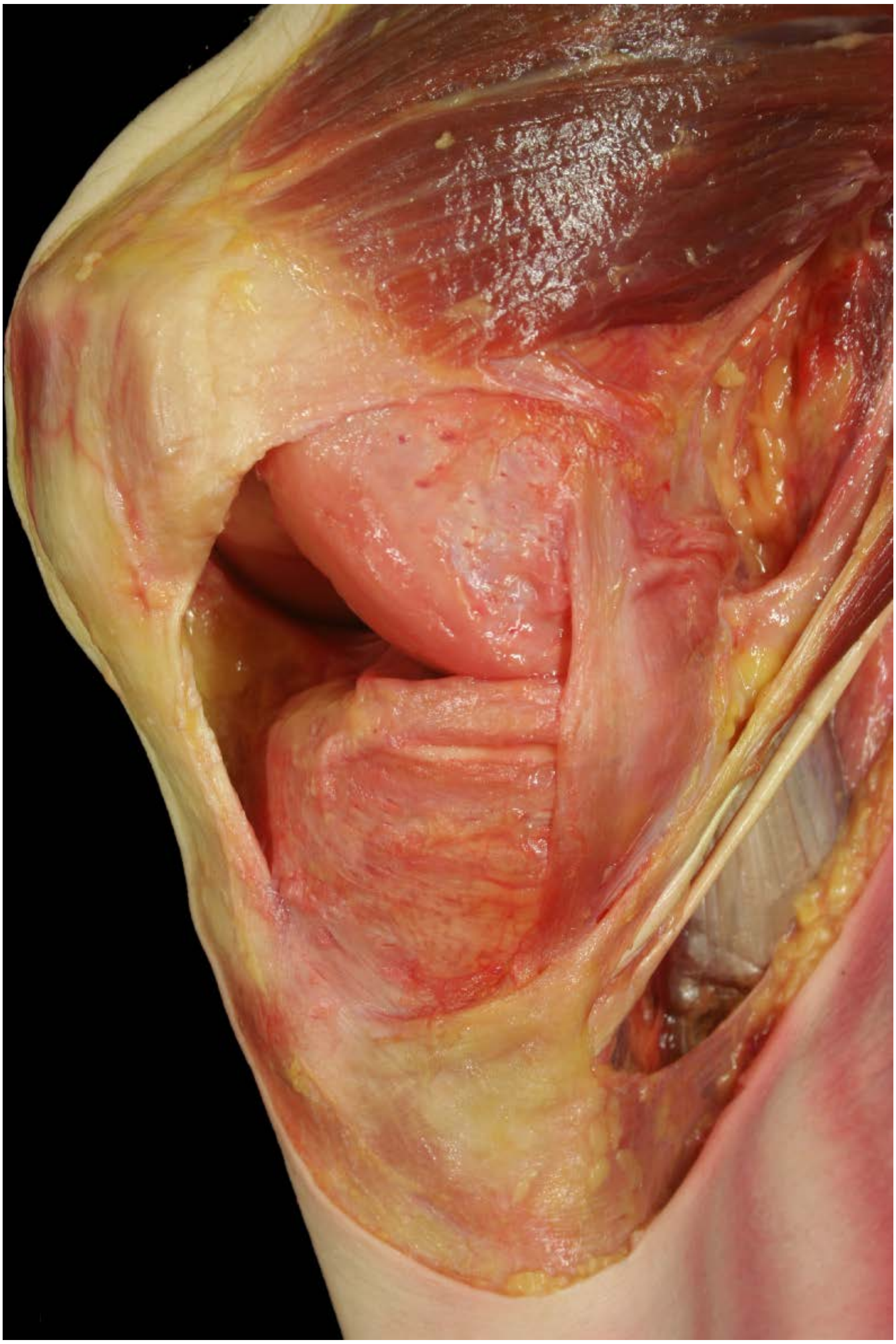

Fig 2. Disección cadavérica de la cara medial de la rodilla. Detalle del LPFM, LCM y pata de ganso. Cortesía Dr Ivan Saez (UB).

escasa atención, en los últimos años esta considerado como el principal estabilizador estático de la traslación lateral rotuliana durante los primeros 30 grados de flexión, siendo el responsable del 60% de la fuerza de restricción medial rotuliana[4-7].

En 1994, Dejour[8] describió la displasia troclear, la patela alta y la distancia TA-GT aumentada, como principales factores de riesgo de inestabilidad rotuliana. Como factores secundarios, raramente responsables por si solos de inestabilidad FP, se encuentran: la báscula rotuliana, considerada como una consecuencia de los factores precedentes que se asocian a una lesión del LPFM[9], las anomalías de la torsión femorotibial, el genuvalgum y genurecurvatum excesivos, la hiperlaxitud, el incremento del ángulo Q y la insuficiencia del vasto medial oblicuo (VMO) [8,9].

Esta comprobado que en una luxación de la rotula se produce de forma constante una lesión del LPFM, mas frecuentemente en su inserción femoral. En las lesiones agudas del LPFM se suele asociar una lesión del VMO. Cuando en un primer episodio de luxación existe esta asociación de lesiones, los resultados del tratamiento conservador, no quirúrgico, parecen ser mas satisfactorios[10,11].

Históricamente, el tratamiento de la inestabilidad FP ha variado con el tiempo. Se ha utilizado tanto tratamiento conservador como quirúrgico. El tratamiento conservador pretende favorecer la cicatrización espontánea de todas las estructuras capsuloligamentosas lesionadas. Consiste en la inmovilización en extensión de la extremidad inferior, durante unas 6 semanas. Sin embargo, las tasa de reluxación tras este tratamiento alcanza hasta un 44%[12].

En cuanto a los tratamientos quirúrgicos, se pueden distinguir una notable variedad de técnicas aunque, en general, dirigidas a corregir aquellos factores frecuentemente asociados a la luxación FP, y que se pueden resumir como sigue:

1. Trocleoplastia

    1. Este procedimiento fue descrito por primera vez en 1915 por Albee[13]. Consiste en una osteotomía de elevación de la cara lateral de la tróclea femoral, que tiene por objeto incrementar su pendiente, de manera que se oponga a la luxación lateral de la patela.

    2. Posteriormente, originalmente Masse[20] y después Dejour[21], modificaron la trocleoplastia de Albee, con la idea de crear un surco troclear, cuando no existía, o de profundizar el preexistente. Está trocleoplastia de profundización está indicada en casos de displasia FP severa. Muy recientemente, Bereiter[22]

(1994) describió una variante menos agresiva de trocleoplastia, en la que se crea un flap osteocartilaginoso delgado y deformable, que evita tener que fracturar el cartílago articular para recrear el surco.

2. Realineación del aparato extensor.

    1. Distal. Tiene por objeto medializar la inserción del cuádriceps a nivel de la tuberosidad anterior de la tibia, o en el mismo tendón patelar, con objeto de disminuir el vector valguizante. Se han descrito distintas técnicas de realineación distal, entre la mas conocidas se cuentan las de Hauser[14] (1938), la de Elmslie-Trillat[15] (1964), la de Roux-Goldthwait[15] (1979). En 1983, Fulkerson[17] introdujo el concepto de anteromedialización que no solo realinea el aparato extensor sino que avanza (ventraliza) su inserción tibial variando las presiones que soporta el cartílago FP (Fig 3). Como promedio, estas técnicas tienen una tasa de reluxación de un 7%[18].

    2. Proximal. Descrita por Insall en 1983, pretende incrementar las fuerzas medializantes dinámicas que actúan sobre la patela, trasladando medial y distalmente la inserción del VMO[19].

3. Liberación del retináculo extensor lateral (*patellar release*). Esta sencilla intervención consiste en la sección del retináculo extensor lateral para eliminar su excesiva tensión y la tendencia luxante de la patela. La técnica fue originalmente descrita por Merchant[23] en 1974. Debido a su poca efectividad para controlar la luxación, en la actualidad, no se recomienda como procedimiento aislado en el tratamiento de la inestabilidad FP[24, 25].

4. Reconstrucción del LPFM. En 1992, Ellera Gomes[26] centró la atención del tratamiento de la inestabilidad FP en la reconstrucción de una estructura largamente olvidada, el LPFM. Desde entonces se han descrito numerosas variantes de la técnica que difieren, básicamente, en tres aspectos: el tipo de injerto de sustitución empleado, el modo de fijación y la posición / puntos de inserción o anclaje del neoligamento.

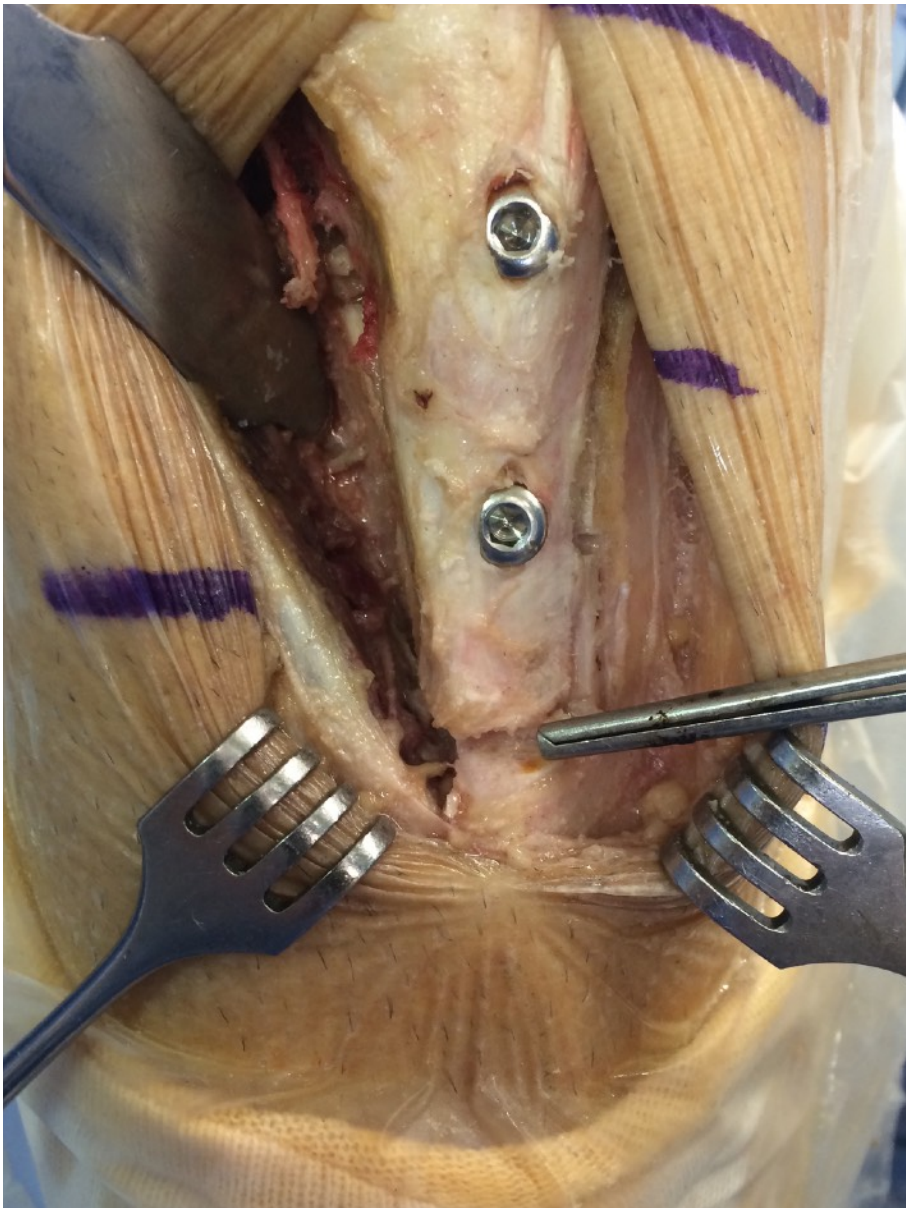

Fig 3. Imagen intraoperatoria. Realineación distal (anteromedialización) del aparato extensor, técnica de Fulkerson.

En lo que concierne al injerto, actualmente se utilizan preferentemente autoinjertos, ya sea de los tendones semitendinoso, gracilis o cuadricipital. La utilización de aloinjertos es menos frecuente y los ligamentos sintéticos, como primera elección, aunque atractiva conceptualmente, han sido abandonados debido a su mayor rigidez[27].

Sorprendentemente, en términos de estabilidad (prevención de nuevas luxaciones), a pesar de la notable variabilidad observada entre las técnicas de reconstrucción del LPFM y los injertos utilizados, la tasa de éxito que se reporta es elevada, oscilando entre un 83% y un 93%[28-31].

La principal controversia técnica estriba en la localización del punto idóneo de anclaje femoral de la plastia del LPFM. En la última década, el método mas utilizado para determinar el punto de inserción femoral del LPFM se ha basado en la radiología intraoperatoria, utilizando unas coordenadas preestablecidas[42]. Sin embargo, pese a la teórica reproductibilidad de este método, recientemente se ha demostrado que es más difícil de lo previamente estimado y que pequeñas desviaciones en la incidencia de los rayos conducen a mucha variabilidad en la precisión conseguida[39].

La precisión en los puntos de inserción es crítica para poder reproducir no solo la anatomía sino, sobretodo, la función del neoligamento. Inserciones inadecuadas, no anatómicas, pueden provocar cambios en su longitud (anisometría) y tensión durante el movimiento de la rodilla[32-36]. La repercusión de estos cambios sobre las presiones que se generan en la superficie articular FP, especialmente en su faceta medial, es relevante puesto que un incremento significativo puede condicionar degeneración artrósica con el tiempo[37-41].

Así pues, se asume que una reconstrucción del LPFM no anatómica debería considerarse anisométrica y, por tanto, conduciría a cambios en la longitud del injerto e incrementos de la tensión del ligamento que aumentarían las presiones de contacto soportadas por la vertiente medial de la FP.

Además, en los pacientes en edad de crecimiento la cercanía entre la zona de inserción original del LPFM y la línea fisaria femoral distal, condiciona que una tunelización a este nivel podría acarrear daño fisario con cierre precoz de la placa de crecimiento (epifisiodesis postquirúrgica), y las inevitables consecuencias para la alineación de la extremidad.

Hace más de 10 años, hacia 2006, la notable controversia existente respecto a las diferentes técnicas de reconstrucción del LPFM, el desconocimiento del emplazamiento más adecuado de los puntos de inserción del injerto y la necesidad de tratar pacientes en edad de crecimiento, nos motivaron a explorar en profundidad nuevos abordajes quirúrgicos para la inestabilidad FP. Así, con objeto de paliar los problemas mencionados, se desarrolló una técnica de reconstrucción del LPFM cuasi-anatómica que, en lugar de una fijación rígida a nivel del epicóndilo femoral, utilizaba el hiato del tendón adductor mayor (AM) como polea de reflexión elástica del injerto[43]. Los prometedores resultados clínicos iniciales que se obtuvieron con esta técnica, motivaron su utilización ulterior en adolescentes y después en adultos.

Aunque actualmente las reconstrucciones del LPFM son un procedimiento habitual en el mundo, pocos estudios han investigado el comportamiento de la articulación FP tras este tipo de reconstrucciones, especialmente teniendo en cuenta la diversidad de técnicas empleadas. Así, el objetivo prioritario del presente proyecto no solo derivó del interés por conocer mejor los fundamentos y el comportamiento biomecánico del procedimiento de reconstrucción propuesto, sino también de sus posibles repercusiones sobre la articulación FP.

El proyecto, se estructuró como un compendio de publicaciones, que pretendía investigar tres aspectos distintos de la reconstrucción del LPFM. Un primer lugar (a) se intentó redefinir la anatomía insercional y la isometría básica del LPFM original, en modelos cadavéricos. En segundo lugar (b) se realizó un análisis clínico y radiológico retrospectivo de los resultados de la técnica cuasi-anatómica, en una serie consecutiva de pacientes intervenidos por inestabilidad FP. En tercer y cuarto lugar, (c) y (d), se diseñó un modelo matemático que pretendía evaluar biomecánicamente algunos de los mas frecuentes procedimientos de reconstrucción del LPFM, incluido el modelo propuesto, para analizar la influencia de distintas técnicas en las presiones soportadas por el cartílago FP. Por último (e), se planteó realizar un análisis funcional, clínico y evolutivo, que comparara la técnica dinámica cuasi-anatómica, motivo de estudio de esta tesis, con un modelo estándar de reconstrucción estática-anatómica del LPFM.

El estudio de las presiones de contacto FP fue el punto que generó mas dudas, puesto que el estudio biomecánico exigía de la combinación de, por una parte, un instrumento capaz de generar movilidad articular controlada de la rodilla, con libertad en los tres planos del espacio - simulador de marcha de última generación o robot - y de un dispositivo para evaluar fidedignamente las presiones generadas a nivel de la superficie articular. Mientras que se disponía de un sistema de sensores de presión ultrafinos, con un software específico asociado, capaz de proveer datos biomecánicos objetivos (Tekscan™), no se disponía, en cambio, de un robot que pudiera generar la movilidad articular tridimensional necesaria, simulando al mismo tiempo las fuerzas ejercidas por los diferentes grupos musculares de la extremidad inferior.

Por este motivo, se decidió diseñar un modelo matemático de elementos finitos con la ayuda de un equipo de ingenieros. Este modelo se desarrolló basado en reconstrucciones paramétricas 3D de la rodilla, especialmente de la articulación femoropatelar. El modelo permitió simular prácticamente todos los elementos de la articulación, para posteriormente analizar los esfuerzos que esta recibe. Así, en síntesis, a partir de estudios de imagen (TAC), se realizó un proceso de identificación, reconstrucción y segmentación de huesos, cartílago articular y ligamentos de la articulación de la rodilla. Tras aplicar fuerzas fisiológicas simuladas, el sistema calculó las fuerzas compresivas en los diferentes componentes modelados de la articulación[44-46].

Finalmente, los artículos que componen esta tesis doctoral por compendio de publicaciones son los siguientes:

1. *The anatomy and isometry of a quasi-anatomical reconstruction of the medial patellofemoral ligament*. Perez-Prieto D, Capurro B, Gelber P, Ginovart G, Reina F, Sanchis-Alfonso V, Monllau JC. *Knee Surg Sports Traumatol Arthrosc.* 2017; 25: 2420-2423.

2. *Clinical and radiological outcomes after a quasi-anatomical reconstruction of medial patellofemoral ligament with gracilis tendon autograft.* Monllau JC, Masferrer-Pino A, Ginovart G, Perez-Prieto D, Gelber P, Sanchis-Alfonso V. *Knee Surg Sports Traumatol Arthrosc.* 2017; 25:2453-2459.

3. *Parametric Finite Element Model of medial patellofemoral ligament Reconstruction. Model development and clinical validation.* Sanchis-Alfonso V, Alastruey-lopez D, Ginovart G, Montesinos-Berry E, Garcia-Castro F, Ramirez-Fuentes C, Monllau JC, Alberich-Bayarri A, Perez-Anson MA. Journal of Experimental Orthopaedics. 2019; 6(1): 32.

4. *Evaluation of Patellar Contact Pressure Changes after Static versus Dynamic Medial Patellofemoral Ligament Reconstructions Using a Finite Element Model.* V Sanchis-Alfonso, G Ginovart, D Alastruey-Lopez, E Montesinos-Berry, JC Monllau, A Alberich-Bayarri, MA Perez. Journal of Clinical Medicine. 2019 Dec 1; 8 (12): 2093.

5. *Isolated reconstruction of medial patellofemoral ligament with an elastic femoral fixation leads to excellent clinical results.* Vincent Marot, Vicente Sanchis Alfonso, Simone Perelli, Pablo Eduardo Gelber, Christian Javier Sanchez Rabago, Gerard Ginovart, Juan Carlos Monllau. Knee Surg Sports Traumatol Arthrosc. 2020 [Epub ahead of print]

2.1 EMBRIOLOGÍA Y ANATOMÍA

El aspecto embriológico más importante de esta parte de la anatomía es probablemente el que concierne al surco troclear. A partir de las 6 semanas de desarrollo embrionario, aparece una banda de tejido mesenquimal entre el fémur y la tibia, que sufrirá posteriormente un proceso de condrogénesis. Pasadas las 8 o 9 semanas de gestación (embrión de 24 mm), el desarrollo de la tróclea femoral es ya evidente y este desarrollo no está condicionado por el contacto o en respuesta a la patela sino mas bien al mecanismo del cuádriceps. En esta fase la patela está en una clara fase de condrogénesis y sobre las 14 semanas empieza su osificación. La morfología de la tróclea femoral presenta todas las características esenciales de la vida adulta. Algunos estudios sugieren que las características anatómicas del surco troclear podrían haber sido integradas en el genoma durante el curso de la evolución humana y, por tanto, que existe una determinación genética en la forma anatómica de la articulación FP. De igual modo, esta teoría sugiere también el origen genético de la displasia troclear[47,48].

En cuanto a la anatomía, nos centraremos en la de la cara medial de la rodilla, donde se ubica el LPFM. Esta cara esta estructurada en tres niveles o capas:

Nivel 1. El Retináculo Medial Superficial constituye la capa mas superficial. Esta compuesto por la fascia crural, limitada y continuada en su parte distal por la fascia del músculo sartorio y en su parte proximal por la del VMO.

Nivel 2. Es el nivel intermedio, situado por debajo de la capa superficial. Aquí se puede encontrar el fascículo superficial del ligamento colateral medial, el LPFM y el ligamento patelo-tibial medial (Fig 4).

Nivel 3. Es el mas profundo y esta compuesto por la cápsula articular de la rodilla, el ligamento patelo-meniscal medial y el fascículo profundo del ligamento colateral medial (Fig 5).

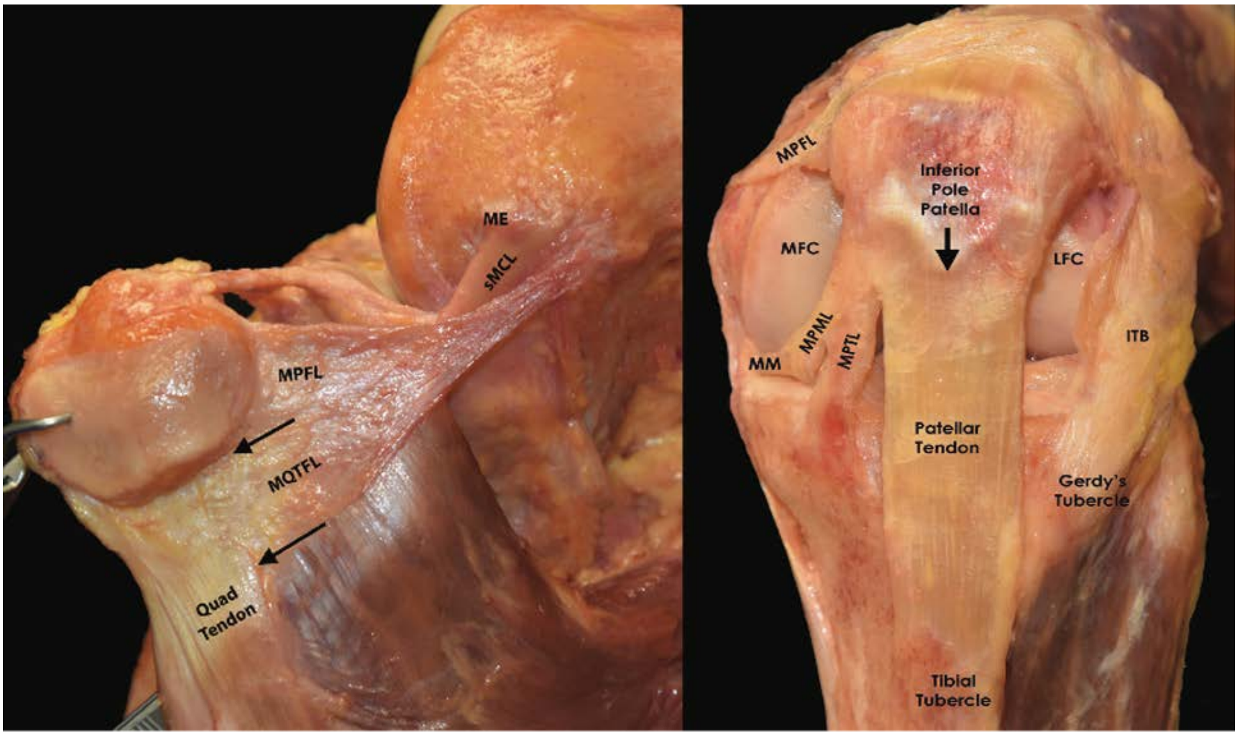

Fig 4. Disección rodilla. a) Patela evertida mostrando el LPFM. b) vista frontal con la rodilla en flexión de 90º (Tomado de Kruckeberg et al. Am J Sports Med. 2018, con permiso del editor).

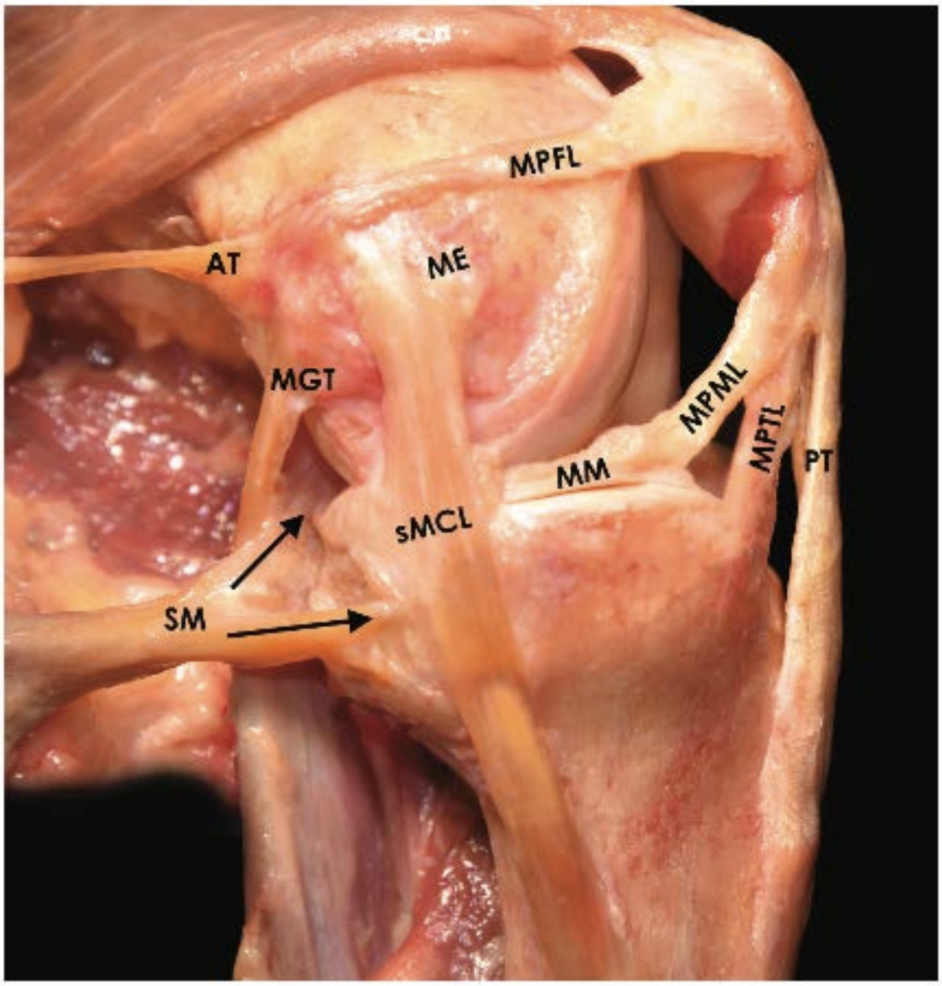

Fig 5. Disección cara medial de la rodilla. LPTM y LPMM (Tomado de Kruckeberg et al. Am J Sports Med. 2018, con permiso del editor).

El LPFM es una estructura fibrosa, de forma triangular-trapezoidal, situado entre la patela y el fémur, con una longitud media de entre 55 y 60 mm y una anchura de 10 a 20 mm. Su inserción rotuliana es la mas ancha y va desde el borde supero-medial al centro-medial, mientras que la inserción femoral se encuentra en un área situada entre el tubérculo del AM y el epicóndilo femoral medial, mas exactamente proximal y dorsal al epicóndilo femoral medial y, aproximadamente, un centímetro distal al tubérculo del AM. El LPFM está formado por dos haces de fibras. El haz superior oblicuo, que conecta con el borde supero medial de la rotula y esta unido también al VMO en una extensión promedio de 27 mm[49], y está considerado una estructura con funciones estáticas y dinámicas. El haz inferior, que es más directo, con trayecto rectilíneo, conectando con la parte centro medial de la rótula, casi horizontalmente, y que posee un función restrictiva estática de la movilidad lateral. El ángulo formado por estos haces es de unos 15 grados[50-52]. Mas recientemente, Fulkerson[53,54] ha descrito un conjunto de fibras más proximales, de inserción en el tendón cuadricipital, a las que denomina ligamento cuádriceps-tendón femoral medial[54].

Esta variabilidad anatómica, con fibras de inserción en rótula y en cuádriceps, ha llevado a algunos autores a denominar a esta estructura fibrosa complejo patelo femoral medial, situando su punto medio en la unión del borde medial del tendón cuadricipital y el borde superomedial de la patela[55,56]. Es en esta misma área de la patela donde se inserta el vasto intermedio y donde, al parecer, se fusiona con las fibras mas proximales del haz oblicuo del LPFM, en una extensión promedio de 24 mm, y sin una estrecha adhesión al VMO[57,58]. Este hecho tiene relevancia cuando se estudia la tensión del LPFM y, especialmente, su función estabilizadora de la patela durante la extensión de la rodilla, puesto que estudios electromiográficos han sugerido una mayor contribución del vasto intermedio (40-50%) respecto al VMO (10-12%)[59]. Sin embargo, es difícil el análisis y la comprensión funcional individual del grupo muscular del cuádriceps, donde los vínculos anatómicos entre vasto intermedio y VMO son estrechos, existiendo múltiples unidades musculares insertadas entre ellos, que representan juntos una compleja unidad funcional muscular de restricción dinámica de la traslación lateral rotuliana[60,61].

2.2 BIOMECÁNICA

La mayoría de los trastornos FP son el resultado de alteraciones anatómicas, que predisponen a la aparición de anormalidades biomecánicas[62]. Es por tanto necesario analizar tanto la anatomía ósea de patela y tróclea femoral, como la anatomía de los tejidos blandos que participan en la cinética FP, puesto que cualquier anormalidad de estas estructuras podrá conllevar la aparición de alteraciones mecánicas y/o funcionales.

2.2.1 Estructuras óseas

La patela o rótula está considerada el mayor hueso sesamoideo del cuerpo humano. Se sitúa frente a la tróclea femoral, enlazando el aparato extensor a través de las conexiones de su polo superior con el tendón cuadricipital y del polo inferior con el tendón rotuliano. La cara articular de la patela se divide en dos facetas, una lateral más grande y excavada y otra medial. La primera se halla en relación con la vertiente lateral de la tróclea femoral. La segunda, ligeramente cóncava, casi plana, está en relación con la vertiente medial de la tróclea. Una pequeña cresta más medial separa una tercera carilla ("*odd facet*" para los aglosajones) que corresponde a la superficie de contacto con el cóndilo medial más allá de los 90º de flexión.

Wiberg clasificó la patela en tres tipos, atendiendo a la localización de la cresta medial rotuliana, y Baumgartl (1944) añadió una cuarta variante (Fig 6). La clasificación describe la asimetría entre las facetas patelares medial y lateral, a medida que aumenta el número existe una mayor asimetría facetaria. En el tipo 4, existe ausencia de faceta medial, adoptando la patela la forma de gorra de cazador o boina vasca.

Fig 6. Clasificación de Wiberg (tomado de Sherman et al. *Clin Sports Med*. 2014, con permiso del editor)

La tróclea femoral es la parte articular de la porción anterior de la epífisis distal del fémur. Consta de dos carillas asimétricas, medial y lateral, que forman un ángulo obtuso abierto hacia delante y están separadas por un surco anteroposterior que se continúa distalmente con la escotadura intercondílea. La profundidad de este surco es un dato importante y puede ser medido por el llamado ángulo del "sulcus". Ambas carillas trocleares están en continuidad con los cóndilos femorales, en la unión entre ambos se encuentra una pequeña melladura o *sulcus terminalis,* producida por el contacto con los meniscos en la extensión completa de la rodilla.

El borde superior de la tróclea es oblicuo en sentido distal y medial. Está separada de la cortical anterior del fémur por la fosita supratroclear. La mayor altura de la carilla lateral y la congruencia existente entre el surco troclear y la cresta medial de la rótula son factores óseos que contribuyen a la estabilidad de la articulación. La pérdida de la normal concavidad anatómica y profundidad del surco troclear se denomina displasia troclear (Dejour[21]). Es una anomalía caracterizada por una superficie mas plana de la tróclea, que a veces es incluso convexa, que predispone a la inestabilidad FP.

2.2.2 Tejidos blandos

La principal estructura muscular es el cuádriceps femoral, que es el músculo más voluminoso de toda la anatomia. Está formado por la convergencia de cuatro unidades - recto femoral, vasto medial, vasto lateral y vasto intermedio o crural - que terminan insertándose en el tendón cuadricipital, que tiene tres capas. Las fibras más superficiales del recto anterior se unen a las del tendón rotuliano y las más profundas se insertan en el polo superior de la rótula. Tres de las unidades musculares del cuádriceps son monoarticulares (vastos medial y lateral, y el crural), mientras que el recto anterior es biarticular, extendiéndose desde la cadera (espina ilíaca anteroinferior) hasta la rodilla.

El vasto medial a nivel de su parte mas distal origina el vasto medial oblicuo (VMO). Las fibras del VMO tienen una dirección más oblicua hacia distal y lateral (de ahí su nombre) y resultan las más eficientes para limitar el desplazamiento lateral de la rótula. El ángulo con que las fibras oblicuas alcanzan la rótula varía entre 55º y 70º, en relación con el eje mayor del tendón del cuádriceps. El VMO se hace tendinoso a pocos milímetros de su inserción en el tercio superior o en la mitad del borde medial de la rótula. Globalmente considerado, el cuádriceps es el músculo fundamental del mecanismo extensor de la rodilla y el gran controlador de la dinámica FP.

El tendón o ligamento rotuliano (puesto que vincula dos huesos) transmite a la tibia la fuerza ejercida por el cuádriceps. Discurre entre el polo inferior de la rotula y la tuberosidad anterior de la tibia, con una longitud promedio de 4.6 cm (entre 3.5 y 5.5 cm). La longitud del tendón determina la altura de la rótula con respecto a la interlínea articular. El tendón describe un ángulo abierto hacia lateral, denominado Q en la literatura anglosajona, que en condiciones normales es de 15º y que traduce el valgo del aparato extensor.

Los principales tejidos blandos en la vertiente medial son: el VMO, el LPFM, el ligamento patelotibial medial, el ligamento patelomeniscal medial y el retináculo medial. El VMO es un importante restrictor dinámico de la traslación lateral de la rótula y, al parecer, actúa conjuntamente con el vasto intermedio (Fig 7), su hipoplasia o displasia dificulta el encarrilamiento de la rótula en la tróclea, siendo una causa mayor de inestabilidad rotuliana. Las lesiones completas del LPFM predisponen a la lesión del VMO y, en adultos, asocian una mayor incidencia de rupturas del VMO (56%) tras un primer episodio de luxación FP. Las lesiones aisladas de lado femoral del LPFM y también las del LPFM combinadas, predisponen a una mayor frecuencia de ruptura del VMO[63].

EL LPFM está considerado el principal tejido blando restrictor de la traslación rotuliana lateral, ejerciendo una fuerza de resistencia de entre un 50 y un 60%, principalmente durante los primeros 20 a 30ª de flexión. Su resistencia aproximada es de 208N y, aunque con cierta controversia, parece tener un comportamiento isométrico entre 0 y 90º de flexión de la rodilla, aceptando como isométricos cambios de longitud menores a 5 mm durante el movimiento articular [64-67].

El ligamento patelotibial medial, el patelomeniscal medial y el retináculo medial son considerados restrictores secundarios, contribuyendo a la limitación de la traslación rotuliana lateral en un 13%, 24% y 13%, respectivamente. A diferencia del LPFM, los ligamentos patelotibial y patelomeniscal mediales incrementan su función estabilizadora a medida que aumenta la flexión de la rodilla, sobre todo a partir de los 45º, e influyen principalmente en la rotación patelar[68-70].

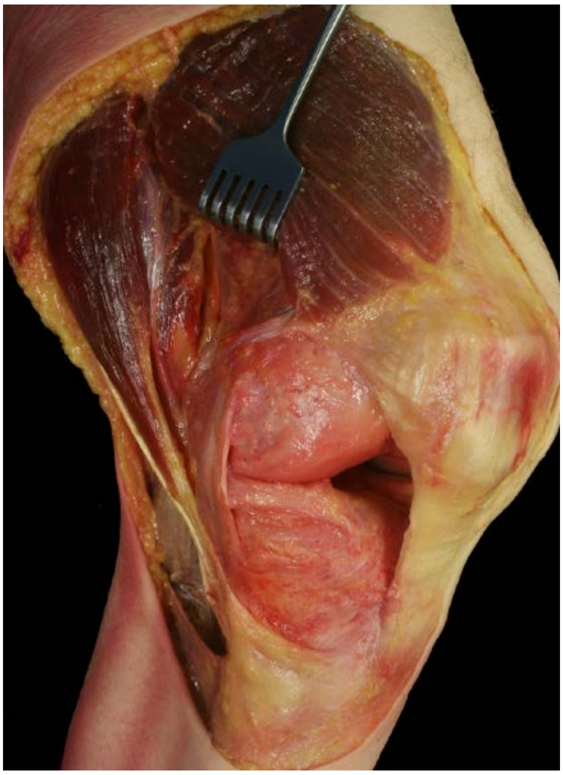

Fig 7. Disección de la cara medial de la rodilla. VMO retraído proximalmente evidenciando el LFPM. Cortesía del Dr. Ivan Saez. (UB)

Los principales tejidos blandos en la vertiente lateral son el retináculo oblicuo-lateral superficial y los fascículos patelo-tibial y patelo-epicondilar mas profundos, que están considerados estabilizadores secundarios de la traslación lateral rotuliana.

2.2.3 Cinética Femoropatelar

Todas estas estructuras juegan un papel de estabilización patelar durante el arco de movilidad de la rodilla. En extensión completa, la patela está en una discreta posición lateralizada, debido al vector de tracción del cuádriceps, y a las mínimas fuerzas de reacción posterior. Durante la flexo-extensión de la rodilla la rótula se desliza sobre el fémur de proximal a distal, recorriendo aproximadamente unos 7 cm. En los primeros 30º de flexión, el LPFM es el principal restrictor a la dislocación lateral de la rótula. De los 30º a los 60º, la patela inicia su encaje o encarrilamiento en la tróclea femoral incrementándose el área de contacto FP y las fuerzas de reacción posterior hasta los 90º. Entre los 90º y 135º de flexión la patela se engrana completamente en la tróclea femoral, por lo que es totalmente estable en el resto del recorrido. La identificación y neutralización de cualquier anormalidad anatómica a este nivel contribuirá a mejorar la biomecánica y estabilidad FP lo que, en último término, determinará mejores resultados clínicos.

2.3 EVALUACIÓN RADIOGRÁFICA

Dejour[8], utilizando radiología simple y tomografía computadorizada (TAC), identificó cuatro factores relevantes que aparecen asociados en las rodillas con sintomatología de inestabilidad FP. Estos factores son:

1. Displasia troclear. Se conoce como displasia troclear toda alteración de la profundidad de la tróclea, y puede cuantificarse mediante el ángulo del sulcus. Henry Dejour clasificó la displasia en tres tipos e identificó tres signos radiológicos, el cruce (*crossover sign*), el espolón supratroclear (*spur*) y el doble contorno, que la definen perfectamente. Mas recientemente, David Dejour añadió un cuarto tipo (Fig 8). Así actualmente, la displasia troclear se clasifica en los siguientes tipos:

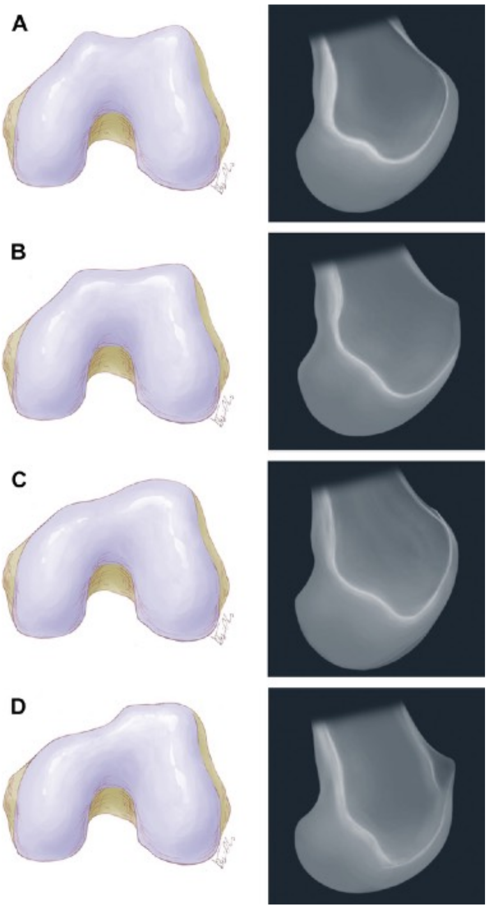

Fig 8. Clasificación de David Dejour. Tomado de Sherman et al. *Clin Sports Med.* 2014, con permiso del editor.

Tipo A: corresponde a la forma más leve de displasia, está definida en la radiología simple por el signo del cruce. En la TAC, la morfología de la tróclea es poco profunda, con un ángulo de sulcus inferior a 140º.

Tipo B: en la radiografía simple, presenta signo del cruce y espolón supratroclear. En la TAC la tróclea es plana o ligeramente convexa.

Tipo C: cursa también con *crossover sign* y doble contorno en la radiología. Además, en la TAC se observa una convexidad lateral y una hipoplasia tróclear medial.

Tipo D: en la radiología simple se parece al tipo C, con signo del cruce, espolón supratroclear y doble contorno. En la TAC, la parte medial muestra una morfología de joroba de camello.

2. Displasia cuadricipital. En extensión completa de rodilla, la rótula está inclinada o basculada lateralmente (*tilt*). En los primeros grados de flexión la faceta lateral contacta con la parte más prominente y alta de la tróclea femoral lateral, simultáneamente se tensan las estructuras mediales y se corrige la báscula automáticamente. En general se estima que la displasia del VMO origina la báscula, aunque es posible que corresponda mas bien a una alteración de la totalidad del cuádriceps, de ahí el nombre. La báscula se define como patológica cuando en la TAC se observa una inclinación patelar en extensión superior a 20º.

3. Altura rotuliana. La patela alta o *supera* es una causa conocida de inestabilidad FP, ya que en esta posición la patela tarda más en encajarse en el surco troclear. La altura patelar ha sido estudiada con diversos métodos radiológicos que definen índices. Uno de los más utilizados en la actualidad es el de Caton-Deschamps, que relaciona la longitud de la cara articular de la patela con la distancia que separa su punto más distal de la porción anterosuperior de la superficie articular tibial. Se define como alta cuando esta relación es mayor que 1.2.

4. Distancia TA-TG. Es la distancia entre el apex de la tuberosidad tibial anterior (TA) y el centro del surco en la parte alta de la tróclea femoral (*Throclear Groove*). Se obtiene mediante superposición de imágenes de TAC y se

considera patológica cuando supera los 20mm. Esta medida es difícil de objetivar en casos extremos de displasia, donde el surco es dificilmente identificable. Recientemente, debido a la exposición radiológica de la TAC, existe cierto debate respecto a la conveniencia de utilizar la Resonancia Magnética (RM) para realizar esta medición[71-72].

Estos cuatro factores de riesgo de inestabilidad, no aportan sin embargo ningún valor predictivo sobre la severidad y localización de las lesiones del LPFM en las luxaciones de rotula[73].

A pesar de que existe alta evidencia de presencia de displasia troclear (96%) en los pacientes con historia de inestabilidad FP[8], las mediciones cuantitativas de la tróclea femoral tienen un valor limitado en la valoración del grado de displasia. Intentando buscar una correlación entre los tipos de displasia descritos por Dejour y la medidas cuantitativas de la tróclea, se ha visto que únicamente las mediciones de la inclinación lateral troclear, la asimetría de las facetas y la profundidad troclear pueden ayudar a valorar y diferenciar entre displasias de bajo (Dejour A y B) y alto grado (Dejour C y D)[74-77].

Recientemente, se ha introducido un nuevo índice para valoración de la altura rotuliana en el plano sagital, que valora el encaje entre tróclea y patela. Este índice se denomina *Sagittal Patellofemoral Engagement* y se mide mediante RM[78]. Las principales ventajas de la RM frente a la TAC serían que permite cuantificar de manera óptima la displasia troclear, la distancia TA-GT, la báscula y altura rotulianas, el ángulo troclear y el índice de *engagement*, así como analizar el estado del LPFM, en cuanto a tipo (completa o incompleta) y localización de la rotura (patelar, femoral o intraligamentaria). Adicionalmente, la RM permite también analizar el estado del cartílago y del hueso subcondral [79].

La desalineación de la extremidad inferior también esta relacionada con problemas FP. Así, la alineación en varo, que causa sobrecarga en la patelofemoral medial y, con el tiempo, artrosis a este nivel, puede estudiarse mediante radiología simple.

De igual manera, en el plano horizontal, los incrementos de la torsión femoral, tibial o combinados, se pueden asociar también a inestabilidad FP y se estudian y miden mediante TAC[80]. El fémur tiene una anteversión (AVF) de aproximadamente 15°, que es característica de la bipedestación en el ser humano. Habitualmente se compensa con una torsión tibial externa (TTE) menor de 35°, que se produce en los primeros centímetros de la epífisis proximal, con el objetivo final de que los pies estén paralelos durante la marcha. Está demostrada una relación estadística entre luxación recidivante de la rótula y aumentos de la TTE y AVF. De igual manera, las alteraciones torsionales se han relacionado también con el dolor anterior de rodilla[80].

Por último, de relevancia para el presente estudio, se debe mencionar que existen criterios radiológicos que sirven como referencia intraoperatoria (mediante intensificador de imágenes), para la localización del punto anatómico de inserción femoral del LPFM [37,40,42].

2.4 EVALUACIÓN CLÍNICA

Para evaluar la estabilidad de la FP, se debe explorar al paciente de pié, sentado y acostado. Es importante detectar alteraciones de los ejes, como el genu valgo o el recurvatum, y trastornos torsionales del miembro inferior, un ángulo Q anormal y, también, la altura y movilidad de la rótula. También deben evaluarse el trofismo muscular, especialmente del cuádriceps, y el arco de movilidad de la rodilla.

El dolor, si está presente, se puede localizar en la zona del LPFM y en el alerón rotuliano lateral. Aunque normalmente es referido por el paciente como un dolor anterior, inespecífico, de rodilla. La palpación directa de las carillas articulares, así como la compresión de la patela contra la tróclea femoral, con la rodilla en 30° de flexión, puede generar dolor.

La semiología está orientada a valorar la estabilidad de la rótula sobre la tróclea, así como la laxitud de los estabilizadores mediales y la rigidez de los estabilizadores laterales. Existe un gran número de signos físicos y escalas funcionales para el diagnóstico y evaluación de la inestabilidad FP. Aunque su sensibilidad y especificidad no queda suficientemente acreditada, deben mencionarse puesto que son ampliamente utilizados. Un análisis de la literatura revela hasta 18 test diagnósticos y 10 escalas de medida de resultados que han sido utilizados con frecuencia en la literatura de la inestabilidad FP. Únicamente 5 de estos tests (*Bassett's sign*, *Aprehension test*, *Gravity subluxation test*, ángulo Q y distancia TA-GT) y 7 de las escalas funcionales (Kujala *Anterior Knee Pain Scale*, Lysholm *Knee Scoring Scale*, Fulkerson *Knee Instability Scale*, MFA *Musculoskeletal Function Assessment Injury and Arthritis Survey*, Tegner A*ctivity Level Scale*, Short Form-36, IKDC M*odified International Knee Documentation Committee Knee Ligament Standard Evaluation Form*) han sido analizados con cierta exactitud.

Aunque recientemente los resultados basados en *pacient reported outcomes measures* (PROM's) han recibido mucha atención, entre otras razones, por la dificultad de efectuar visitas presenciales de seguimiento a medio o largo plazo, es razonable concluir que la evidencia que proporcionan estas escalas de evaluación de resultados, basadas en opiniones subjetivas del paciente, es ciertamente limitada[81-83].

2.5 RECONSTRUCCIÓN DEL LPFM

Como se ha comentado anteriormente, son numerosas las técnicas descritas para tratar la inestabilidad recurrente FP. En las últimas décadas, debido al papel fundamental que juega el LPFM en la estabilidad medio-lateral de la patela, su reconstrucción quirúrgica se ha generalizado como una parte fundamental del tratamiento. Desde su descripción inicial a principios de los 90, son numerosas las técnicas descritas para la reconstrucción del LPFM. El análisis comparativo de estas técnicas es difícil dada la gran cantidad de variables individuales que cada una de ellas presenta (p.e. injerto utilizado, disposición anatómica, posicionamiento de los puntos de inserción, tipo de fijación, asociación de otras técnicas quirúrgicas, etc) y la escasa literatura previa al respecto[84-88].

A modo de recuerdo se citan a continuación algunas de las técnicas que se han considerado pioneras o más relevantes en cada uno de estos aspectos (especialmente, tipo de injerto, disposición más o menos anatómica, fijación elástica o dinámica, dispositivos de estabilización variados, etc) para ilustrar la variabilidad de la literatura preexistente y la dificultad para extraer conclusiones sólidas.

Ahmad[89], fue de los primeros en proponer la reparación directa mediante sutura primaria del LPFM y VMO en casos agudos, en el primer episodio de luxación. En el mismo sentido, también en casos agudos, sin historial previo de inestabilidad, Yamamoto[90] propuso la reparación mediante sutura del retináculo medial y la cápsula, combinándolos con la liberación del retináculo lateral, utilizando técnica artroscópica.

Schottle[91] estandarizó el uso de unas referencias radiológicas intraoperatorias para ayudar en la localización del punto de anclaje femoral. La técnica utiliza un autoinjerto del semitendinoso, que se fija con tornillo interferencial en el túnel del epicóndilo femoral medial y dos suturas de anclaje en el borde rotuliano supero medial. Esta técnica es considerada por muchos el patrón oro de la reconstrucción anatómica del LPFM y es ampliamente utilizada.

Ellera Gomes[92] fue el primero en proponer la reconstrucción del LPFM tal y como se entiende actualmente. Para ello utilizó un autoinjerto del semitendinoso que rodeaba el hiato del adductor magno (fijación elástica a nivel femoral) y un túnel único transversal en la rótula. Panagopoulos[93] propuso una variante, usando también un autoinjerto de semitendinoso que mantiene su inserción anatómica distal, pasa por el septo intermuscular del adductor magno y va a fijarse en un túnel rotuliano, perforado en dirección oblicua craneocaudal desde el borde superomedial al ínferolateral, con un tornillo de interferencia. Ostermeier[94] describió otro tipo de reconstrucción dinámica, en la que desinsertaba distalmente el semitendinoso, lo pasaba por un túnel taladrado por debajo de la inserción proximal del ligamento colateral medial, para fijarlo finalmente en la rótula, a través de un túnel oblicuo, y también en el VMO mediante suturas.

Nomura[27] fue el primero en utilizar un ligamento artificial de polyester para la sustitución del LPFM. El neoligamento se fijaba, subperiósticamente con una grapa, en un punto justo distal del tubérculo del adductor mayor y en la rótula mediante un hemitúnel transversal. Mas recientemente, el mismo autor ha propuesto una reconstrucción híbrida mediante autoinjerto libre del semitendinoso recubierto con periostio. El anclaje femoral es óseo, en el área anatómica epicondílea, mediante tornillo interferencial y sutura perióstica, y mediante tunelización transversal y anterior, en lazo, en la rótula[95].

Zaffagnini[96] propuso utilizar un aloinjerto de fascia lata, fijado mediante un tornillo interferencial en un túnel asimétrico de 30mm, taladrado desde epicóndilo medial a lateral, y dos suturas de anclaje óseo en el borde rotuliano superomedial.

Steensen[97] y Fulkerson[53] fueron los primeros en proponer la utilización de un autoinjerto del tendón cuadricipital, pediculado distalmente, para la reconstrucción del LPFM. En el primer caso, la fijación en epicóndilo femoral medial se realiza con suturas transóseas, mientras que en el segundo, mediante un túnel intraóseo en el área anatómica (entre epicóndilo medial y tubérculo del adductor).

Drez[98] recomendó la utilización de diferentes autoinjertos (semitendinoso, fascia lata y semitendinoso mas gracilis) que se fijaban con un anclaje óseo en borde rotuliano superomedial y suturas periósticas en tubérculo del adductor y en el área del ligamento patelotibial medial en la tibia.

Deie[99], propugnó la reconstrucción con autoinjerto de semitendinoso, combinado con un realineamiento próximal del aparato extensor. Los autores, mantenían la inserción distal anatómica del semitendinoso, que se pasaba por detrás del tercio proximal del ligamento colateral medial y se suturaba en un túnel taladrado en la mitad proximal de la rótula. Matthews[100], utilizó también autoinjerto de semitendinoso o gracilis, pero realizando un túnel longitudinal en la rotula (*tendon loop*) y otro en la región anatómica epicondílea, que finalmente fijaba mediante tornillo interferencial. Carmont[30], propugnó otra variante, con autoinjerto de semitendinoso o gracilis, y fijación en lazo a través de dos túneles transversales, paralelos, en la rótula. El anclaje femoral era óseo, con túnel taladrado en el área anatómica epicondílea y tornillo interferencial. Schiavonne-Panni[101] publicó otra variante, utilizando autoinjerto de semitendinoso, fijación rotuliana en lazo a través de dos tunes tranversales divergentes, y fijación femoral anatómica, a 20º de flexión, con un tornillo bioreabsorbible.

Toritsuka[102] propuso la reconstrucción con autoinjerto de semitendinoso, realizando la fijación rotuliana en dos túneles transversales y la femoral en el área anatómica epicondílea, mediante túnel óseo. El autor introdujo el uso de dispositivos de suspensión tipo Endo-Button (Smith and Nephew. Andover. USA) en ambos extremos del injerto.

Kang[103], publicó un tipo de reconstrucción con configuración en forma de Y, con autoinjerto de semitendinoso. La fijación femoral era también anatómica, mediante anclaje óseo con tornillo interferencial, y la patelar mediante sutura por debajo de la fascia prepatelar de los dos haces de la Y. El haz proximal de esta última se suturaba adicionalmente al VMO, unos 20mm.

Steiner[104] introdujo la reconstrucción con autoinjerto del tendón adductor magno que, manteniendo la inserción femoral epicondílea, se reflejaba por un túnel practicado bajo el tubérculo del adductor, para posteriormente dirigirse a un túnel transversal taladrado en la rótula y finalmente ser suturado sobre toda la superficie ventral de la misma.

Cossey[105] propuso otra variante en que la reconstrucción se realizaba mediante un autoinjerto del retináculo medial, con segmento libre longitudinal, que se suturaba subperiósticamente y la asociaba a una realineación distal de la tuberosidad tibial anterior y liberación del retináculo lateral.

Por último, Witonski[106] propuso una reconstrucción con autoinjerto del tercio medial del tendón rotuliano, que fijaba en un túnel óseo en zona anatómica femoral, mediante un tornillo interferencial de titanio, con la rodilla entre 15° y 30° de flexión. Además, realiza una sutura de la parte rotuliana del injerto al VMO.

De la diversidad de técnicas expuestas podemos concluir que seguramente ninguna es perfecta y que probablemente todas consiguen aumentar significativamente la estabilidad FP. Cualquier otra análisis o comparación se encuentra en el terreno de la especulación, se plantean múltiples interrogantes y no se pueden extraer conclusiones sólidas sobre cual es la técnica de elección.

Atendiendo a los datos publicados, entre un 83% y un 93% de los casos obtienen buenos resultados en términos de reluxación. La mayor parte de los estudios son series clínicas, retrospectivas, con recogida de datos subjetivos (*patient reported outcomes*) y no hay evidencia de superioridad de una técnica quirúrgica respecto a las otras[26]. No obstante, se comprueba una nada desdeñable tasa de complicaciones, que alcanza el 26%[85,107-108]. Entre las complicaciones reportadas se incluyen:

A. Inestabilidad recurrente. Probablemente la mas importante, puesto que el objetivo fundamental del tratamiento es corregir la inestabilidad. Se puede presentar en forma de subluxaciones, de auténticas luxaciones (alrededor del 5%) y/o de hipermovilidad o aprensión positivas, sin subluxación (7% a 12% de casos). Aunque en estos casos cabe la posibilidad de concomitancia de otros factores de inestabilidad FP subyacentes, no corregidos en el momento de la reconstrucción, no puede descartarse que alguna técnica de reconstrucción del LPFM sea menos efectiva en el control de la estabilidad FP. En general, parece deducirse que las técnicas de reconstrucción que utilizan suturas como método de fijación, presentan un mayor tasa de inestabilidad recurrente (4.8%) y de hipermovilidad o aprehensión positiva (24%), que las técnicas que fijan el injerto en túneles óseos (3.3% y 8.6%, respectivamente)[85].

B. Complicaciones de las heridas quirúrgicas. Estas complicaciones son inherentes a cualquier procedimiento quirúrgico en esta zona anatómica. Incluyen desde hematomas subcutáneos y dehiscencias de las heridas quirúrgicas a infecciones locales y alcanzan el 2.5%.

C. Fracturas de la patela. Aparecen mas frecuentemente en las técnicas que realizan una o varias tunelizaciones rotulianas, que en aquellas en las que los injertos se fijan en el borde medial de la patela, mediante suturas simples o con anclajes. De hecho, en estas últimas no se han reportado fracturas. Incluso la tunelización de la cortical ventral patelar parece también estar asociada a mayor riesgo de fracturas.

D. Dolor postoperatorio. Aparece en alrededor del 5.4% de casos y es también un tema relevante. Aproximadamente, en un 40% de casos parece estar en relación con el material implantado, aunque no se pueden descartar otros orígenes (p.e. malposición del injerto y sobrecarga cartilaginosa). Algunos estudios demuestran como inserciones no anatómicas del neoligamento conducen a incrementos de presión aberrantes en la FP[111] que indefectiblemente producen dolor.

E. Déficit de flexión de la rodilla. Se presenta en un 13% de pacientes, de los cuales el 50% requieren manipulación bajo anestesia para recuperar movilidad, y es también motivo de preocupación. La persistencia de un 3.5% de pérdidas de flexión residuales, obliga a analizar la influencia de la tensión y la isometría, o mejor fisiometría, que obtienen las diferentes técnicas de reconstrucción[109,111]. En la actualidad, no existen datos concluyentes sobre las diferencias clínicas entre los injertos de reconstrucción fijados en un grado de flexión superior o inferior a 60º. Sin embargo, Burrus[110] y Sanchis-Alfonso[38] han sugerido que las fijaciones realizadas a 30º de flexión, donde teóricamente es mayor la longitud del injerto, comportarían una mejor isometría y resultados clínicos en este tipo de reconstrucciones.

Existe cierto consenso en cuanto al posicionamiento del túnel femoral del injerto y su consiguiente comportamiento. Así, tunelizaciones femorales proximales y ventrales al punto anatómico idóneo, condicionan injertos con progresivo incremento de tensión a medida que aumenta la flexión de la rodilla, factor que a su vez incrementa las presiones FP y, posiblemente, a mas largo plazo, el dolor y la degeneración artrósica FP, especialmente en la vertiente medial de la articulación. En este sentido, Elias[111] señala que pequeños errores (5mm) en la posición de la parte femoral del injerto y/o un acortamiento de 3mm del mismo, incrementan la fuerza compresiva aplicada sobre el compartimento FP medial y pueden evolucionar con dolor, degradación cartilaginosa precoz y artrosis tardía.

Contrariamente, Melegari[112] no encuentra diferencias en el porcentaje de las áreas articulares FP en contacto, ni en las presiones, al comparar reconstrucciones realizadas con autoinjerto cuadricipital no isométricas (no anatómicas), con fijación en el tubérculo del adductor, con aquellas isométricas (anatómicas), en las que la fijación se realizó en la región epicondílea posteromedial.

Un reciente estudio realizado mediante TAC 3D, sugiere que un 83% de casos con una fijación femoral no anatómica presentan buenos resultados clínicos. Por lo que, pese a la teórica importancia de la fijación femoral anatómica en la reconstrucción del LPFM, es posible que una reconstrucción no anatómica, que reproduzca una buena isometría durante los 0º, 30º y 60º de flexión de la rodilla, conduzca también a buenos resultados clínicos[38].

Por otra parte, recientes estudios en modelos cadavéricos demuestran que las reconstrucciones del LPFM que utilizan injertos de semitendinoso y gracilis, con inserciones femorales anatómicas fijadas a baja tensión (2N), entre los 30º y 60º de flexión, restauran tanto la cinética como las presiones rotulianas, mientras que, injertos sobretensionados o con fijaciones femorales proximales o distales al punto anatómico, causan elevaciones significativas en las presiones incrementando la tendencia a la inclinación patelar medial[113, 114].

De manera que, aunque existe cierta evidencia de que la reconstrucción del LPFM puede reducir el riesgo evolutivo de aparición de artrosis FP al evitar las dislocaciones recurrentes[115,116], también es posible que reconstrucciones técnicamente erróneas provoquen sobrecarga articular y artrosis con el tiempo. Por otra parte, dado que no existen estudios comparativos entre las diferentes técnicas de reconstrucción, no se puede concluir que todas se comporten de igual manera en términos de prevención artrósica.

Los escasos trabajos que han comparado técnicas de reconstrucción del LPFM estáticas y dinámicas, muestran resultados dispares[116-118]. Aunque es difícil generalizar y extraer resultados válidos, puesto que no se analizan exactamente los mismos procedimientos, los resultados clínicos parecen indicar más ventajas cuando se utiliza un tipo de fijación femoral dinámica[117,120].

En cuanto a las comparaciones de reconstrucciones anatómicas que utilizan autoinjerto (semitendinoso o gracilis) en un único fascículo o en doble haz (que en teoría reproduce mas fielmente la anatomía del LPFM original), estos últimos muestran mejores resultados[121,122].

2.6 TÉCNICA QUIRÚRGICA PROPUESTA

La técnica cuasi-anatómica que se estudia en este proyecto de tesis ha sido descrita con anterioridad por Monllau y cols.[43]

Se posiciona al paciente en decúbito supino, en una mesa quirúrgica estándar, con la rodilla flexionada 90° y la ayuda de un soporte para el pie. La utilización del torniquete colocado en la raíz del muslo es opcional. Tras limpieza aséptica y entallado quirúrgico convencional para cirugía de rodilla, se realizan tres pequeñas incisiones. La primera, vertical, de aproximadamente 25 mm, sobre la zona de inserción tibial de la pata de ganso, 30 mm (3 traveses de dedo) distal a la interlínea articular y 10 mm medial a la tuberosidad anterior de la tibia. Tras disecar el tejido celular subcutáneo, se visualiza y diseca la fascia del sartorio que se incide horizontalmente, inmediatamente por debajo aparecen los tendones del gracilis y, mas distalmente, el semitendinoso. El tendón gracilis se aísla con la ayuda de un disector de 90°, se escinden las posibles vinculas para evitar una amputación precoz durante la extracción y, finalmente, se extirpa con un tenotomo. El injerto se limpia de restos grasos y musculares, se suturan sus extremos con un hilo irreabsorbible del 0 y se mantiene húmedo envuelto en una gasa empapada con una solución de suero salino (100 ml) y vancomicina (500 mg) hasta su implantación[123].

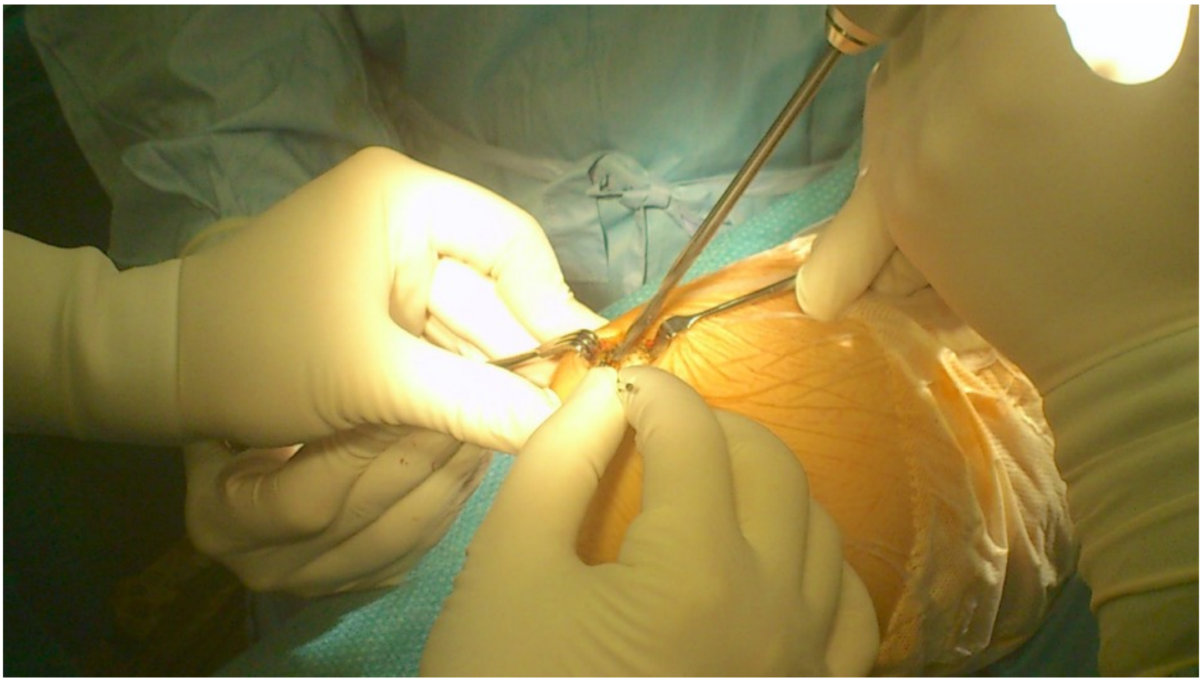

Fig 9. Detalle quirúrgico. Disección de la cara medial de la rótula y perforación de túneles óseos.

A continuación, se practica una segunda incisión vertical, de unos 30 mm, sobre el borde superomedial de la rotula, permitiendo la exposición de su tercio proximal. Tras disecar el periostio y la capa medial, se expone el borde patelar medial sin interrumpir la capa sinovial. Aquí se perforan dos túneles óseos convergentes, en forma de V, de 4.5 mm de diámetro y unos 15 mm de profundidad, separados por un puente óseo de al menos 10 mm, que se comunican en su vértice. Por el túnel en V resultante se introduce un hilo pasador con ayuda de una pinza de mosquito (Fig 9).

Finalmente, se realiza una tercera incisión de 30 mm, a lo largo del tendón adductor mayor, ligeramente proximal a su inserción en la vecindad del epicóndilo femoral medial. Se identifica y diseca el hiato tendinoso del adductor y se pasa otro hilo conductor (Fig 10). A continuación, a través de la incisión rotuliana, se diseca la segunda capa de la cara medial de la rodilla, donde se deja también un hilo tractor. Por último, se conduce el injerto con la ayuda de los hilos fiadores a través de los túneles rotulianos (Fig 11), por debajo de la fascia crural superficial (segunda capa), en bucle a través del hiato de adductor mayor y de vuelta, en dirección ventral, hacia la incisión rotuliana, de forma que el injerto adopte una configuración triangular, en forma de abanico (Fig 12). Tras realizar repetidos ciclos de movilidad completa de la rodilla, mientras se mantiene el injerto bajo ligera tensión, de manera que la rótula pueda desplazarse lateralmente unos 10 o 15 mm, se suturan entre si los dos haces del injerto a 30º de flexión de la rodilla, evitando sobretensionarlo. En caso de injerto muy largo, el extremo medial puede suturarse adicionalmente en la capa subperióstica de la patela. En última instancia, se realiza una revisión artroscópica de la articulación, para observar el posicionamiento final extrarticular del LPFM (Fig 13) y comprobar el encarrilamiento correcto de la rótula con el movimiento articular.

La técnica no requiere ningún tipo de implante, la fijación del injerto es elástica y dado que no hay tunelización ósea en el fémur, no hay riesgo de invasión de la fisis, lo que supone una ventaja adicional en pacientes en edad de crecimiento. La extremidad intervenida se inmoviliza con una ortésis rígida en extensión completa durante 10 días. La carga a tolerancia, con ayuda de bastones, se permite inmediatamente.

Fig 10. Detalle quirúrgico. Disección del tendón del adductor mayor (AM).

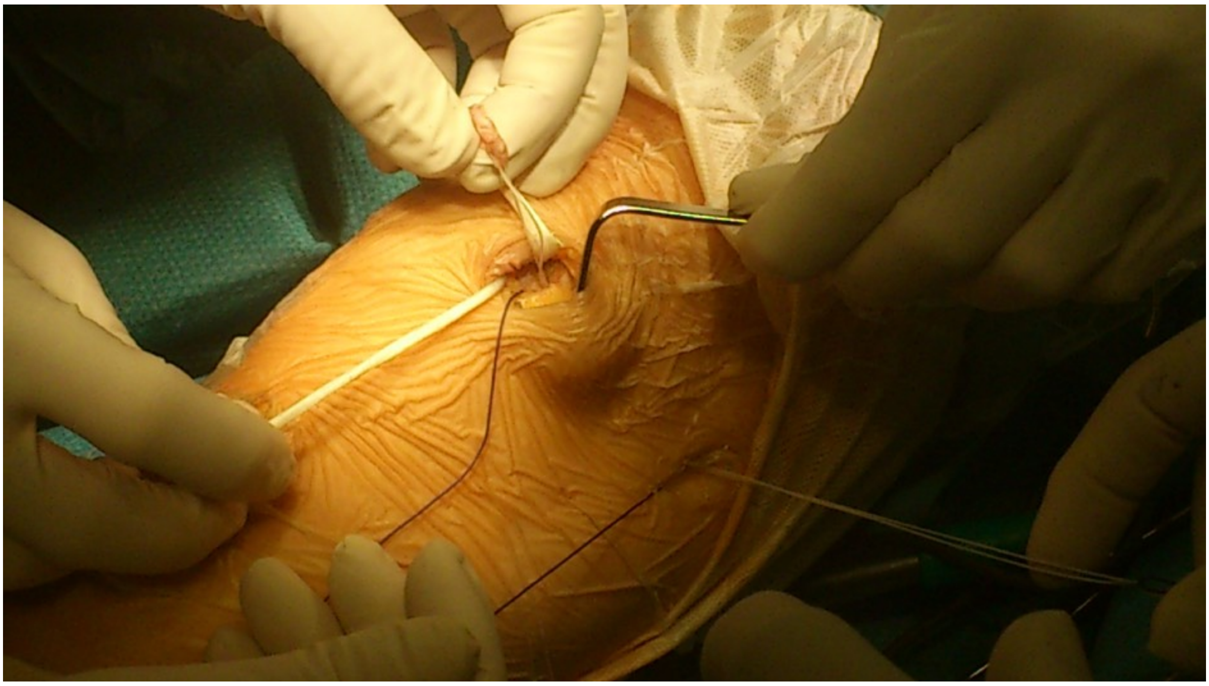

Fig 11. Detalle quirúrgico de la reconstrucción. Injerto conducido a través de los túneles patelares.

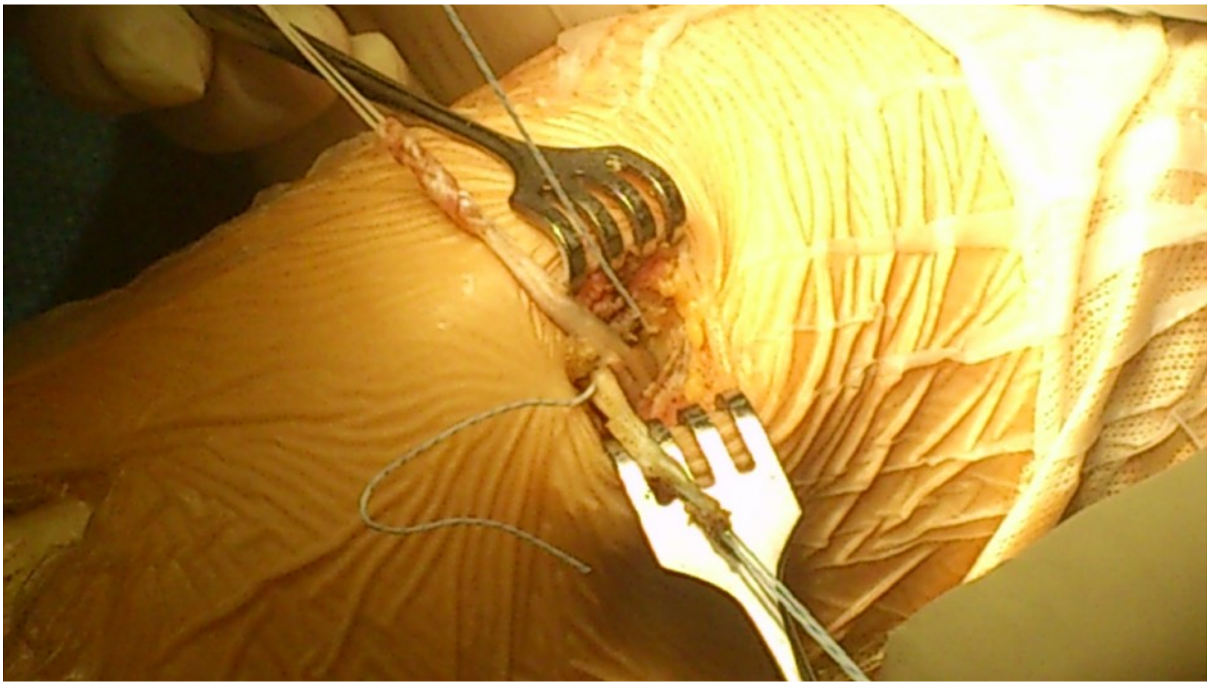

Fig 12. Detalle quirúrgico. Reflexión de la plastia del LPFM y sutura sobre si misma.

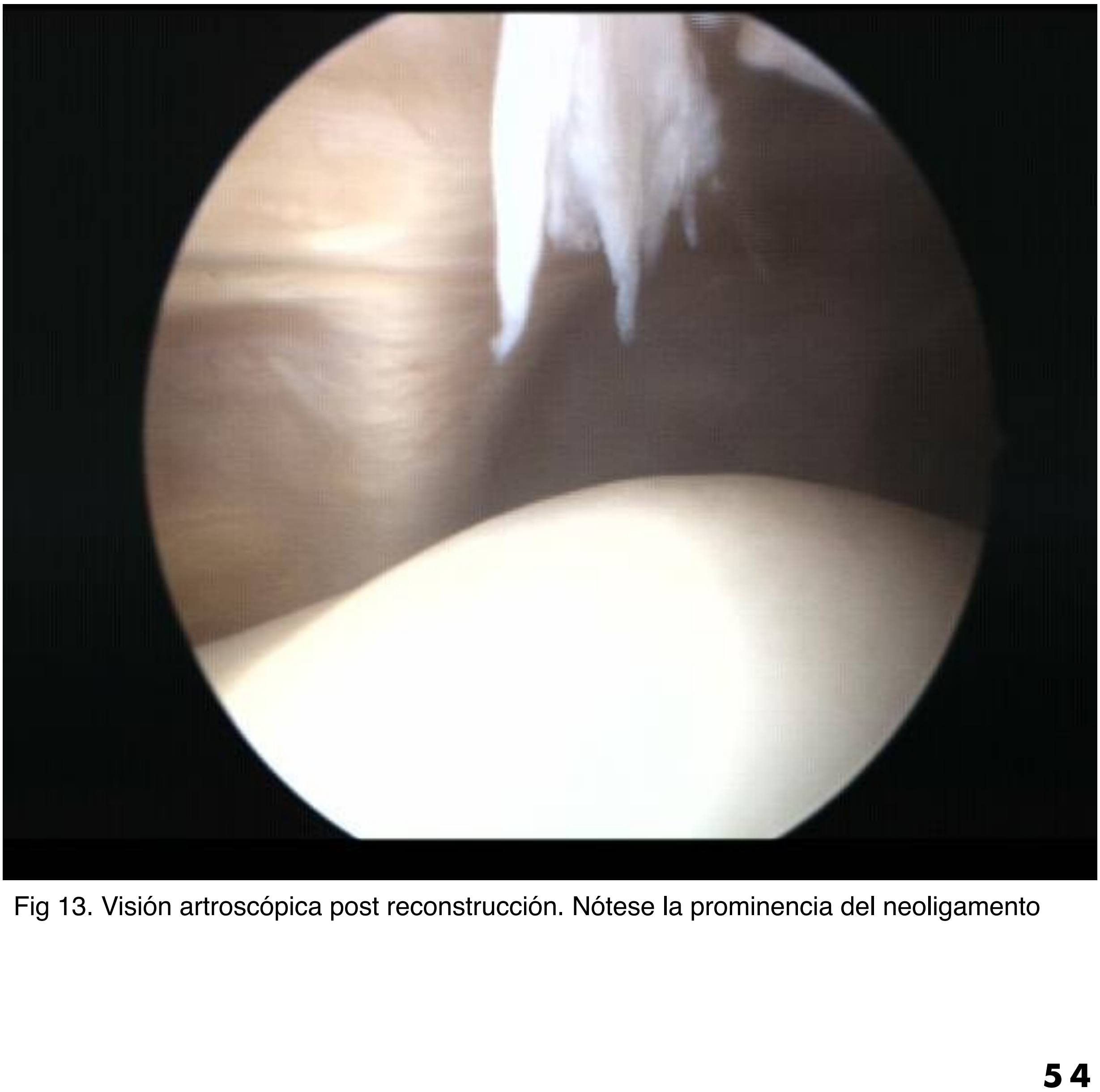

Fig 13. Visión artroscópica post reconstrucción. Nótese la prominencia del neoligamento

2.7 HIPÓTESIS DE LOS TRABAJOS

2.7.1 Hipótesis de trabajo nº 1.

La utilización de una técnica cuasi-anatómica de reconstrucción del LPFM, que toma como inserción femoral el hiato del AM, tendrá un comportamiento biomecánico similar a la de la técnica con inserción femoral anatómica.

2.7.2 Hipótesis de trabajo nº 2.

La reconstrucción cuasi-anatómica del MPFL con autoinjerto del tendón gracilis, en pacientes con episodios recurrentes de inestabilidad FP, proporciona buenos resultados clínicos y no será causa de degeneración articular FP.

2.7.3 Hipótesis de trabajo nº 3.

El desarrollo de un modelo paramétrico de la FP permitirá la evaluación de las presiones de contacto FP en cada tipo especifico de reconstrucción del MPFL y en diferentes grados de flexo-extensión de la rodilla.

2.7.4 Hipótesis de trabajo nº 4.

La reconstrucción cuasi-anatómica propuesta en esta tesis, proporciona una resistencia suficiente para oponerse a la luxación lateral de la patela sin generar presiones excesivas en el compartimento FP medial.

2.7.5 Hipótesis de trabajo nº 5.

La reconstrucción cuasi-anatomica obtiene unos resultados clínicos evolutivos semejantes a los de una técnica reconstructiva tradicional anatómica.

2.8 OBJETIVOS

2.8.1 Objetivo de Trabajo nº 1.

Describir la anatomía del LPFM y su relación con el AM. Obtener mediciones anatómicas del LPFM y de sus fascículos patelares superior e inferior .Estudiar su isometría en diferentes rangos de flexion de la rodilla y su relación con la inserción del AM.

2.8.2 Objetivo de trabajo nº 2.

Analizar los resultados clínicos y radiológicos de la reconstrucción cuasi-anatómica del LPFM, utilizando autoinjerto del tendón gracilis, en una serie de pacientes con inestabilidad FP.

2.8.3 Objetivo de trabajo nº 3.

Validar el desarrollo de un modelo paramétrico de la FP que, mediante el estudio con elementos finitos, permita evaluar objetivamente diferentes tipos de reconstrucción del LPFM.

2.8.4 Objetivo del trabajo nº 4.

Evaluar la biomecánica de la técnica de reconstrucción cuasi-anatómica del LPFM, mediante la metodología del sistema de elementos finitos y analizar las presiones de contacto generadas en la FP.

2.8.5 Objetivo del trabajo nº 5.

El objetivo principal, comparar los resultados funcionales después de una reconstrucción aislada del LPFM mediante técnica cuasi-anatómica (grupo A) y técnica anatómica (grupo B). Los objetivos secundarios fueron comparar los ratios de reluxación, rangos de movilidad y signos subjetivos de inestabilidad (Smillie test) en ambos grupos.

3. MATERIAL I MÉTODOS

Este apartado se corresponde con lo reportado en los estudios de investigación que conforman esta tesis.

3.1 TRABAJO Nº1.

The Anatomy and Isometry of a Quasi-anatomical Reconstruction of the Medial Patellofemoral Ligament.

Se trata de un estudio experimental en un modelo cadavérico. Tras la descongelación a temperatura ambiente, se realizaron disecciones anatómicas en diez rodillas correspondientes a siete cadáveres congelados. Siete rodillas eran de varones y tres de mujeres, con un rango de edad entre 59 y 74 años. Ninguna había sufrido cirugía previa, ni padecía enfermedad reumática alguna.

Siguiendo la misma sistemática de disección propuesta por LaPrade y cols.[5], se identificaron las siguientes referencias anatómicas.

MPFL-F	(inserción femoral del ligamento femoropatelar medial)
MPFL-SP	(inserción superior patelar del ligamento femoropatelar medial)
MPFL –IP	(inserción inferior patelar ligamento femoropatelar medial)
AM- F	(inserción femoral tendón adductor mayor)

Se efectuaron cuatro mediciones de las siguientes distancias anatómicas: MPFL-F y MPFL-SP, MPFL-F y MPFL-IP, AM-F y MPFL-SP, AM-F y MPFL-IP, en cinco diferentes ángulos de flexión de la rodilla (0º, 30º, 60º, 90º y 120º). Las mediciones fueron realizadas utilizando de manera simultánea, un calibre digital (*Digimatic Caliper.* Mitutoyo, Japan) con una precisión de 0.01 mm, y un goniómetro digital (*Absolute Goniometer*. White Plains, NY, USA) de 0.5º de exactitud.

A fin de evitar los errores entre observadores, todas las mediciones fueron obtenidas por la misma persona y realizadas un mínimo de dos veces para minimizar también los errores intra-observador. Finalmente fueron incluidas también mediciones entre el AM-F y el canal de Hunter. El análisis estadístico se realizó con el software SPSS 18.0 (SPSS Inc. Chicago, Illinois, USA). Para la comparación de dos situaciones o datos pareados se utilizo el test de la T de Student.

El protocolo de estudio fue aprobado por el comité ético del Hospital Universitario Dexeus (3/2014).

3.2 TRABAJO Nº 2

Clinical and Radiological Outcomes after a Quasi-anatomical Reconstruction of Medial Patellofemoral Ligament with Gracilis Tendón Autograft.

Se realizó un estudio clínico longitudinal descriptivo, en pacientes con inestabilidad objetiva rotuliana, que habían sido intervenidos quirúrgicamente entre 2006 y 2012, mediante reconstrucción cuasi-anatómica del LPFM con autoinjerto bifascicular de tendón gracilis (técnica descrita previamente).

Las valoraciones clínicas, preoperatorias y de seguimiento final, fueron realizadas mediante las escalas de IKDC, Kujala, Tegner, Lysholm y la escala visual analógica de valoración del dolor. Las evaluaciones radiológicas, pre y post intervención, incluyeron la radiología simple (para análisis de la altura y báscula rotuliana), y la TAC (para la distancia TA-TG, los signos de displasia troclear femoral y el grado de artrosis). Dos observadores independientes recogieron y analizaron todos los datos.

El análisis estadístico se realizó con el *software* SPSS 19.0 (SPSS Inc. Chicago, Illinois, USA). Para comparar los resultados clínicos pre y post-operatorios obtenidos por las diferentes escalas de valoración se utilizó el test de Wilcoxon.

El estudio fue aprobado por el comité ético local (ICATME-Institut Universitari Dexeus, 2/2014).

3.3 TRABAJO Nº 3

Parametric Finite Element Model of Medial Patellofemoral Ligament Reconstruction. Model Development and Clinical Validation.

Para este estudio, se desarrolló un modelo paramétrico tridimensional de la articulación FP para posteriormente poder aplicar metodología de elementos finitos (FEM). El modelo se obtuvo a partir de datos disponibles de TAC 3D de 24 rodillas de pacientes intervenidos por inestabilidad FP, entre 2002 y 2012. Para el desarrollo y análisis se utilizaron el software Abaqus/CAE v.6.14 (Dassault Systemes. France)

Los elementos parametrizados como elementos rígidos, fueron los huesos femoral (cóndilos) y patelar. Como elementos deformables hexahedrales se parametrizaron el cartílago hialino de los cóndilos femorales y el patelar, También se parametrizaron los tendones del cuádriceps, rotuliano, el LPFM y el retináculo lateral, cuyas propiedades mecánicas fueron extraídas de estudios previos[95,108].

El espesor estimado del cartílago hialino fue de 3 mm, con un modulo de elasticidad (Young) de 10 MPa y una proporción de Poisson de 0.45. El contacto entre las superficies cartilaginosas de fémur y rotula fue resuelto utilizando un contacto superficie-superficie con coeficiente de fricción de 0.02.

Para la simulación se consideraron cuatro supuestos quirúrgicos de reconstrucción del LPFM, en los que siempre se utilizó como injerto el tendón semitendinoso:

1. Inserción femoral anatómica con túnel óseo.
2. Inserción femoral no anatómica (anterior/ventral), con túnel óseo.
3. Inserción femoral no anatómica (posterior/dorsal), con túnel óseo.
4. Inserción femoral no anatómica (posterior/dorsal), sin túnel óseo (adductor mayor).

Las cuatro técnicas fueron analizadas en cinco puntos de flexión de la rodilla: 0º, 30º, 60º, 90º y 120º, valorándose en todas ellas las presiones de contacto en el cartílago patelar y las tensiones (cambios de longitud) del injerto. Los datos obtenidos se compararon también con los correspondientes a condiciones anatómicas basales (LPFM intacto).

Para la validación del modelo paramétrico desarrollado, este se aplicó en seis casos clínicos intervenidos previamente y de resultado conocido, adaptando para ello la geometría de cada paciente. Los resultados de la simulación se compararon con los que se habían obtenido.

3.4 TRABAJO Nº 4

Evaluation of Patellar Contact Pressure Changes after Static versus Dynamic Medial Patellofemoral Ligament Reconstructions Using a Finite Element Model.

A partir de la parametrización realizada en el tercer trabajo de la presente tesis, utilizando el modelo de elementos finitos de la articulación FP desarrollado previamente, ya descrito y validado, se compararon los supuestos de comportamiento del LPFM intacto y el de diferentes reconstrucciones del LPFM, tanto estáticas como dinámicas y, muy especialmente, la reconstrucción cuasi-anatómica, es decir, sin túnel óseo femoral, con polea de reflexión en el AM. Se compararon reconstrucciones realizadas alternativamente con injerto del semitendinoso y del gracilis, en cinco diferentes grados de flexión de rodilla. Se asumió como posición de referencia, la de flexión de rodilla a 40º, posición en que el LPFM no está sujeto a tensión.

3.5 TRABAJO Nº 5

Isolated reconstruction of medial patellofemoral ligament with an elastic femoral fixation leads to excellent clinical results.

Se realiza un estudio longitudinal, prospectivo, comparativo entre dos series homogéneas de 29 y 28 pacientes respectivamente (grupo A reconstrucción LPFM cuasi-anatómica, grupo B reconstrucción anatómica). Fueron descartados pacientes con displasia troclear tipos C y D, así como pacientes con técnicas quirúrgicas asociadas a la reconstrucción del LPFM, ya fueran trocleoplastias y/o técnicas de realineación distal del aparato extensor.

4. RESULTADOS

Este apartado se corresponde con lo reportado en cada uno de los trabajos de investigación que conforman esta tesis.

4.1 TRABAJO Nº 1

The Anatomy and Isometry of a Quasi-anatomical Reconstruction of the Medial Patellofemoral Ligament.

La distancia entre la inserción anatómica femoral del LPFM y su inserción patelar superior fue de 57.8 mm (SD 6.4 mm), mientras que con la inserción patelar inferior fue de 55.7 mm (SD 6.6 mm).

La distancia entre la inserción cuasi-anatómica femoral en el AM y la inserción patelar superior del LPFM fue de 60.7 mm (SD 5.7 mm), mientras que, con la inserción patelar inferior fue de 59.5 mm (SD 6.1 mm).

Los cambios de longitud de los haces superior e inferior del LPFM durante la flexión de la rodilla, desde 0° a 120°, tanto respecto a su inserción anatómica femoral como a la no-anatómica (inserción en el AM) presentaron un comportamiento isométrico, es decir con diferencias (cambios de longitud) menores a 5 mm entre 0° y 90°.

La distancia entre la inserción femoral del AM y el canal de Hunter fue de 78.6 mm (SD 9.4 mm).

4.2 TRABAJO Nº 2

Clinical and Radiological Outcomes after a Quasi-anatomical Reconstruction of Medial Patellofemoral Ligament with Gracilis Tendon Autograft.

Se analizaron preoperatoriamente y a 37.6 meses de seguimiento medio, 36 rodillas intervenidas por inestabilidad FP lateral. En 15 casos (44.4%) se realizó reconstrucción aislada del LPFM (técnica cuasi-anatómica) y en los 20 restantes (55.6%) esta técnica se combinó con una realineación distal del aparato extensor.

Ningún paciente sufrió episodios de reluxación rotuliana postoperatoria durante el periodo de estudio aunque en un caso persistió un signo de aprensión positivo. Respecto al dolor medido con la escala visual analógica (EVA) disminuyó de 6 (SD 2.48) en el preoperatorio a 2 (SD 1.58) en el último seguimiento ($p < 0.001$). Todas las escalas funcionales, Lysholm, Kujala, IKDC y Tegner, experimentaron mejorías significativas postoperatorias ($p < 0.001$). La inclinación (báscula) rotuliana mejoró significativamente desde un promedio preoperatorio de 20.4º (SD 9.7) a 14.9º (SD 8.0) en el postoperatorio ($p < 0.001$). La distancia TA-GT no sufrió cambios significativos, ni tampoco se observaron en la altura rotuliana, medida según el índice de Caton-Deschamps. Según los criterios de Crosby e Insall, no se observaron cambios radiológicos FP, es decir, que no hubo progresión de la artrosis durante el seguimiento de los pacientes.

Tres pacientes (8.3%) sufrieron complicaciones postoperatorias y precisaron una segunda intervención. Dos por presentar un déficit de flexión de unos 25º y otro por intolerancia al material osteosíntesis utilizado en la osteotomía de la tuberosidad anterior de la tibia, que precisó su extracción.

4.3 TRABAJO Nº 3

Parametric Finite Element Model of Medial Patellofemoral Ligament Reconstruction. Model Development and Clinical Validation.

Se analizaron las presiones de contacto en el cartílago hialino rotuliano y la tensión y longitud del LPFM intacto, en condiciones anatómicas estándar, y en cuatro supuestos distintos de técnicas reconstructivas del LPFM. En todos los casos se utilizó un injerto de semitendinoso, y el análisis se realizó a 0º, 30º, 60º, 90º y 120º de flexión de la rodilla.

Se observó un incremento de las presiones de contacto en la patela entre 0º y 30º de flexión de la rodilla, tanto en las reconstrucciones anatómicas como en las no anatómicas pero con comportamiento fisiométrico. En ambos tipos de reconstrucción, el ligamento estaba tenso entre los 0º y 30º, pero a 60º, 90º y 120º no mostraba tensión. En el tercer tipo de reconstrucción del MPFL analizado (no anatómica ni fisiométrica el comportamiento fue completamente opuesto. En general, la reconstrucción cuasi-anatómica del LPFM, obtuvo unas presiones de contacto en el cartílago rotuliano mas bajas que el modelo estándar, y unas medidas de tensión del LPFM muy cercanas a las originales.

La aplicación del sistema paramétrico de EF, en el análisis de los diferentes casos clínicos, corroboró la influencia del tipo de reconstrucción del LPFM en los cambios de longitud y tensión del injerto y en las variaciones de la presión de contacto en el cartílago rotuliano. Aquellos casos con presiones de contacto superiores a 5 MPa, a partir de los 60º de flexión de la rodilla, estaban siempre asociados con fijaciones femorales del LPFM no anatómicas.

4.4 TRABAJO Nº 4

Evaluation of Patellar Contact Pressure Changes after Static versus Dynamic Medial Patellofemoral Ligament Reconstructions Using a Finite Element Model.

La comparación entre técnicas de reconstrucción del LPFM estáticas y dinámicas mostró que estas últimas generaban presiones de contacto FP mucho más similares a las de una rodilla sana que las que producían las técnicas estáticas.

Al analizar específicamente el modelo de reconstrucción cuasi-anatómico propuesto en esta tesis, ya fuera realizado con semitendinoso o con gracilis, con la situación de LPFM intacto, se observó que las presiones rotulianas con la rodilla a 0° de flexión eran muy similares en todos los supuestos. Con la rodilla a 30° de flexión, las presiones de contacto rotulianas fueron ligeramente mas elevadas respecto a las del LPFM original. A mayores grados de flexión, el comportamiento volvía a ser muy parejo en todas las situaciones analizadas. En todos los supuestos el gracilis se comportó igual o mejor que el semitendinoso en términos de la presión generada en las superficies articulares FP. Cuando se estudio la fuerza necesaria para la rotura / fracaso del injerto, el injerto de semitendinoso, como parece lógico por sus características mecánicas intrínsecas, mostró ser superior

4.5 TRABAJO Nº 5

Isolated reconstruction of medial patellofemoral ligament with an elastic femoral fixation leads to excellent clinical results.

El promedio postoperatorio del Score Funcional de Kujala fue de 90.4 (89.4 para el grupo A y 92.1 para el grupo B, respectivamente). Al comparar los valores pre y postoperatorios obtenidos en ambas series, no se detectaron diferencias significativas entre grupos en ninguna de la siguientes escalas, Kujala, IKDC y VAS. La evaluación de la influencia del index de Caton-Deschamps y de la mediciones de la TT-TG no detectaron diferencias significativas,en pacientes sin displasia troclear y /o con displasias tipos A y B. Tampoco existieron diferencias en las tasas de reluxación ni en los rangos de movilidad postoperatoria.

5. DISCUSIÓN

El análisis de la literatura evidencia que todavía existe notable controversia en muchos aspectos de la cinemática FP[51,65-66], anatomía del LPFM (p.e. sus relaciones con el VMO y Vasto Intermedio[56,57]) y, como no, en la corrección quirúrgica de la inestabilidad FP. La presente tesis doctoral pretende aportar conocimiento en algunos de los aspectos mas controvertidos de este tema.

El principal hallazgo del primer estudio del presente compendio, basado en la disección anatómica en cadáveres congelados, es que un injerto de LPFM fijado a nivel del hiato del AM, tiene un comportamiento biomecánico muy similar a las reconstrucciones del LPFM con fijación femoral anatómica. Aceptando como isométricas variaciones de la longitud del ligamento menores a 5 mm (Smirk[63]), la reconstrucción cuasi-anatómica mostró isometría entre los 0° y 90° de flexión, con menores variaciones en las fibras de inserción patelar inferior del LPFM.

Según la literatura previa, el autoinjerto de tendón semitendinoso es el mas comúnmente utilizado para la reconstrucción del LPFM. El LPFM posee una resistencia a la tensión de 208 N, mientras que la del tendón del semitendinoso es de 1915 +/- 159 N (casi 10 veces mayor) y la del tendón Gracilis es de 837+/-138 N. Aunque no hay estudios concluyentes sobre el particular, se puede asumir que la utilización de un injerto mucho mas robusto que el LPFM original podría condicionar un aumento de presiones en la vertiente medial rotuliana. Por tanto, parece mas razonable el uso del gracilis como injerto de sustitución, tal como se propone en el presente trabajo.

El principal hallazgo del segundo estudio es que la reconstrucción del LPFM con la técnica cuasi-anatómica da buen resultado clínico y corrige la báscula patelar. Como en otras muchas técnicas ortopédicas, dado que las escalas funcionales de valoración son subjetivas (PROM's), los buenos resultados clínicos obtenidos con la técnica cuasi-anatómica, podrían ser cuestionables. Sin embargo, la no aparición de casos de reluxación en la serie presentada en este trabajo, apoya la bondad de esta técnica de reconstrucción para su principal objetivo, corregir las inestabilidad. Además, la ausencia de signos de artrosis FP, a pesar del relativamente corto periodo de seguimiento clínico aporta un dato relevante, mas importante si cabe, como es la ausencia de efectos deletéreos para la FP, que también contribuiría a confirmar la bondad del procedimiento. Una explicación plausible sería el comportamiento cuasi-isométrico, o mejor fisiométrico, del injerto observado en el estudio cadavérico (trabajo 1). En el campo experimental, Melegary[82] y Panagopoulos[65], utilizaron también este tipo de reconstrucciones no anatómicas, en modelos cadavéricos, encontrando hallazgos similares. La naturaleza elástica de la fijación, polea de reflexión en un hiato tendinoso, podría compensar pequeños cambios de longitud del injerto, evitando aumentos de presión en la vertiente medial de la FP. Del mismo modo, la mejora observada en el índice de inclinación rotuliana, sugiere también la positiva influencia de esta reconstrucción en la cinética patelar.

Como siempre en cirugía, la posibilidad de error en el intento de identificar intraoperatoriamente una referencia anatómica, como es el punto idóneo de fijación femoral, aún con ayuda de radiología, es una de las preocupaciones principales para los cirujanos en el momento de reconstruir el LPFM. La malposición del neoligamento conllevará cambios en su isometría y esto puede condicionar alteraciones en las presiones de contacto rotulianas. De nuevo, la fijación elástica, pese a no respetar estrictamente la anatomía original, podría contribuir a minimizar estos efectos. El bajo porcentaje de complicaciones obtenido con la técnica cuasi-anatómica (8,3%), respeto a lo referido en la literatura previa (26%) con este tipo de reconstrucción, podría sorprender. Sin embargo, en esta serie clínica (trabajo 2) se realizó una cuidadosa selección de los pacientes, añadiendo cirugía correctora de factores predisponentes especialmente relevantes - como es la distancia TA-GT > a 20 mm - siempre que se consideró necesario. Este hecho, unido a la utilización de un sistema de fijación elástico en la reconstrucción del LPFM, puede contribuir a explicar las pocas complicaciones observadas.

La reconstrucción cuasi-anatómica presenta algunas ventajas adicionales como: evitar la utilización de material de síntesis para la fijación ósea, perforar la vecindad de la línea fisaria (lo que resulta especialmente útil en aquellos pacientes mas jóvenes, todavía en edad de crecimiento) y disponer de una referencia anatómica constante, que facilita la identificación manual y a simple vista del punto de fijación femoral. Todo ello la convierte en una técnica simple, barata, segura y reproducible.

Sin embargo, pese a los resultados clínicos obtenidos, las ventajas teóricas de la técnica son difíciles de verificar y la comparación con otras técnicas, resulta especialmente difícil. Para obviar estos problemas se diseñó el modelo paramétrico de EF. Los hallazgos de su estudio específico (Trabajo 3) muestran, en general, concordancia con otros trabajos biomecánicos reportados previamente, confirmando que el LPFM actúa de forma preferente como un elemento restrictor al desplazamiento lateral de la patela durante los primeros 30° de flexión de la rodilla y que se va destensando progresivamente a medida que aumenta la flexión. Del mismo modo, con la flexión de la rodilla también decrece la presión de contacto FP. Este estudio confirma además la relación entre el punto de fijación femoral, la presión de contacto FP y el patrón de longitud–tensión del injerto del LPFM, ya observado por otros autores[38].

Segal et al.[124], estimaron mediante *Discrete Element Analysis* (DEA), que el umbral de presiones en la FP que puede predecir la aparición de artrosis sintomática, oscila entre 3.42 y 3.61 MPa, con una sensibilidad del 73.3% y una especificidad de entre el 46.7% y 66.7%. En el presente estudio, utilizando el modelo de EF, las reconstrucciones cuasi-anatómicas del LPFM han generado unas presiones máximas en la FP del orden de 2.77 MPa. Aunque estos datos, obtenidos mediante el modelo paramétrico, no son directamente extrapolables a la clínica, sugieren, de nuevo, que las presiones generadas a nivel de la FP están en el rango fisiológico y que por tanto cabría esperar un buen comportamiento a largo plazo.

La evaluación de las reconstrucciones del LPFM mediante el sistema de EF (Trabajo 4) aporta mayor especificidad y sensibilidad que la simple utilización de escalas subjetivas de valoración de los resultados clínicos (PROM's). En términos de presiones generadas a nivel de la articulación FP, el presente estudio muestra como la reconstrucción cuasi-anatómica propuesta se comporta biomecánicamente de manera muy similar a una reconstrucción anatómica del LPFM. El modelo también permite analizar las diferencias de comportamiento de distintos tipos de injertos, implantados con la misma técnica quirúrgica. Este última cuestión, muy difícil de reproducir con otro tipo de estudios, abre el camino al modelo para su ulterior utilización en estudios concernientes a la estabilidad femoropatelar.

Finalmente, en el último trabajo de este compendio, se comprueban los buenos resultados clínicos obtenidos en la serie previa de reconstrucción cuasi anatómica del LPFM (Trabajo 2), se valida la bondad de la técnica al compararla con la anatómica considerada patrón de oro y, por último, se ratifican a la vez algunos de los hallazgos observados con el modelo de EF. la inexistencia de literatura previa consistente que compare técnicas anatómicas y no anatómicas, dificulta la discusión de este particular. Sin embargo, datos como son la eficiencia en la corrección de la inestabilidad, el balance articular conservado y, sobretodo, la ausencia de dolor patelofemoral medial, probable predecesor de cambios artríticos definitivos, sugieren que el modelo propuesto tiene un valor claro en el arsenal terapéutico de esta patología.

5.1 LIMITACIONES DE LOS ESTUDIOS PRESENTADOS

Muchas son las limitaciones que pueden identificarse en los presentes estudios. La primera, en referencia al estudio cadavérico (trabajo 1), el número limitado de la muestra, que corresponde, en general, a personas de edad avanzada, de las que no se dispone de radiología previa, ni de información clínica otra que la observable macroscópicamente. Aunque estos son problemas inherentes a los estudios cadavéricos en nuestro medio. El estudio a priori del cálculo muestral parece adecuado a la luz de la uniformidad de resultados obtenidos. Además, se pueden criticar también las mediciones lineales realizadas, con un calibre lineal, y efectuadas sobre un tejido cadavérico, que pueden diferir respecto a las reales y a las simplemente obtenidas en el individuo vivo.

En cuanto al trabajo 2, cabe decir que se trata de una revisión clínica retrospectiva, con todas las limitaciones inherentes a un estudio de este tipo. Además las cirugías fueron todas efectuadas por un solo cirujano y no existió un grupo de control. El tamaño muestral (número de pacientes) y el tiempo de seguimiento son también limitados, aunque 2 años es un punto de corte aceptado para la mayoría de trabajos en el campo de la ortopedia. Además, a un número significativo de pacientes se les realizó adicionalmente un procedimiento de realineación distal del aparato extensor, con efecto *per se* sobre la inestabilidad. Sin embargo, la no corrección de estos factores conduciría a cualquier reconstrucción aislada del LPFM a un fracaso anunciado.

Respecto a los trabajos 3 y 4, cabe decir que el desarrollo del estudio con EF, a partir de datos obtenidos de TAC, limita la inclusión de valores correspondientes a tejidos blandos, así como de las propiedades del tejido-matriz cartilaginoso, cuestión esta que quizás la resonancia magnética podría contribuir a paliar, pero común por otra parte, en los estudios que emplean EF. Finalmente, la influencia de la rotación femoral en la fuerzas de cizallamiento del cartílago patelar, así como la tensión de la musculatura isquiotibial y del VMO sobre la báscula rotuliana y la presión de contacto patelar, son factores conocidos que pueden influir en la distribución de presiones en la FP y que no ha sido valorados en este modelo[126-128].

Respecto al trabajo 5, a pesar de ser uno de los de mayor nivel de comprobación científica de este compendio, también se podrían aducir que las cirugía fueron practicadas por cirujanos distintos (introduciendo un posible performance bias), se emplearon injertos distintos y no se analizaron dos series aleatorizadas sino que se compararon dos de demográficamente similares. No obstante, la consistencia de los resultados observados, hacen pensar que todas estos posibles sesgos no influyeron a los resultados obtenidos.

6. CONCLUSIONES

6.1 TRABAJO Nº1

The Anatomy and Isometry of a Quasi-anatomical Reconstruction of the Medial Patellofemoral Ligament.

La reconstrucción cuasi-anatómica, utilizando el hiato del AM como polea de reflexión, muestra un comportamiento biomecánico similar al del LPFM original. Ambos modelos han mostrado isometría desde 0° a 90°, siendo esta mas precisa para las fibras con inserción patelar mas distal.

6.2 TRABAJO Nº2

Clinical and Radiological Outcomes after a Quasi-anatomical Reconstruction of Medial Patellofemoral Ligament with Gracilis Tendon Autograft.

La reconstrucción cuasi-anatómica del LPFM ha obtenido buenos resultados clínicos, mejora la inclinación patelar, y no produce a corto plazo signos de artrosis FP en el análisis por TAC. La baja tasa de complicaciones sugiere que es una técnica segura, fiable y reproducible en el tratamiento de la inestabilidad rotuliana, siendo especialmente útil en pacientes adolescentes con fisis abiertas.

6.3 TRABAJO Nº3

Parametric Finite Element Model of Medial Patellofemoral Ligament Reconstruction. Model Development and Clinical Validation.

El estudio de la FP mediante un modelo paramétrico de EF ha permitido evaluar los diferentes tipos de técnicas de reconstrucción del LPFM, observar su repercusión sobre las presiones de contacto FP y su comportamiento cinemático, cambios de longitud, en diferentes grados de flexión de la rodilla.

6.4 TRABAJO Nº4

Evaluation of Patellar Contact Pressure Changes after Static versus Dynamic Medial Patellofemoral Ligament Reconstructions Using a Finite Element Model.

Las presiones de contacto tras la reconstrucción dinámica (cuasi-anatómica) del LPFM son iguales que las del ligamento original (nativo), mientras que las que genera la reconstrucción estática (anatómica) son mayores, lo que puede comportar, a la larga, un incremento del riesgo de artrosis. Por tanto, la reconstrución del LPFM dinámica parece una opción más segura desde el punto de vista biomecánico que la estática.

6.5 TRABAJO Nº 5

Isolated reconstruction of medial patellofemoral ligament with an elastic femoral fixation leads to excellent clinical results.

La reconstrucción cuasi-anatómica del LPFM realizada con autoinjerto del tendón Gracilis proporciona unos resultados clínicos tan buenos como los de la reconstrucción anatómica, en pacientes con inestabilidad FP sin displasia trocleofemoral o con displasias de bajo grado, tipos A y B, tras cinco años de seguimiento.

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ANEXO FIGURAS

Fig 1. Inestabilidad FP. Monumento funerario Georgio Meisellio. Cementerio teutónico Ciudad del Vaticano. Roma (Italia).

Fig 2. Disección cadavérica de la cara medial de la rodilla. Una vez extirpada la piel, el tejido celular subcutáneo y la cápsula articular de la rodilla (primera capa) se evidencia el LPFM con su habitual disposición en abanico.

Fig 3. Imagen quirúrgica de una realineación distal del aparato extensor. Osteotomía de la tuberosidad tibial anterior según técnica de Fulkerson.

Fig 4. Disección del LPFM. Tomado con permiso de Kruckeberg B et al. Quantitative and Qualitative Analysis of the Medial Patelar Ligaments. An anatomic and radiographic Study. Am J Sports Med. 2018 Jan; 46(1): 153-152.

Fig 5. Disección Ligamento Patelo Tibial medial y Ligamento Patelo Meniscal Medial. Tomado con permiso de Kruckeberg B et al. Quantitative and Qualitative Analysis of the Medial Patelar Ligaments. An anatomic and radiographic Study. Am J Sports Med. 2018 Jan; 46(1):153-62.

Fig 6. Clasificación de Wiberg. Tomado con permiso de Sherman S et al. Patellofemoral Anatomy and Biomechanics. Clin Sports Med. 2014: 33(3): 389-401.

Fig 7. Disección de la cara medial de una rodilla izqda. El VMO es separado proximalmente, mostrando así su intima relación con el LPFM.

Fig 8. Clasificación de Dejour de las displasias trocleares. Tomado con permiso de Sherman S et al. Patellofemoral Anatomy and Biomechanics. Clin Sports Med. 2014 Jul:33(3):389-401

Fig 9. Imagen quirúrgica de una rodilla derecha. Incisión pararotuliana medial y perforacion de túneles patelares.

Fig 10. Imagen quirúrgica de una rodilla derecha. Disección del tendón del Adductor Mayor (AM) y pinza pasada por el hiato.

Fig 11. Imagen quirúrgica de una rodilla derecha. El injerto es conducido a través de los túneles rotulianos con la ayuda de un hilo fiador.

Fig 12. Imagen quirúrgica de una rodilla derecha. El injerto pasa por debajo de la fascia crural superficial (segunda capa), se refleja a través del hiato del Adductor Mayor (AM) y finalmente retorna hacia la incisión rotuliana.

Fig 13. Visión artroscópica de la gotera medial de una rodilla izquierda post-reconstrucción del LPFM. Nótese el relieve del neoligamento.

ANEXO ARTÍCULOS

Trabajo 1

Knee Surg Sports Traumatol Arthrosc
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KNEE

The anatomy and isometry of a quasi-anatomical reconstruction of the medial patellofemoral ligament

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Abstract

Purpose To describe the anatomy of the medial patellofemoral ligament (MPFL) and its relationship to the *Adductor Magnus* (AM) tendon as well as the behaviour exhibited in length changes during knee flexion.

Methods Ten cadaveric knees were dissected. The length from the superior and inferior patellar origin of the MPFL to its femoral insertion was measured at different degrees of knee flexion (0°, 30°, 60°, 90° and 120°). The same measures were made from both patellar origins of the MPFL up to the femoral insertion of the AM. The distance between the insertion of the AM and the Hunter canal was also measured.

Results In general, isometry up to 90° was seen in all measures of the MPFL and those of the AM. The most isometric behaviour was seen in 2 measures: the length of the AM femoral insertion up to the inferior origin of the MPFL on the patella and the length of the femoral insertion of the MPFL up to the inferior origin of the MPFL on the patella. Similar behaviour was seen regardless of the anatomical or quasi-anatomical femoral point of attachment (n.s.). The distance from the AM tendon to the Hunter canal had a mean value of 78.6 mm (SD 9.4 mm).

Conclusion The behaviour exhibited during the changes in the length of the anatomical femoral footprint of the MPFL and the AM is similar. Neurovascular structures were not seen at risk. This is relevant in the daily clinical practice since the AM tendon might be a suitable point of insertion for MPFL reconstruction.

Keywords Medial patellofemoral ligament · Femoral attachment · Quasi-anatomical reconstruction · Patellofemoral instability

Introduction

The medial patellofemoral ligament (MPFL) is the main restrictor of lateral dislocation of the patellofemoral joint [7, 14, 19, 22]. It is usually torn in cases of objective patellofemoral instability, and therefore its reconstruction is crucial to the treatment of the aforementioned pathology [4, 17].

Knowing the biomechanical performance of the MPFL is essential to carrying out a correct surgical technique [1, 2, 5]. Several researchers have studied the anatomy of the MPFL and its behaviour at different degrees of knee flexion [6, 18, 21]. Recently, a new non-anatomical technique in which the *Adductor Magnus* (AM) tendon was used as a pulley instead of the classical femoral attachment for MPFL reconstruction has been reported [9]. Although the authors reported excellent outcomes in patients treated with that procedure, the anatomical relationships of this type of MPFL reconstruction as well as its behaviour during knee motion have not been thoroughly analysed.

The purpose of this study was to describe the anatomy of the MPFL and AM. First, the functional length of the

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MPFL during knee flexion in cadaveric knees was measured. Then, the functional distance between the AM femoral insertion and the patellar insertion of the MPFL (as it is described in the aforementioned non-anatomical reconstruction technique [9]) was also calculated. The behaviour of both measures during flexion was then compared. The hypothesis was that the non-anatomical AM attachment behaves, biomechanically speaking, similarly to the anatomical femoral insertion of the MPFL. This might be of clinical interest to use the AM tendon as a pulley in the reconstruction of the MPFL.

Materials and methods

Ten fresh-frozen cadaveric knees (whole leg specimen) from 7 cadavers were dissected. Seven knees were from male cadavers and 3 were from female cadavers, all of which corresponded to elderly people and the ages ranged from 59 to 74 years old. None of them had reported any history of rheumatic disease. Neither had the included knees undergone any previous surgery.

The first part of this study consisted in defining the anatomy of the AM and the MPFL. After the dissection and removal of the broad skin and soft tissue window of the anteromedial aspect of the joint, a blunt dissection was made to identify the triangular/trapezoidal shape of the MPFL. The AM was also dissected from its attachment up to the Hunter canal. Three points were identified. They were the MPFL femoral attachment (MPFL-F), its superior origin on the patella (MPFL-SP) and its inferior origin on the patella (MPFL-IP). Subsequently, the femoral insertion of the AM (AM-F) was also identified. All points were identified following the LaPrade anatomical studies [7].

During the second part of the study, isometry was evaluated at 5 fixed angles of knee flexion (0°, 30°, 60°, 90° and 120°). Four measures were taken at each degree of motion (Fig. 1): the distance between MPFL-F and MPFL-SP, the distance between MPFL-F and MPFL-IP, the distance between the AM-F and MPFL-SP and the distance between AM-F and MPFL-IP. Some other measures such as the distance between the insertion of the AM and the Hunter canal were included.

Measures were made using a digital calliper (Digimatic Caliper, Mitutoyo, Japan; 0.01 accuracy) and a digital goniometer (Absolute Goniometer; Fabrication Enterprises Inc., White Plains, NY, USA; 0.5° accuracy). All measurements were obtained by the same individual so as to avoid interobserver error. The distances between all the points were measured at least twice so as to minimize intraobserver error and were then rounded to the nearest decimal of millimetre.

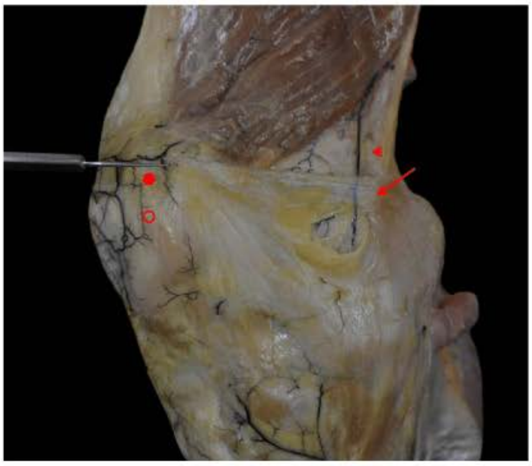

Fig. 1 Detail of one specimen that shows the anatomical landmarks. *Arrow* femoral insertion of the medial patellofemoral ligament. *Head arrow* femoral insertion of the adductor magnus. *Solid ring* superior patellar origin of the patellofemoral ligament. *Outlined ring* inferior patellar origin of the patellofemoral ligament

IRB approval

The study was approved by the local Ethics Committee (ICATME—Institut Universitari Dexeus, 3/2014).

Statistical analysis

Continuous variables are expressed as mean and standard deviations (SD). When 2 related items of data were analysed, the Student's t test was used. In all cases, a p value of <0.05 was considered statistically significant. The statistical analysis was done using the SPSS 18.0 (SPSS Inc., Chicago, IL, USA) statistical package. No sample size analysis was made because of the descriptive aim of this study and also because the specimens were limited in number.

Results

The distance from the AM tendon attachment to the Hunter canal had a mean value of 78.6 mm (SD 9.4 mm).

The mean distance from the femoral attachment of the MPFL up to its superior patellar origin was 57.8 mm (SD 6.4 mm), while the mean distance up to its inferior patellar origin was 55.7 mm (SD 6.6 mm). The distances from the quasi-anatomical attachment, which were described by Monllau et al. [9], up to the anatomical origin of the MPFL were also measured. In that sense, the mean distance from the femoral insertion of the AM up to the superior patellar origin of the MPFL was 60.7 mm (SD 5.7 mm), while the mean distance up to the inferior patellar origin of the MPFL was 59.5 mm (SD 6.1 mm).

According to Smirk and Morris [18], all MPFL measures and those from the AM showed isometry up to 90°. The most isometric behaviour was seen in the measure between the AM femoral insertion and femoral insertion of the MPFL up to the inferior origin of the MPFL on the patella. Therefore, similar performance (n.s.) might be expected of those two bundles, as can be seen in Fig. 2. The measures from the superior origin of the MPFL showed a small decrease from 0° to 30° and a bigger drop from 90° to 120°. However, similar behaviour (n.s.) was seen regardless of the anatomical or quasi-anatomical femoral point, as can be seen in Fig. 3.

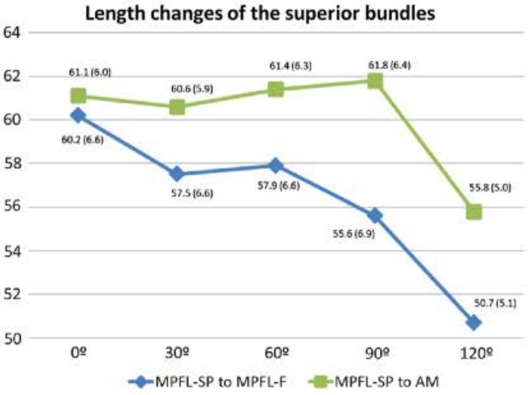

Fig. 2 Length changes of superior bundles. Results are expressed as mean and standard deviation (in parentheses)

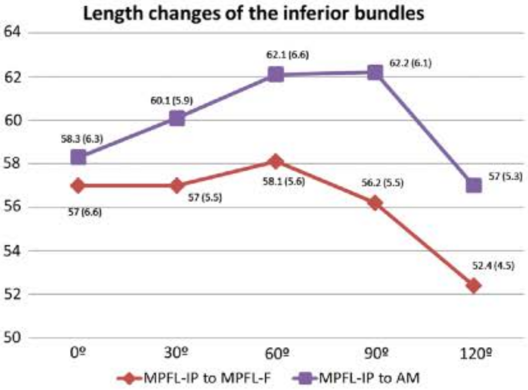

Fig. 3 Length changes of inferior bundles. Results are expressed as mean and standard deviation (in parentheses)

Discussion

The most important finding of the present study was that the non-anatomical AM attachment has biomechanical behaviour similar to the anatomical femoral insertion of the MPFL. In that sense, the hypothesis was confirmed. As secondary findings, the isometry of the MPFL has been demonstrated to range from 0° to 90°, most importantly in the fibres that originate in the inferior part of the patella.

There is substantive controversy with respect to the anatomy of the MPFL [25]. There are authors who have described it as a continuation of the vastus medialis obliquus, while others see it as an independent structure [1, 2, 11, 14, 18, 21]. It has also been described as both a single bundle ligament and as a complex ligament with different attachments at the patella and femur [8, 15]. In terms of isometry, there is also significant debate [3, 10, 12, 23]. Nonetheless, taking a difference of less than 5 mm as an isometric ligament (as proposed by Smirk [18]), the present results showed isometry between 0° and 90°. However, the superior fibres of the ligament may exhibit biphasic behaviour from 0° to 30° and then from 30° to 90°.

The aforementioned anatomical studies have been used to suggest different surgical techniques to treat MPFL tears. There are several authors who propose an anatomical reconstruction of the MPFL [17, 20], even using minimally invasive techniques [26]. They state that finding the femoral insertion of the MPFL is crucial to achieving good outcomes. Although they report positive results using anatomical techniques, there is no prospective randomized study that compares anatomical and non-anatomical surgical techniques for MPFL reconstruction. However, there are in vivo anatomical studies that report on the superior behaviour of a non-anatomical reconstruction of the MPFL [13, 25]. Similarly, good results have been described with non-anatomical (or quasi-anatomical) techniques [9, 16]. Monllau et al. [9] recently reported an improvement in functional scores using their technique, with no recurrence at a minimum 27 month follow-up. In that study, a quasi-anatomical reconstruction of the MPFL was performed with the AM tendon as a pulley. Although the anatomy of the AM insertion into the distal femur and its relationship with the MPFL femoral insertion have been defined by LaPrade et al. [7, 24], their biomechanics and the functional length during flexion haven not been well defined. The results found in the present study show similar behaviour in the distances between the patellar insertion of the MPFL and both its insertion in the femur and the AM femoral insertion. Moreover, a mean distance from the AM insertion up to the Hunter canal was found to be some 78 mm, enough to avoid damage to the neurovascular structures.

Several limitations can be attributed to the present study. First, and most important, the cadavers used were all elderly. Neither an arthrotomy nor radiographs were performed to assess the presence of patellofemoral arthrosis. Additionally, there was a lack of information about any previous patellofemoral instability. Second, soft tissues of the cadavers can be damaged, but not those in young in vivo patients. An additional limitation is the fact that linear measures were taken in the cadavers, whereas the in vivo MPFL has a somewhat curved shape. The last limitation is the small number of specimens used in the present study.

Conclusion

In conclusion, similar biomechanical behaviour has been found in the anatomy of the MPFL and the quasi-anatomical reconstruction of the MPFL using the AM femoral insertion. Both of them showed isometry from 0° to 90°, most importantly the fibres that originate in the inferior part of the patella.

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KNEE

Clinical and radiological outcomes after a quasi-anatomical reconstruction of medial patellofemoral ligament with gracilis tendon autograft

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Abstract

Purpose To analyse the clinical and radiological outcomes of a quasi-anatomical reconstruction of the medial patellofemoral ligament (MPFL) with a gracilis tendon autograft.

Methods Patients with objective recurrent patellar instability that were operated on from 2006 to 2012 were included. A quasi-anatomical surgical technique was performed using a gracilis tendon autograft. It was anatomically attached at the patella, and the adductor magnus tendon was also used as a pulley for femoral fixation (non-anatomical reconstruction). The IKDC, Kujala and Lysholm scores as well as Tegner and VAS for pain were collected preoperatively and at final follow-up. Radiographic measurements of patellar position tilt and signs of osteoarthritis (OA) as well as trochlear dysplasia were also recorded.

Results Thirty-six patients were included. The mean age at surgery was 25.6 years. After a minimum 27 months of follow-up, all functional scores significantly improved ($p < 0.001$) with respect to the preoperative values. The VAS dropped from 6 (SD 2.48) to 2 (SD 1.58). No recurrence of dislocation was observed in this series. The apprehension sign was still apparent in one patient. The CT scan evaluation showed a significant decrease in patellar tilt ($p < 0.001$). On the Crosby and Insall grading scale, there were no changes in the radiological signs of OA.

Conclusion This specific MPFL reconstruction gives good clinical results and corrects patellar tilt. It did not affect the patellofemoral surfaces at the short term, as shown by the absence of radiological signs of OA in the CT scan. The procedure has been shown to be safe and suitable for the treatment of chronic patellar instability, including in adolescents with open physis. A new effective, inexpensive and easy-to-perform technique is described to reconstruct MPFL in the daily clinical practice.

Level of evidence Therapeutic case series, Level IV.

Keywords Patella · Medial patellofemoral ligament reconstruction · Patella dislocation · Patellofemoral joint

Introduction

More than one hundred techniques for patella stabilization, including transference of the tibial tuberosity (TT), patellar lateral release, *vastus medialis obliquus* advancement, trochleoplasty and derotational osteotomies have been described [1, 15]. Although an "à la carte" plan based on reconstructing anatomical disorders has been advocated, a standard surgical technique to treat recurrent patella dislocations remains undetermined [12].

The medial patellofemoral ligament (MPFL) is the primary passive restraint in pathologic lateral translation of the patella [2, 7, 13]. Consequently, it tears when the patella dislocates laterally [10, 19, 30]. The efficacy of MPFL reconstruction in the control of lateral patellar instability has already been demonstrated, and therefore, its reconstruction is currently one of the most widely used surgical

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techniques for the treatment of chronic patellar instability [18, 29].

Several methods of MPFL reconstruction have been described. They vary in terms of graft choice, patellar and femoral fixation and graft tension at the time of fixation. In general, it is thought that a non-anatomical graft tends to over-constrain the patellofemoral (PF) joint [9, 16, 31]. Theoretically, this pressure results in the loss of knee motion and increases PF osteoarthritis (OA) [9]. Conversely, in a biomechanical laboratory study using cadaver knees, a non-anatomical femoral attachment point in the adductor tubercle did not alter the pressures on the PF joint in comparison with an anatomical attachment [16]. Then again, controversy persists relative to defining the optimal attachment points for the MPFL graft.

The main objective of this study was to analyse the clinical and radiological outcomes in a series of patients with chronic patellar instability after a quasi-anatomical MPFL reconstruction using a gracilis tendon autograft. The hypothesis was that this type of reconstruction for recurrent patellar dislocation would provide good outcomes and would not cause degeneration of the patellofemoral joint.

In the present study, a new easy-to-perform technique to reconstruct MPFL is described.

Materials and methods

A longitudinal descriptive study was performed. Patients with objective recurrent patellar instability that were operated on from 2006 to 2012 were included. A double-bundle MPFL reconstruction with *gracilis tendon* (GT) autograft was performed in all cases, and therefore, no control group was available.

The preoperative and final follow-up clinical evaluation and data on knee scales were recorded. It included the International Knee Documentation Committee (IKDC) form, Kujala score, Tegner activity level scale, Lysholm functional score and the Visual Analogue Scale (VAS) for pain.

Radiological assessment included radiographs as well as CT scan imaging before and after surgery. Patellar height (in accordance with the Caton-Deschamps index [6]) was studied by means of plain radiographs in a lateral view at 30° of flexion. Patellar tilt and TT–TG distance were analysed in a CT scan. Data on preoperative trochlear dysplasia (based on the Dejour classification [6]) were also recorded. Finally, radiological signs of OA were graded in accordance with the Crosby and Insall grading system (three grades: none to mild, moderate and severe) [4].

Functional as well as radiographic evaluations were carried out by two independent observers.

Data on complications and/or surgical reoperations were also documented.

Surgical technique

The homolateral GT autograft was always the graft of choice. The tendon was sized and stored in gauze soaked in vancomycin [22]. A 2-cm vertical skin incision was then made over the superior medial border of the patella to expose its proximal third. Two convergent drill holes (usually 4.5 mm in size) of approximately 10 mm depth are created leaving a bone bridge of 10 mm, obtaining a V-shaped tunnel (Fig. 1). Another 2- to 3-cm skin incision was made along the *adductor magnus* (AM) tendon slightly proximal to the medial femoral epicondyle. The tendon of the AM was identified and dissected so as to be used as a pulley for the graft (Fig. 1). The graft was then passed through the patella, then under the fascia and finally looped around the AM tendon back to the patella. The knee was cycled several times through full range of motion while keeping the graft under slight tension. Finally, both graft ends were sutured together at 30° of flexion with No. 0 high-resistance non-absorbable sutures. Tension was calculated on the basis that the patella could still be manually lateralized some 10 mm to avoid over-constraint. The lower limb was finally immobilized in a brace locked at full extension.

No lateral retinacular release was performed in the present series. Distal realignment was associated in cases of a preoperative TT–TG distance exceeding 20 mm. Patella lowering was concomitantly performed in those cases in which patella supera was observed, as defined by a Caton-Deschamps index of more than 1.2.

IRB approval

The study was approved by the local ethics committee (ICATME—Institut Universitari Dexeus, 2/2014).

Statistical analysis

Categorical variables are presented as frequencies and percentages. Mean and range (or the 25–75 percentiles) were calculated for each continuous variable.

The Wilcoxon test was used to compare the pre- and postoperative results of different knee tests. In other cases, the Chi-square test was used to compare the results of different groups of patients. No sample size calculation was performed because of the descriptive purpose of the present study without any control group. Statistical analysis was performed using the SPSS 19 (SPSS Inc., Chicago, Illinois, USA) statistical package. The significance level was set at $p < 0.05$.

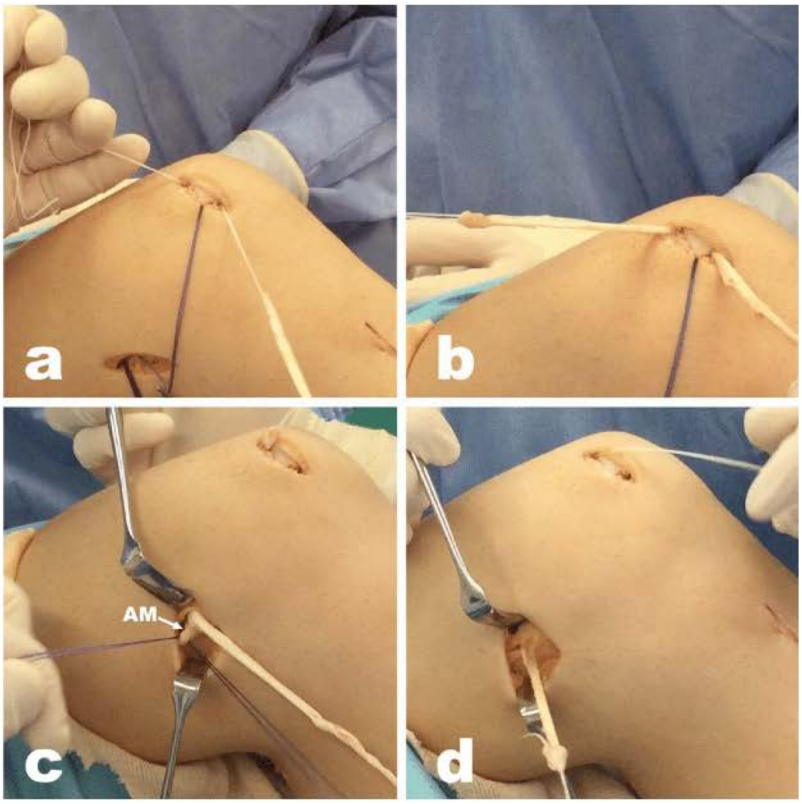

Fig. 1 Different steps of the surgical technique. **a** A *V*-shaped tunnel is drilled in the medial aspect of the patella; **b** the gracilis tendon is introduced in the patellar tunnel; **c** the adductor magnus (AM) tendon is identified; **d** the gracilis tendon is then looped around the AM tendon

Table 1 Differences between knee functional scores before and after surgery

Knee scale	Pre-op Med [P_{25}–P_{75}]	Post-op Med [P_{25}–P_{75}]	Change Med [P_{25}–P_{75}]	*p* value (*)
Lysholm	53 [41–65]	95 [85–99]	39 [20–50]	<0.001
Kujala	63 [49–70]	90 [79–98]	25 [22–37]	<0.001
IKDC	51 [39–72]	85 [78–96]	32 [20–41]	<0.001
Tegner	4 [3–4]	5 [3–7]	1 [0–3]	<0.001
VAS	6 [5–7]	2 [0–3]	5 [4–6] (neg.)	<0.001

(*) Assessed with the nonparametric Wilcoxon signed-rank test

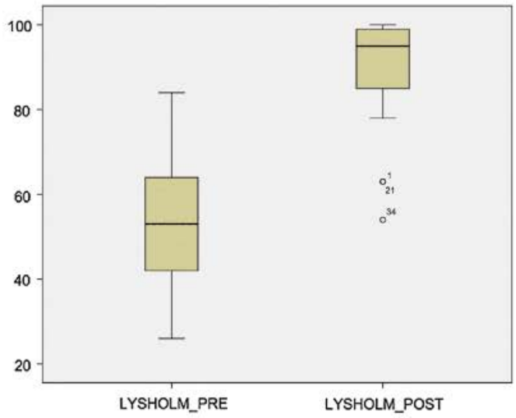

Fig. 2 Pre- and postoperative Lysholm scores ($p < 0.001$)

Results

Thirty-six knees (thirty-five patients) were included. No patient was lost during follow-up. The number of previous dislocations ranged from 3 to 15. The mean follow-up time

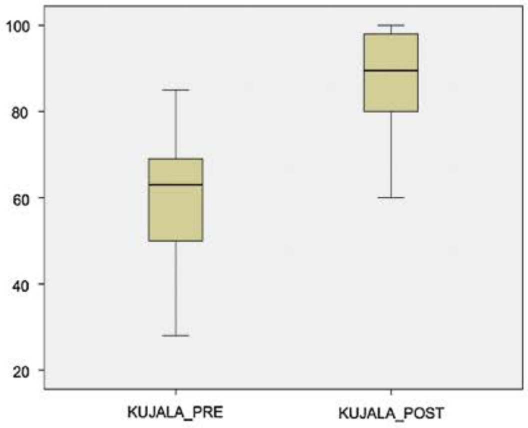

Fig. 3 Pre- and postoperative Kujala scores ($p < 0.001$)

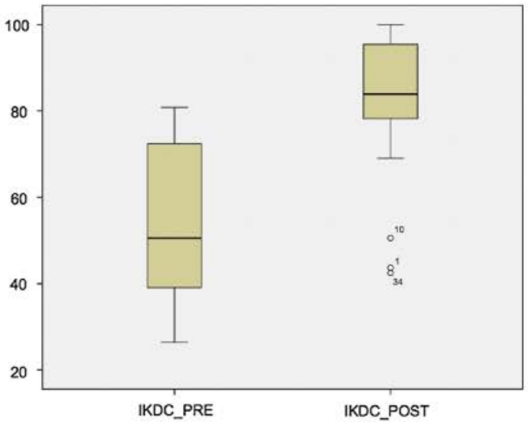

Fig. 4 Pre- and postoperative IKDC scores ($p < 0.001$)

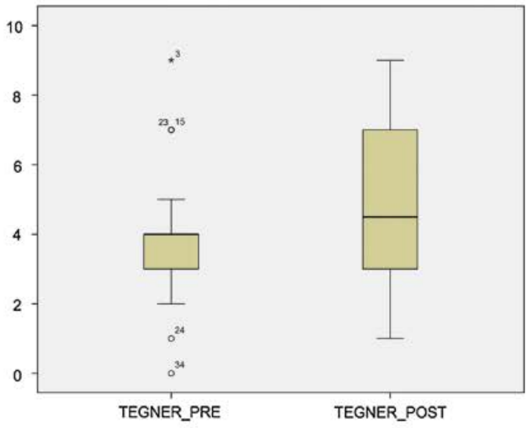

Fig. 5 Pre- and postoperative Tegner scores ($p < 0.001$)

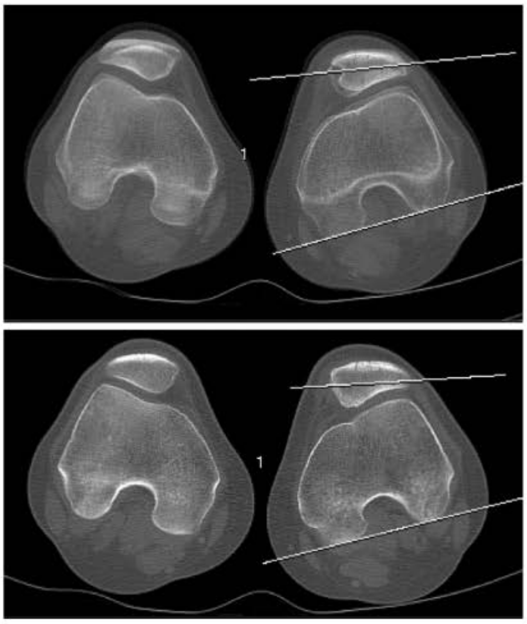

Fig. 6 Preoperative CT scan and final follow-up

was 37.6 months (SD 18.1 months). There were 19 female (52.8 %) and 17 male (47.2 %) patients with a mean age of 25.6 years (SD 9.4 years). The right side was involved in 23 (63.9 %) patients and the left in 13 (39.1 %) patients. The MPFL was solely reconstructed in 16 knees (44.4 %), while an associated distal realignment procedure was performed in 20 cases (55.6 %).

No patient experienced recurrent patellar dislocation in this series although one patient complained while having an apprehension test. All the functional scores showed a significant improvement (Table 1). The mean Lysholm, Kujala and IKDC scores improved significantly ($p < 0.001$) in all cases (Figs. 2, 3, 4). A significant improvement ($p < 0.001$) was also seen in the Tegner scale (Fig. 5). The preoperative VAS was a mean of 6 points (SD 2.5) and dropped to a mean of 2 points (SD 1.6) at final follow-up ($p < 0.001$).

No significant changes were found in patellar height. The mean preoperative Caton-Deschamps index was 1.2 (SD 0.2), while it was 1.1 (SD 0.1) at the last follow-up (n.s.). The average preoperative patellar tilt of 20.4° (SD 9.7°) improved to 14.9° (SD 8.0°) (Fig. 6) at the last follow-up ($p < 0.001$). The preoperative TT–TG distance of

Table 2 Differences between clinical outcomes in patients with isolated MPFL reconstruction versus MPFL reconstruction associated with other surgical procedures

Variable	Surgery	Pre-op Med [P_{25}–P_{75}]	Post-op Med [P_{25}–P_{75}]	Change Med [P_{25}–P_{75}]	*p* value (*)
Lysholm	LPFM (Alo)	56 [43–71]	95 [94–100]	40 [25–52]	n.s.
	LPFM + Otr.	52 [35–62]	93 [85–95]	39 [19–50]	
Kujala	LPFM (Alo)	64 [54–78]	90 [88–100]	26 [21–40]	n.s.
	LPFM + Otr.	62 [45–65]	89 [75–97]	25 [22–35]	
IKDC	LPFM (Alo)	52 [49–73]	91 [81–97]	31 [23–46]	n.s.
	LPFM + Otr.	51 [39–72]	80 [72–89]	32 [17–40]	
Tegner	LPFM (Alo)	4 [3–4]	6 [4–7]	1 [0–3]	n.s.
	LPFM + Otr.	4 [2–4]	4 [3–7]	1 [0–2]	
VAS	LPFM (Alo)	7 [4–7]	1 [0–2]	5 [4–6] (neg.)	n.s.
	LPFM + Otr.	6 [5–8]	2 [1–3]	5 [2–6] (neg.)	

(*) Assessed based on the change between groups with the nonparametric Mann–Whitney *U* test

16.6 mm (SD 5.1 mm) remained unchanged with a mean 15.2 mm (SD 5.2 mm) at the final follow-up evaluation (n.s.).

Using the Crosby and Insall [4] criteria, all the patients were graded as none to mild OA at the preoperative assessment. No radiological progression of PF OA was seen in any case at the final follow-up evaluation.

When comparing the clinical and radiological results in the isolated MPFL reconstructions or when this procedure was combined with bony distal realignment techniques, no differences were seen in any of the evaluated parameters (Table 2).

Few complications were observed in the present series. Two cases (5.8 %) showed reduced ROM (flexion deficit of 25°) during the rehabilitation period. Both of them were successfully treated. While full ROM was restored in one of the patients after mobilization under anaesthesia, the other patient required arthroscopic arthrolysis. Another patient with an associated distal realignment required hardware removal from the osteotomy site. These three patients (5.8 %) were the only cases that needed to return to the operating room for additional procedures. Six additional knees (16.7 %) developed a painless hypertrophic wound scar that was considered a minor complication. No patellar fractures were seen in this series.

Discussion

The most important finding of the present investigation is that postoperative patellar instability was not observed in any case. Additionally, all the functional scores improved. Regardless of the non-anatomical type of reconstruction, no signs of OA were observed, which suggests that no harm to the patellofemoral joint was caused, at least during this short-term follow-up period. Therefore, the hypothesis has been confirmed.

Despite the good results generally obtained with MPFL reconstruction, several surgical aspects are still controversial. Some authors have recommended the use of the semitendinous tendon as a graft to reconstruct the MPFL [5, 8, 24]. However, the GT was used in this study. The native MPFL was found to have a mean tensile strength of 208 N [17]. The mean maximum load for one strand of a GT was found to be 837 ± 138 N and two strands of the same tendon had approximately twice the strength and stiffness as one strand [11]. Therefore, the GT appears to be long and strong enough to duplicate MPFL function.

The location of the femoral attachment of the MPFL has been widely debated. According to some authors, the native femoral attachment is centred approximately 10 mm distal to the adductor tubercle [19, 20, 24]. The MPFL is a non-isometric ligament intended to restrain lateral patellar mobility. In cases of patella supera, further anisometry of the MPFL can arise, as has been recently shown [31]. Shifting the femoral attachment site more proximally will increase the distance between the attachment points of the ligament during flexion and increases its tension and, theoretically, will increase the force and pressure applied to the medial aspect of the patellofemoral joint [9]. In the current work, the AM tendon, which is proximal to the MPFL's original attachment, was used instead as a femoral attachment. Interestingly enough, no clinical signs of PF overload or radiological OA were observed during the follow-up period. Melegari et al. [16] conducted a biomechanical study using cadaveric knees with a non-anatomical femoral attachment point in the *adductor tubercle*. They also found no alterations in PF joint pressures when comparing this type of non-anatomical MPFL reconstruction to an anatomical MPFL reconstruction [16]. These non-anatomical reconstructions may exhibit quasi-isometric behaviour that prevents over-constraint of the patellofemoral joint as suggested by Panagopoulos et al. [21]. A possible explanation might be the very limited changes in length during knee flexion from 0° to 90° seen in the MPFL, which was calculated to be of only 1.1 mm [28]. In addition, it might also be possible that the elastic nature of the adductor pulley may be able to adapt itself to a small potential length mismatch, which occurs throughout the knee's ROM [23].

Excellent results have often been reported at short- and mid-term follow-up, regardless of the type of MPFL reconstruction, even in the presence of degenerative conditions [3, 5, 8, 24, 25, 28, 29]. In the present series, the outcomes were also good in terms of the functional scores analysed, which favourably compares with the more anatomical types of reconstruction [14, 25, 27, 28]. In a recent review, Shah et al. [26] found an overall rate of complications after MPFL reconstruction of 26.1 %. More specifically, the percentage of patients with a recurrence of patellar instability was found to be 3.7 % of the 629 patients included in the review. Conversely, the complications reported with the current technique were lower than the aforementioned rates. The isolated case of apprehension and no cases of recurrence of dislocation and the considerably lower rate of reinterventions seen in the present study positively compare to the current results with those previously published works [3, 5, 26, 29].

Patellar tilt reflects the soft tissue imbalance associated with lateral patellar dislocation [9]. As a significant decrease in the patellar tilt was achieved with the proposed non-anatomical type of reconstruction, it is likely that the tension developed in the reconstructed MPFL positively influences the tilt moment as well as patellar tracking.

The surgical technique presented here showed some advantages. It is simple, safe, inexpensive and reproducible. It turns into a simple soft tissue procedure in which the femoral physeal plate is not affected as no tunnel needs to be drilled and no hardware to fix the graft to the bone needs to be used. Additionally, there is no need to use intraoperative fluoroscopy. This technique entered into use in 2005 in a short series of adolescents with symptomatic recurrent patellar instability. Following the good results obtained in this series of skeletally immature patients, it came to be indicated in adult patients.

The present investigation has several limitations. Although the design was prospective, this is a single surgeon work with the absence of a control group. The cohort may be considered small, and the follow-up is rather short, particularly in terms of PF OA. In addition, some patients included had not only a MPFL reconstruction but also a distal realignment procedure. However, this also made it possible observe the outcomes of surgical techniques performed concomitantly, which is something commonly seen in patellofemoral instability surgeries. Although no OA changes were observed in any case, a longer follow-up period is needed to better assess this specific outcome.

Patellar tilt improvement and the absence of clinical symptoms of medial patellar overload and signs of OA seem to prove that this procedure does not have any deleterious effect on the PF joint. Hence, it seems that the anatomical placement of the MPFL graft is not essential to the preservation of knee function after MPFL reconstruction.

The present technique might be of clinical relevance. This technique is easy to perform, safe and inexpensive. It is particularly useful in children and adolescents, as drilling holes near the femoral growth line are no longer needed.

Conclusion

This specific MPFL reconstruction gave good clinical results and corrected patellar tilt. It did not affect the patellofemoral surfaces at short term as shown by the absence of radiological signs of OA in the CT scan. The procedure has proven to be safe and adequate for the treatment of recurrent patellar instability, including in adolescents with an open physis.

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Trabajo 3

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RESEARCH **Open Access**

Parametric finite element model of medial patellofemoral ligament reconstruction model development and clinical validation

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Abstract

Background: Currently, there is uncertainty regarding the long-term outcome of medial patellofemoral ligament reconstructions (MPFLr). Our objectives were: (1) to develop a parametric model of the patellofemoral joint (PFJ) enabling us to simulate different surgical techniques for MPFLr; (2) to determine the negative effects on the PFJ associated with each technique, which could be related to long-term deterioration of the PFJ.

Methods: A finite element model of the PFJ was created based on CT data from 24 knees with chronic lateral patellar instability. Patella contact pressure and maximum MPFL-graft stress at five angles of knee flexion (0, 30, 60, 90 and 120°) were analysed in three types of MPFLr: anatomic, non-anatomic with physiometric behaviour, and non-anatomic with non-physiometric behaviour.

Results: An increase in patella contact pressure was observed at 0 and 30° of knee flexion after both anatomic and non-anatomic MPFLr with physiometric behaviour. In both reconstructions, the ligament was tense between 0 and 30° of knee flexion, but at 60, 90 and 120°, it had no tension. In the third reconstruction, the behaviour was completely the opposite.

Conclusion: A parametric model of the PFJ enables us to evaluate different types of MPFLr throughout the full range of motion of the knee, regarding the effect on the patellofemoral contact pressure, as well as the kinematic behaviour of the MPFL-graft and the maximum MPFL-graft stress.

Keywords: Patellofemoral joint, Medial patellofemoral ligament, MPFL reconstruction, Finite element methodology, Patellofemoral contact pressure, MPFL-stress

Background

Currently, medial patellofemoral ligament reconstruction (MPFLr) is the "gold standard" in chronic lateral patellar instability surgery. It is typically performed whenever there have been at least two previous episodes of lateral patellar dislocation (Sanchis-Alfonso 2014, 2016). Different surgical techniques with different attachment points, different types of grafts and different configurations for the reconstruction have been described for MPFLr. Each one has good short-term clinical results (Fink et al. 2014; Fulkerson and Edgar 2013; Sanchis-Alfonso 2014; Teitge and Torga-Spak 2004; Weinberger et al. 2017). However, there is uncertainty regarding the long-term outcome of these MPFL reconstructions techniques. To classify a surgical technique for MPFLr as being effective, it is not enough for the instability and pain to disappear. For a surgical technique to be considered effective, new problems like 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 MPFLr (Elias and Cosgarea 2006; Rood et al. 2015; Stephen et al. 2014, 2016), which is clinically relevant because surgery for lateral patellar instability is generally performed in young individuals. Moreover, the development of symptomatic PFOA in young persons does not currently have a good

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solution. In an ideal MPFLr, the graft should be tense at 0–30° of knee flexion. Beyond 30°, the graft should be loose (Sanchis-Alfonso et al. 2017). All the other parameters should be considered inadequate (Sanchis-Alfonso et al. 2017). Given that in the daily clinical practice many MPFL reconstructions with a clearly incorrect femoral fixation point can be seen, we must evaluate not only the correct reconstructions but also the clearly incorrect ones. An effective way to evaluate patellofemoral contact pressure throughout the range of motion of the knee after MPFLr is by using the Finite element methodology (FEM) (DeVries et al. 2015; Elias et al. 2005; Elias and Cosgarea 2006; Shah et al. 2015). 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.

The objective was to create a parametric model of the patellofemoral joint (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, the aim was that the parametric model would enable a surgeon to simulate different types of surgical techniques for MPFLr. It is hypothesized that this model would allow to evaluate patellofemoral contact pressure and the maximum MPFL-graft stress in each specific reconstruction at different knee flexion-extension angles. The objective was to determine the negative theoretical effects (patellofemoral contact pressure and the maximum MPFL-graft stress) on the PFJ in each type of MPFLr. This negative effect could be related to long-term deterioration of the PFJ.

Methods

Parametric finite element model of the patellofemoral joint

From a previous study (Sanchis-Alfonso et al. 2017), high spatial resolution Computerized Tomography (CT) data were available from 24 knees of patients with chronic lateral patellar instability. 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 ($0.255 \times 0.255 \times 0.672$ 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 (femur and patella bone dimensions) from the 24 knees (Sanchis-Alfonso et al. 2017). Knee geometry was simplified to construct a 3D parametric model that achieved nearly anatomical geometry with variable parameters (i.e., trochlear dysplasia, patellar width, patellar diameters, geometry of the patella). The parameters were measured from CT scans both on the axial plane and by using a multi-planar reformatting (MPR) technique. 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 (Fig. 1a-d). As previously stated, each part was simplified to obtain nearly anatomical geometry with variable parameters (Elias et al. 2016). The patellar bone was modelled starting from a concave-revolution-solid shape, with the parametric radius, height and radius curvature (Fig. 1e). Several revolution cuts were performed on the solid part, and its final geometry was obtained (Fig. 1b). The patellar cartilage was created following the same procedure while maintaining the patellar dimensions (Fig. 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 (lateral and medial); a solid loft for the irregular section, with different width and length parametric sections (width, width 2, width 3, length, length 2, length 3); a revolution shape in the posterior geometry, where the radius can be modified; and two revolution shapes (Fig. 1f) that represent the femoral epicondyles (Fig. 1c). Width and length parameters corresponded to the maximum distance between both femoral epicondyles. Width 2 and length 2 were taken at the point where the medial epicondyle joins the main femoral bone. Width 3 and length 3 were measured at the same point as the highest position of the patella (0° knee flexion angle). The posterior radius defined the contact region between the patellar and femoral cartilages. The femoral cartilage was defined as deformable, and its generation was based on femur geometry and consisted of a revolution shape for the bottom geometry and a combination of elements that defined the upper region (Fig. 1d). The PFJ parametric model was developed using the Abaqus/CAE v.6.14 software (Dassault Systèmes, France). Measuring previous geometrical characteristics on the 24 knees, a mean parametric model was generated (Table 1).

As cartilages cannot be reconstructed correctly from a CT, a fixed thickness of 3 mm was assumed (Cohen et al. 2003). Tendons and ligaments were also included since they help to stabilize the patella and better distribute patellofemoral pressures (Fig. 2a). 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 (Fig. 2a) whilst the MPFL and the lateral retinaculum (LR) were defined as beam elements (B33) (Fig. 2a). The QT was oriented from the insertion site on the patella to the muscle origin or the most distal

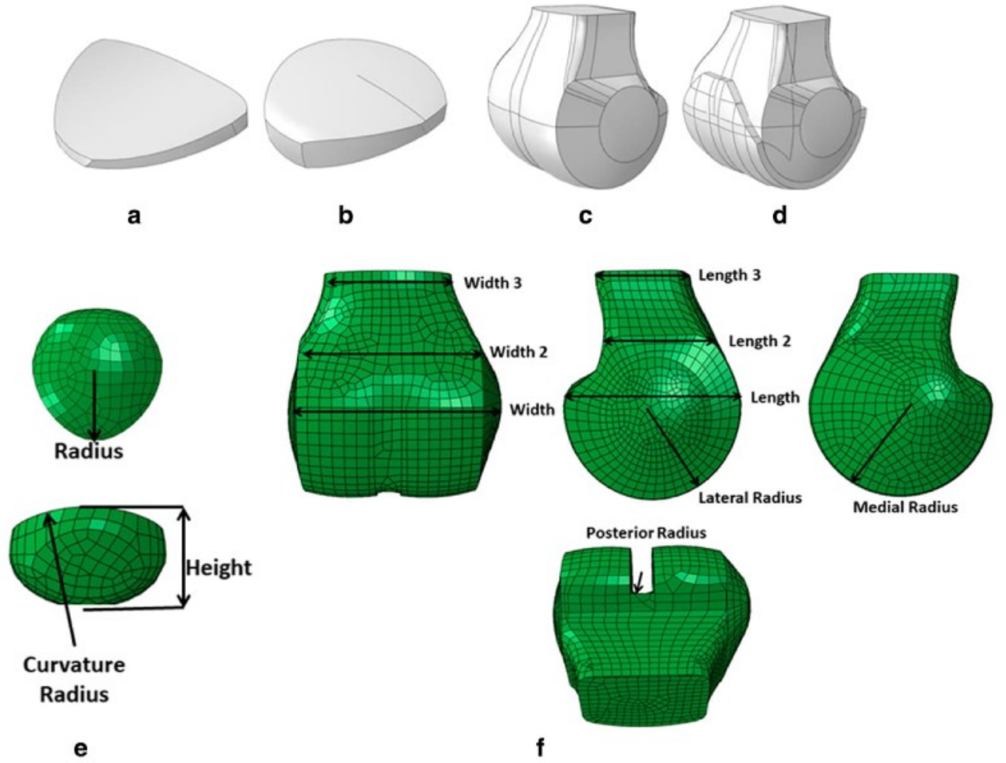

Fig. 1 Parametric geometry of the four main parts of the PFJ model: **a** Patellar cartilage; **b** patellar bone; **c** femoral bone; **d** femoral cartilage; **e** geometric parameters of the patellar bone; **f** geometric parameters of the femoral bone

wrapping point on the femur. The PT was oriented from the distal patella to the tibia (Elias et al. 2005; Elias and Cosgarea 2006; Elias et al. 2006). The tendon and ligament properties were taken from previous studies (Ciccone II et al. 2006; Drez Jr et al. 2001; Elias and Cosgarea 2006) and are summarized in Table 2. 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 5756 nodes and 4125 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 (Blankevoort and Huiskes 1991; Fernandez et al. 2012; Shah et al. 2015).

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

Table 1 Mean values (mm) and standard deviation (±) (mm) of the geometrical parameters defining the parametric PFJ measured on the 24 knees (Sanchis-Alfonso et al. 2017)

Femoral geometrical characteristics								
Width	Width 2	Width 3	Length	Length 2	Length 3	Medial radius	Lateral radius	Posterior radius
72.28 ± 8.92	54.00 ± 5.83	39.01 ± 3.85	47.71 ± 5.21	33.99 ± 3.40	28.44 ± 3.00	28.91 ± 4.75	26.09 ± 4.21	13.84 ± 2.71
Patella geometrical characteristics								
Radius			Curvature radius			Height		
20.26 ± 6.24			45.49 ± 3.31			19.09 ± 2.46		

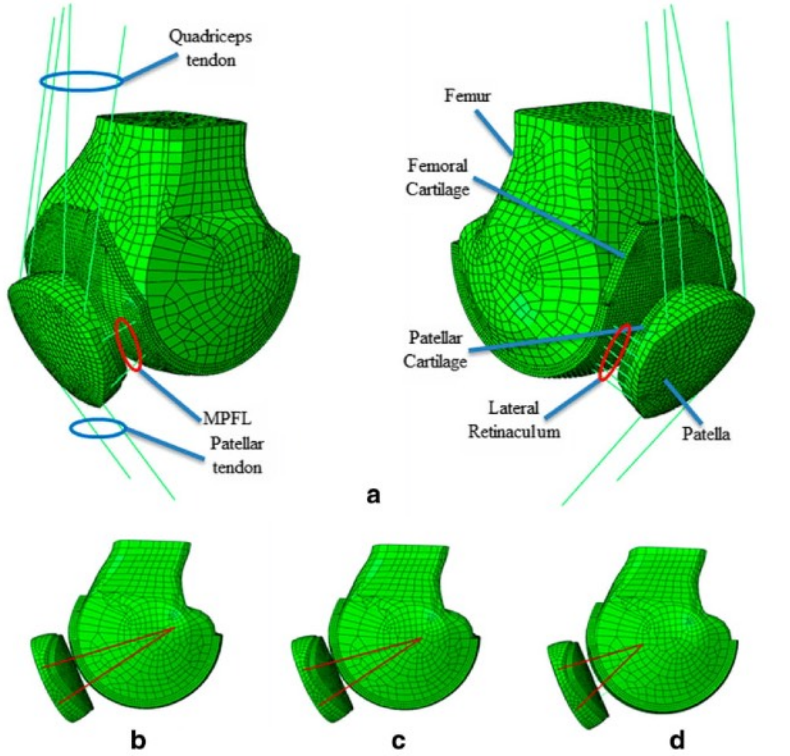

Fig. 2 **a** Final model reconstruction including the joint ligaments and tendons. **b** Reconstruction with a patellar bone fixation point and an anatomic femoral fixation point. **c** Reconstruction with a patellar bone fixation point and a non-anatomic femoral fixation point that has physiometric behaviour. **d** Reconstruction with a patellar bone fixation point and a femoral fixation point that is too far anterior and without physiometric behaviour

Table 2 Material properties considered for ligaments and tendons in the FEM simulation

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

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 (Besier et al. 2008). A sensitivity analysis was performed changing the friction coefficient (see Additional file 1).

MPFL reconstruction techniques

Three types of MPFL double-bundle semitendinosus reconstructions with patellar and femoral bony attachment were simulated based on a previous study (Sanchis-Alfonso et al. 2017): anatomic reconstruction, meaning a reconstruction with a femoral anatomic fixation point (Fig. 2b); non-anatomic but physiometric reconstruction, meaning the femoral fixation point is not anatomic, but behaves kinematically like a native MPFL (Fig. 2c); and non-anatomic and non-physiometric reconstruction (Fig. 2d). 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, the opposite of a native ligament (Sanchis-Alfonso et al. 2017). The length of a normal MPFL increases during flexion from 0 to 30° and decreases from 30 to 120° (Sanchis-Alfonso et al. 2017). This pattern is considered as the in vivo MPFL standard dynamic length change. In a normal (anatomic) MPFL reconstruction, the graft is isometric in all the cases between 0 and 30° of knee flexion (Sanchis-Alfonso et al. 2017). In 83% of cases, it is isometric from 0 to 60° of knee flexion (Sanchis-Alfonso et al. 2017). Beyond 60° of knee flexion, the MPFL becomes progressively lax and isometry is lost (Sanchis-Alfonso et al. 2017). Regarding isometry, a ligament is considered isometric when there is less than 5 mm of length change throughout the range-of-motion (Smirk and Morris 2003).

Simulation of the different surgical techniques

The three surgical techniques were analysed for 5 knee flexion positions: 0, 30, 60, 90 and 120°, as in a previous dynamic CT scan study (Sanchis-Alfonso et al. 2017). 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, initial contact pressures were stored. Then, the ligaments and tendons were included and the three surgical MPFLr 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 subtracted from the ones generated with the ligaments and tendons inclusions. Therefore, the results are presented in terms of relative contact pressures, which we subsequently refer to as the contact pressure, to compare the different surgical techniques under the same conditions. 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 (Sanchis-Alfonso et al. 2017). Table 3 summarizes the mean distance between the patella and femoral insertion points for the different MPFL reconstructions. Based on that data, the insertion nodes 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 knee flexion at 40°. The average MPFL lengths were considered, in this part of the study, to compare the performance of the different surgical techniques over the mean parametric FEM of the PFJ. LR lengths were assumed to be the same as the MPFL length to preserve the equilibrium on both sides of the joint.

The average length of the MPFL for each surgical technique was analysed (Table 3), indicating that the distance between the femur and patella insertion points was smaller than the reference distance (40°) in some knee flexion positions. That means that the ligament is not experiencing any type of stress. Thus, analysis of certain positions was not necessary (Table 3, cases indicated by [a]). 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 3, cases indicated by [b]). Second, several positions showed an MPFL length that was only possible if the cartilage was compressed because the distance between the patella and femoral insertion point was further than in the reference position (40°). As only-tension elements

Table 3 Distance between the patellar and femoral insertion points for the MPFL reconstruction techniques analyzed

Flexion Angle (°)	Anatomic MPFL Reconstruction		Non-anatomic MPFL Reconstruction with Physiometric Behavior		Non-Anatomic MPFL Reconstruction but Non-Physiometric	
	Length (mm)	SD (mm)	Length (mm)	SD (mm)	Length (mm)	SD (mm)
0	60.2[b]	± 6.1	51.6[b]	± 4.6	37.5[b]	± 7.8
30	57.9[b]	± 6.8	50.8[b]	± 5.4	36.5[b]	± 9.2
40	57.7	± 6.0	48.8	± 5.0	36.2[c]	± 8.1
60	57.3[a]	± 6.4	44.9[a]	± 5.2	35.7[c]	± 10.1
90	55.6[a]	± 5.7	38.3[a]	± 4.9	35.6[c]	± 7.9
120	50.7[a]	± 4.9	33.7[a]	± 4.8	35.4[c]	± 5.6

MPFL with non-anatomical femoral attachment point with satisfactory results is always physiometric. MPFL with non-anatomical femoral attachment point with non-satisfactory results is always non-physiometric

[a] No tension

[b] Tension type 1

[c] Tension type 2

can be compressed, only working under tension, this relative position change was simulated with a temperature reduction 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 °C^{-1}). This type of simulation allows cartilages to be modelled in a compressed state. 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 3, cases indicated by [c]), 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.

Clinical validation of the parametric model

Five patient-specific cases were used for clinical validation of our parametric model. The geometry of each patient was generated by modifying the main knee parameters of the parametric model (femur and patella dimensions – see parametric finite element model of the patella femoral joint section-Fig. 1). Patient-specific geometrical data is indicated in Table 4. MPFLr 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 MPFLr. Each specific case was simulated bearing the surgeon's MPFL measurements in mind, as indicated in Table 5. Moreover, all five cases were clinically evaluated by one of the authors (V S-A).

Results

In a knee with a virtual intact MPFL, which was used as a reference for the comparison among different reconstruction techniques, the maximum patellar cartilage contact pressures at 60, 90 and 120° were very low compared to the pressures at 0 and 30°. Anatomic reconstruction increased the pressure in all of the knee angles, but the amount of pressure increase was only relevant at 0°. In non-anatomic reconstructions with a physiometric behavior, an increase in all of the positions was found, but the amount of pressure was relevant only at 0 and 30°. In non-anatomic reconstruction without physiometric behavior the pressure increased in all the knee positions and with a relevant amount of pressure. The maximum patellar cartilage contact pressures are displayed in Fig. 3.

Table 4 Patient-specific geometrical data (Fig. 1). Measurements in mm

	Case 1	Case 2	Case 3	Case 4	Case 5
Width	71.6	89.55	66	65.03	70.5
Width 2	49.71	60.13	50.2	46	53.48
Width 3	41.38	41.97	38.78	31.9	40.72
Length	52.74	48.28	51.25	39.09	47.01
Length 2	32.42	40.16	31.3	30.95	33.05
Length 3	28.75	33.47	25.35	28.66	25.4
Medial radius	27.43	36.94	29.56	27.57	22.28
Lateral radius	27.12	33.47	22.09	23.79	23.18
Posterior radius	14.07	11.2	12.43	14.73	12.09
Radius	19.01	20.32	17.12	16.54	32.23
Curvarture radius	44.94	51.24	42.41	43.51	43.17
Height	19.61	23.02	17.94	20.72	16.22

In a native knee, both the MPFL and LR are under tension at 0 and 30° of knee flexion. At 60, 90 and 120°, 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 it had no tension at 60, 90 and 120°. 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 6.

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 (Fig. 4 and Table 7)

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 1.19 MPa for 60° of knee flexion, 2.25 MPa for the 90° position and an important contact pressure of 5.84 MPa for 120° of knee flexion (Fig. 4). The maximum MPFL stress at 60° was 59.03 MPa. At 90°, it was 119.2 MPa and 252 MPa at 120°. At 0 and 30°, the MPFL was loose. The maximum lateral retinaculum (LR) stress at 60° was 1.62 MPa, 5.38 MPa at 90° and 7.06 MPa at 120°. At 0 and 30°, the LR was loose. From that data, we predicted that the patient would develop patellar chondropathy, which was in fact seen during the arthroscopy performed during the MPFL revision surgery (Fig. 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 very clearly be seen in the last preoperative 3D CT scan (Fig. 4c).

Case # 2 (Fig. 5 and Table 7)

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

Table 5 Patient-specific data for the model validation

Case	Graft Material Configuration	Measured length for each position (mm)					
		0°	30°	40°	60°	90°	120°
1 Non-Anatomic Femoral Attachment point with Non-Satisfactory Result	Semitendinosus SB	36.3[a]	35.9[a]	36.83	38.7[b]	43.7[b]	46.3[b]
2 Non-Anatomic Femoral Attachment Point with Non-Satisfactory Result	Semitendinosus DB (Proximal)	23.1[a]	33.3[a]	36.33[b]	42.4[b]	46.6[b]	48.6[b]
	Semitendinosus DB (Distal)	25.4[a]	39.7[a]	42.77[b]	48.9[b]	54.3[b]	54.8[b]
3 Non-Anatomic Femoral Attachment Point with Non-Satisfactory Result	Quadriceps Tendon SB	56.2[b]	46.8[b]	43.03	35.5[a]	24.2[a]	22.4[a]
4 Anatomic Femoral Attachment Point with Satisfactory Result	Semitendinosus DB (Proximal)	52.2[b]	51.1[b]	50.17	48.3[a]	41.3[a]	35[a]
	Semitendinosus DB (Distal)	49.9[b]	49.7[b]	48.37	45.7[a]	39.7[a]	35.1[a]
5 Anatomic Femoral Attachment Point with Sastisfactory Result	Semitendinosus DB (Proximal)	56.4[b]	57[b]	55.07	51.2[a]	46.9[a]	42.3[a]
	Semitendinosus DB (Distal)	55.1[b]	56[b]	54.17	50.5[a]	45.8[a]	41.9[a]

Cases # 1, 2 and 3 are non-anatomic and non-physiometric

SB Single bundle, *DB* Double bundle

[a] No tension

[b] Tension type 1

and incapacitating lateral patellar instability. The simulation predicted higher contact pressures than in the previous simulation: 6.17 MPa for the 60° knee flexion position, 5.18 MPa for the 90° knee flexion position and 7.13 MPa for the 120° knee flexion position (Fig. 5). The maximum MPFL stress at 60° was 19.51 MPa, 29.52 MPa at 90° and 34.7 MPa at 120°. At 0 and 30°, the MPFL was loose. The maximum LR stress at 60° was 4.56 MPa, 7.54 MPa at 90° and 8.37 MPa at 120°. At 0 and 30°, 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 (Fig. 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 scan in which the graft exhibits non-physiometric behaviour (Fig. 5c).

Case # 3 (Fig. 6 and Table 7)

A 38-year-old woman was operated on for lateral patellar instability with an MPFL single-bundle reconstruction 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 (Fig. 6a). The maximum MPFL and LR stresses predicted for the 0° knee flexion position were 12.28 MPa and 8.22 MPa, respectively. They were 3.93 MPa and 2.68 MPa for 30°, respectively. The prediction fulfils the requirements for an effective MPFLr: a tense graft at 0 and 30° of knee flexion, with greater stress than a native MPFL, and the patellofemoral pressure was below the normal values that could cause symptomatic PFOA. In fact, no chondropathy was seen in this patient during the arthroscopy performed in the revision surgery (Fig. 6d).

Case # 4 (Fig. 7 and Table 7)

An 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 0° of knee flexion and 0.91 MPa at 30° of knee flexion. The maximum MPFL and LR stresses predicted for the 30° of knee flexion position were 29.47 MPa and 0.79 MPa, respectively. For 0° of knee flexion, they were 60.02 MPa and 1.15 MPa, respectively. The prediction fulfils the requirements for an ideal MPFLr; a tense graft at 0 and 30° of knee flexion with far greater stress to failure than a native ligament. The patellofemoral pressures were kept below the values that could cause symptomatic PFOA. This tension pattern is typical of an anatomic femoral fixation point as is clearly seen in the 3D CT scan (Fig. 7c).

Case # 5 (Fig. 8 and Table 7)

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 0° of

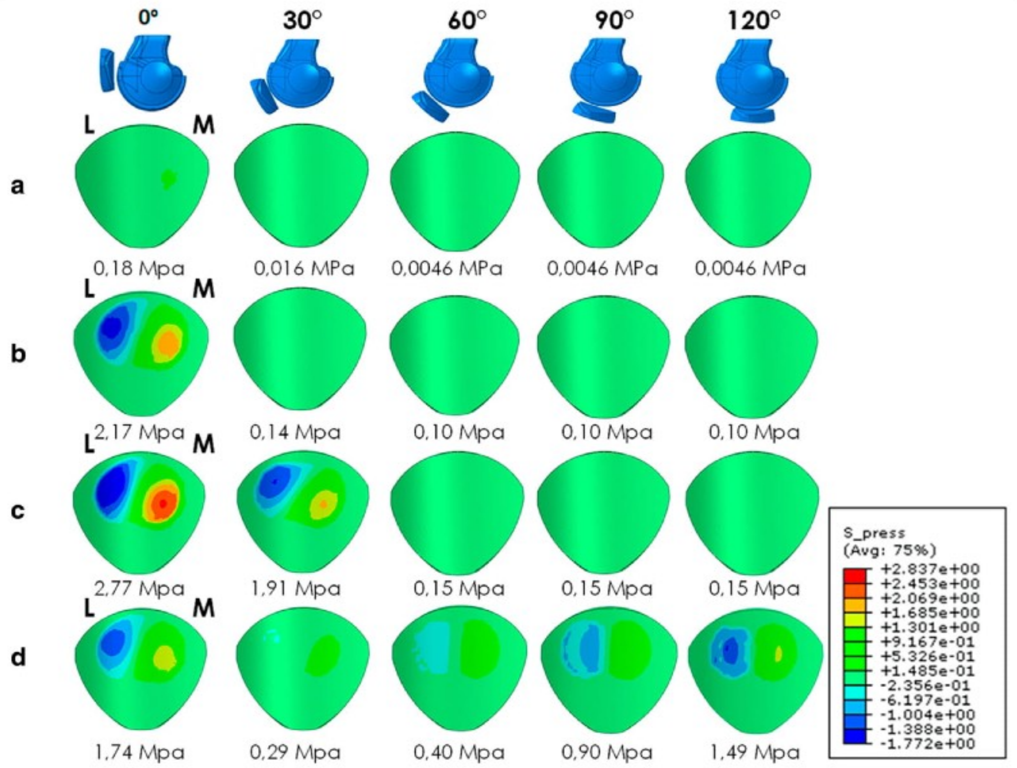

Fig. 3 Patellar cartilage contact pressure (MPa): **a** Native knee. **b** Anatomic MPFL reconstruction. **c** Non-anatomic MPFL reconstruction with physiometric behaviour. **d** Non-anatomic MPFL reconstruction with a femoral fixation that is too far anterior and without physiometric behaviour (M-medial; L-Lateral)

knee flexion position and 1.63 MPa for 30° of knee flexion position. The maximum MPFL and LR stresses predicted for the 30° knee flexion position were 70.3 MPa and 1.27 MPa, respectively. At 0° of knee flexion, they were 40.24 MPa and 0.53 MPa, respectively. The prediction fulfils the requirements for an ideal MPFLr; a tense graft at 0 and 30° of knee flexion with a far higher stress to failure than a native ligament. The patellofemoral pressure values were below those thought to cause a symptomatic PFOA. This tension pattern is typical of an anatomic femoral fixation point as is clearly seen in the 3D CT scan (Fig. 8c).

Table 6 MPFL and LR stress

	Maximum MPFL Stress (MPa)					Maximun LR Stress (MPa)				
	0°	30°	60°	90°	120°	0°	30°	60°	90°	120°
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

A) Native knee
B) Anatomic MPFL reconstruction with semitendinosus
C) Non-anatomic MPFL reconstruction with a physiometric behavior
D) Non-anatomic MPFL reconstruction with a femoral fixation that is too anterior and without a physiometric behavior

Model's accuracy

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 relative to the maximum stress and patellofemoral pressure. However, the patient had pain and instability after surgery. The instability could be explained by the single-bundle configuration of the graft, the vertical direction of the graft because of the non-anatomic femoral fixation point (Fig. 6b) and the patella alta. All of them make this graft non-functional. All these factors can contribute to instability and therefore to pain.

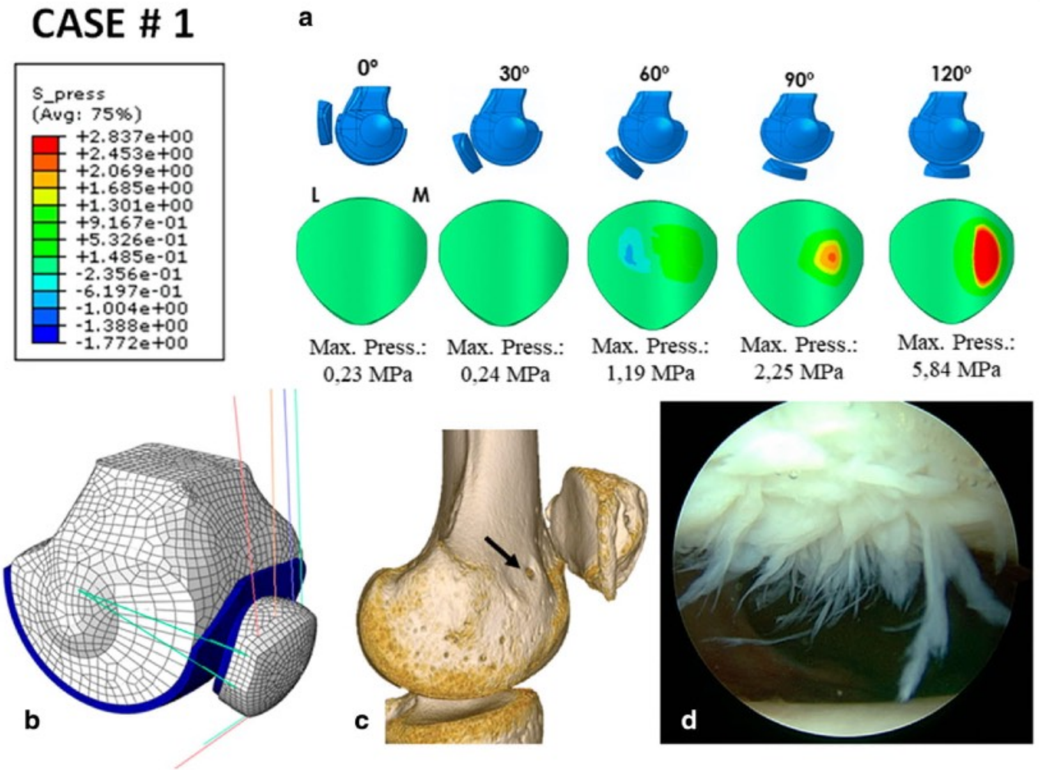

Fig. 4 Case # 1 Surgical failure: **a** Contact pressure (MPa) on the patellar cartilage L=lateral, M= Medial. **b** Parametric model of patient # 1. **c** Femoral attachment point is too far anterior (black arrow). **d** Visible patellar chondropathy during arthroscopy

Table 7 MPFL and LR ligaments stress obtained for each reconstruction and position analyzed

Case	Flexion Angle (°)	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

Discussion

This model is the first parametric 3D FEM of the PFJ that 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-motion of the knee.

Generation of a patient-specific FEM (i.e., a real FEM) of the PFJ requires CT images to be processed, segmented and then converted into a 3D finite element model. This process is complex, expensive and very time-consuming. However, the parametric model is the opposite. Segmentation is a process that requires manual correction to eliminate undesired tissues, and the computational burden makes the real model unsuitable for clinical integration as a tool for MPFLr planning. A parametric model is a generic model, that is a simplified model valid for any knee that could have direct clinical application.

The difference between the current work and previous ones is that in this paper the contact pressures for all the angles of knee flexion (from 0 to 120°) in both

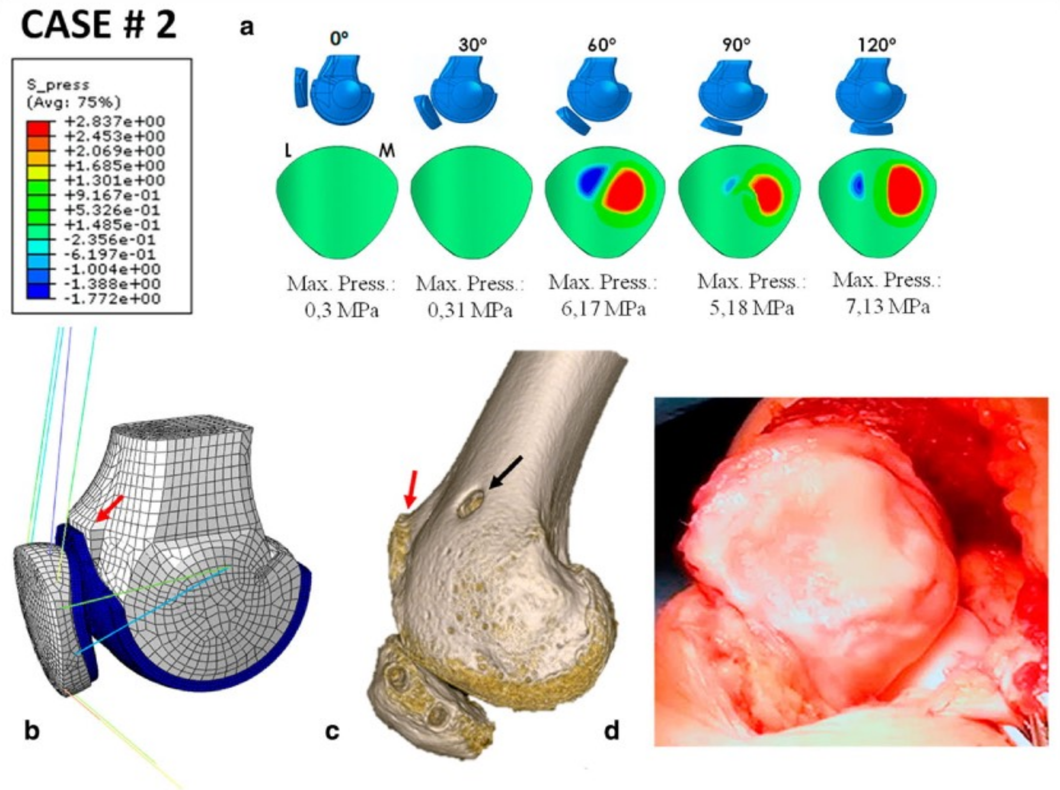

Fig. 5 Case # 2 Surgical failure: **a** Contact pressure (MPa) on the patellar cartilage L = Lateral M = Medial. **b** Parametric model of patient # 2. Trochlear dysplasia type D (red arrow). **c** Superior femoral attachment point is too far anterior (black arrow) Trochlear dysplasia (red arrow). **d** Visible patellofemoral osteoarthritis

anatomical and non-anatomical (physiometric and non-physiometric) MPFL reconstructions are analysed. Since this is a novel method, we focused on clinical validation. In this way, five clinical cases are presented to demonstrate the accuracy of the 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 these results is the introduction of FEM in daily clinical practice to optimize surgical procedures by using personalized treatments.

Findings using the FEM are in agreement with those reported in previous computational studies (Elias et al. 2005; Elias and Cosgarea 2006; Shah et al. 2015) and could have meaningful potential implications for clinicians performing MPFLr surgery (Conlan et al. 1993; Desio et al. 1998; Elias and Cosgarea 2006; Hautamaa et al. 1998; Sanchis-Alfonso et al. 2017; Servien et al. 2011). Elias et al. evaluated medial patellofemoral cartilage overload in cases with technical errors during MPFLr estimating contact pressures between 3 and 6 MPa (Elias and Cosgarea 2006; Elias et al. 2016). Shah et al. also obtained very similar values to previous computational studies. 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 (Good 1995; Moritomo et al. 2009; Sanchis-Alfonso et al. 2017; Seo et al. 2014; Tan et al. 2011). Based on this observation, in a previous study using a dynamic CT scan, it has been concluded that the native MPFL was tense during the first 30° of knee flexion in all cases and progressively loosened after 30° (Sanchis-Alfonso et al. 2017). The explanation behind this conclusion lies in the fact that the attachment points of the MPFL are separated further during the first 30° of knee flexion and become progressively closer from 30° onwards. It is called the physiometric behaviour of the ligament. The 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

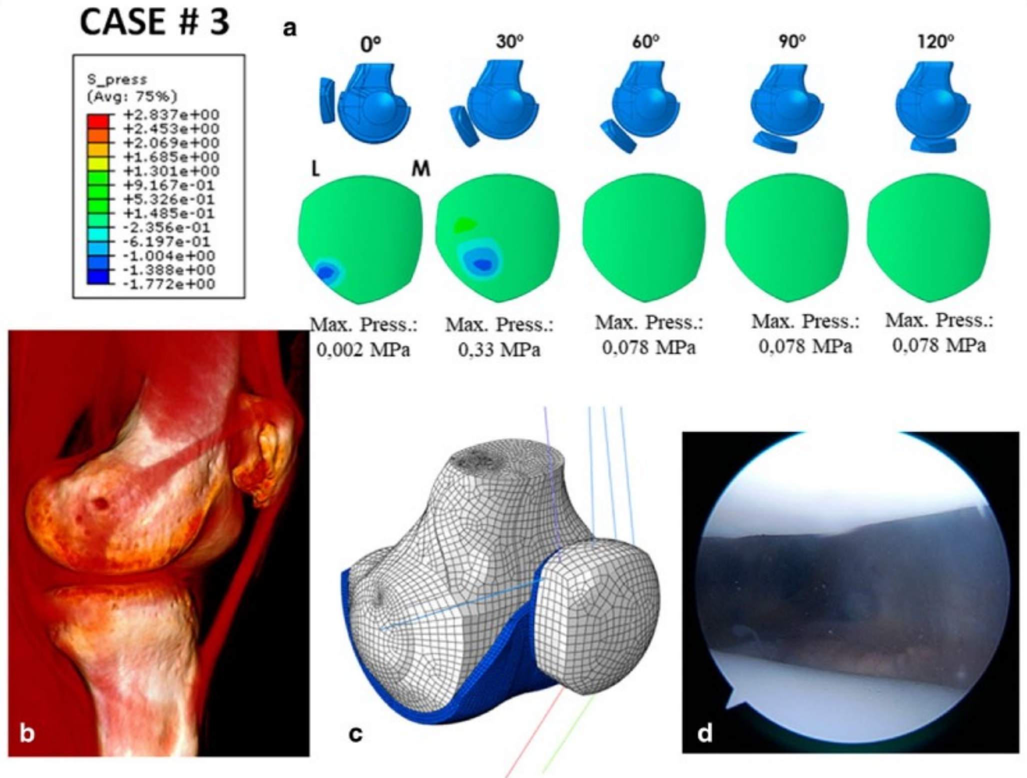

Fig. 6 Case # 3 Surgical failure: **a** Contact pressure (MPa) on the patellar cartilage L = Lateral M = Medial. **b** One can see that the graft is preserved; however, the orientation is too oblique and extremely vertical. **c** Parametric model of patient # 3. **d** Arthroscopy at the time of the revision surgery shows normal patellofemoral cartilage

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 30° of knee flexion. After 30°, the ligament loosens and the patellofemoral contact pressure, which also contributes somewhat to patellofemoral stability and is already low during the first 30° (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 0 to 30° of knee flexion (Conlan et al. 1993; Desio et al. 1998; Hautamaa et al. 1998). After 30° of knee flexion, lateral patella stability depends on the femoral trochlea. Additionally, this study confirms previous findings that show that the location of the femoral attachment point is of utmost importance to obtain satisfactory clinical results (Sanchis-Alfonso et al. 2017). The femoral attachment point is related to the patellofemoral contact pressure, tension of the MPFL-graft and physiometry of the reconstruction.

The ideal MPFLr technique must combine a precise balance between an optimal patellofemoral pressure with maximum graft stress. It makes a new tear less likely. The patellofemoral contact pressure of a virgin knee must be reproduced, and a maximum MPFL-graft stress greater than that of the native MPFL must be created with the intention to compensate for the anatomic factors (increased tibial tuberosity – trochlear groove (TT-TG) distance, patella alta and trochlear dysplasia) that predispose to lateral patellar dislocation (Sanchis-Alfonso 2014). 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 not to increase maximum MPFL-graft stress with a subsequent increase in the patellofemoral pressure because the technique will have a suitable result in the short term but will have a deleterious effect and will lead to degenerative changes in the long term. MPFLr evaluation by means of the

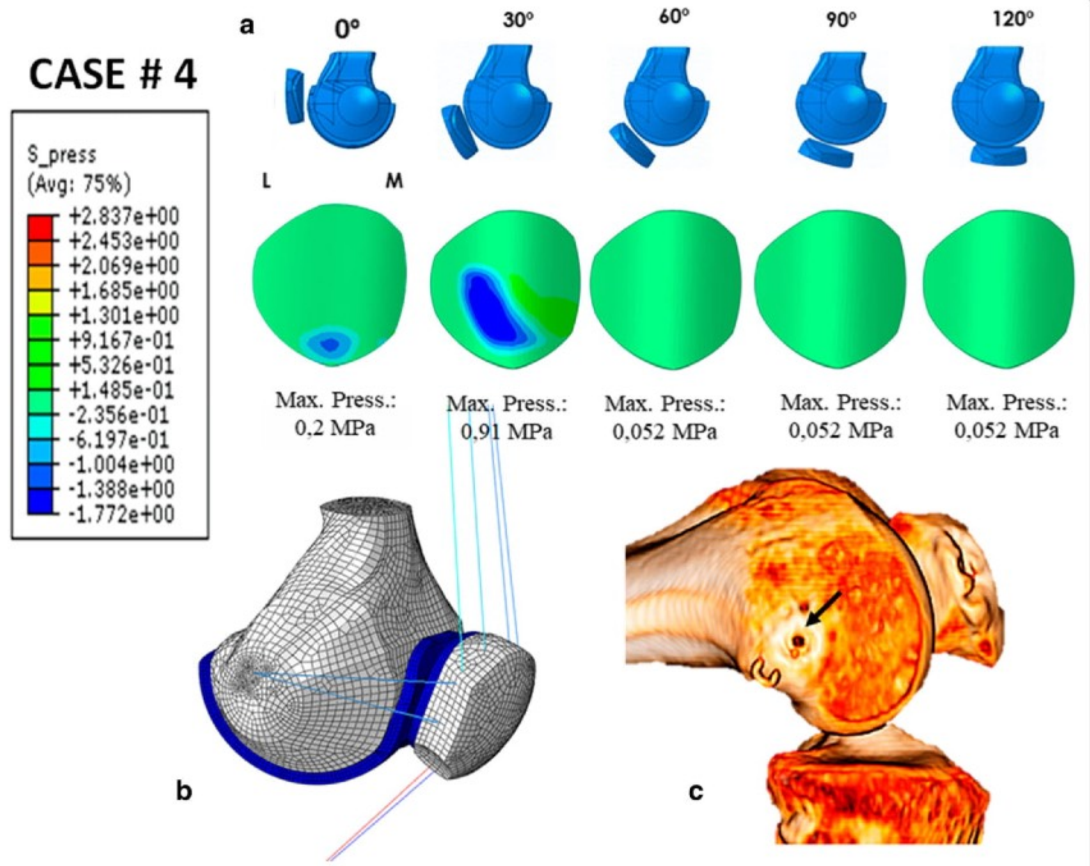

Fig. 7 Case # 4 Primary surgery with an excellent result: **a** Contact pressure (MPa) on the patellar cartilage L = Lateral M = Medial. **b** Parametric model of patient # 4. **c** Anatomic femoral attachment point (black arrow)

FEM is more sensitive than evaluations using only clinical or radiological tests. The FEM can 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. The elevated MPFL graft tension or an incorrect femoral tunnel position will increase the pressure applied to patellofemoral cartilage (Stephen et al. 2014, 2016), and this increase in PFJ contact pressure might result in joint degeneration (Rood et al. 2015; Stephen et al. 2014). Rood et al. in 2015 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 increase the chance of PFOA in the long term. While Rood et al. showed elevated contact pressures with MPFLr, Stephen et al. in 2014 did not show a pressure increase. In this way Stephen et al., in 2014 and 2016, found that an anatomic MPFLr with a tension of 2 N and fixed at 0, 30 or 60° of knee flexion, regardless of the type of graft used, restores PFJ contact pressures to the intact state. However, graft overtensioning and/or non-anatomic positioning of the femoral attachment increases PFJ contact pressures (Elias et al. 2016; Stephen et al. 2014, 2016). A broad variability in patellofemoral anatomy, graft tension and non-anatomic femoral attachment could explain these different findings.

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 pressures at 0 and 30° of knee flexion after an MPFL reconstruction (2.17 MPa at 0° and 0.14 MPa at 30° when using the semitendinosus as a graft) compared to the pressure found in a normal non-operated knee (0.18 MPa at 0° and 0.016 MPa at

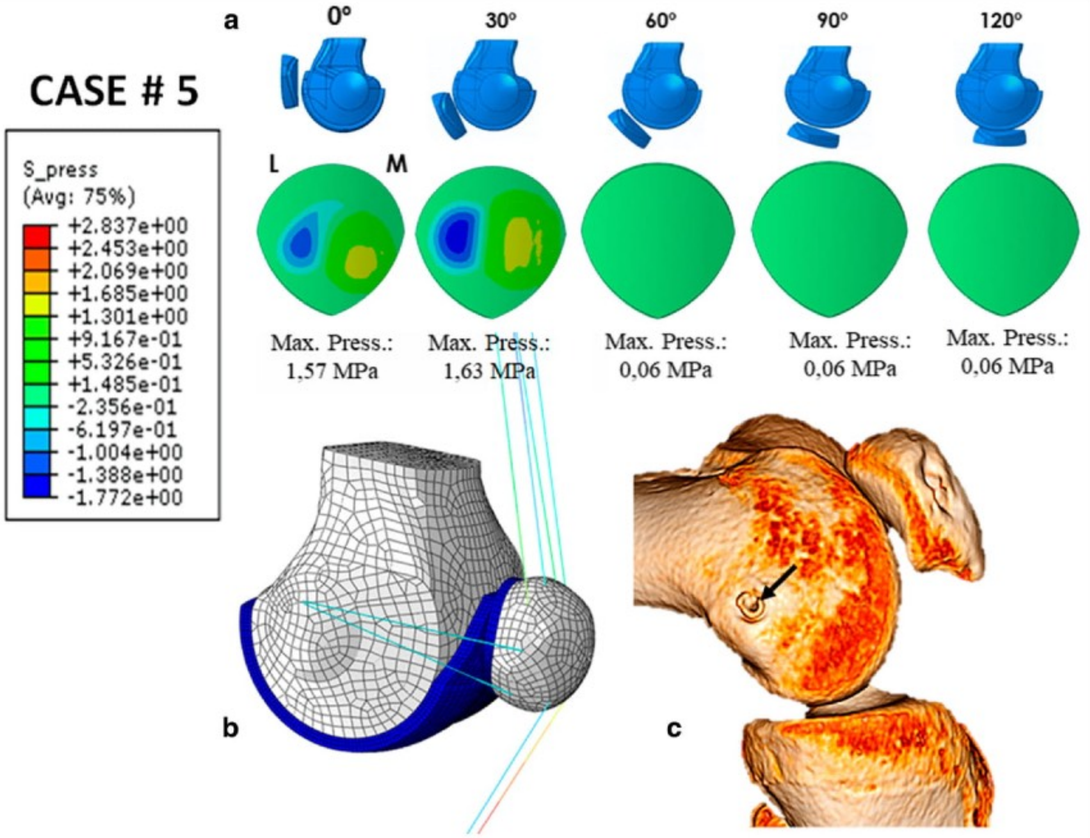

Fig. 8 Case # 5 Primary surgery with an excellent result: **a** Contact pressure (MPa) on the patella cartilage L = Lateral M = Medial. **b** Parametric model of patient # 5. **c** Anatomic femoral attachment point (black arrow)

30°). This leads us to consider the possible long-term effects from a slightly greater patellofemoral contact pressures. However, in theory, the patellofemoral contact pressures found in the anatomic reconstructions are not great enough to cause symptomatic PFOA since they are lower than those causing knee osteoarthritis (Segal et al. 2009). The objective would be not to exceed safe levels of patellofemoral pressure to induce patellofemoral chondropathy and ultimately PFOA. It should also be remembered that the increase in patellofemoral contact pressures 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, what is being discussed is the precise consequences of the clinical results of the non-anatomical techniques for the MPFLr in which the MPFL-graft behaves like a native MPFL (physiometric behaviour) from the physiological point of view. Servien et al. in 2011 and Sanchis-Alfonso et al. in 2017 found no negative clinical effects after 2 years when using these reconstructions, which could be due to the short follow-up in both cases. In this type of reconstruction, the FEM shows an increase in patellofemoral contact pressure at 0 and 30° of knee flexion in comparison to these pressures in the native knee (2.77 MPa at 0° and 1.91 MPa at 30° vs 0.18 MPa at 0° and 0.016 MPa at 30°). This pressure increase mainly occurs on the medial patellar facet. According to Jones et al. (2016), the average contact stress at 30° is 1.7 ± 0.6 MPa, with a peak of 3.2 ± 0.6 on the surface of the patellar cartilage and of 2.8 ± 0.7 MPa at the deepest point. The differences found between this study and the one by Jones et al. in 2016 can be explained by the fact that Jones uses a laboratory controlled study with cadaver knees using a different method than us. What is not known 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. in 2009 observed that a threshold of 3.42 to 3.61 MPa had a 73.3% sensitivity with 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 greater. In non-anatomical MPFL reconstructions, the maximum patellofemoral contact pressures are on 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. Consequently, it would seem more important for the ligament to be "physiometric" rather than perfectly anatomical.

With the FEM, it is possible to predict which MPFLr have an increased risk of 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 0 to 30°, and was tense from 60° onward. In these cases, the patellofemoral contact pressures were over 5 MPa from 60° onward, the femoral attachment point being extremely non-anatomical (too far anterior) and the MPFLr was not physiometric. The predictive value of the parametric model of the PFJ has made its clinical validation possible.

A limitation of this study is that the patellar and femoral cartilages had a constant thickness of approximately 3 mm. 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. Accordingly, 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 (Ciccone II et al. 2006; Drez Jr et al. 2001; Elias and Cosgarea 2006). In the future, patient-specific material properties should be considered. The inclusion of magnetic resonance (MR) data from the same patients and the use of image registration techniques might combine MR and CT data. It which would not only make it possible 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 (Martí-Bonmatí et al. 2008). Another limitation is that there was no estimation of the amount of error in the patient-specific shape when creating the patient-specific model. There was only qualitative assessment of the global patient-specific shape. Additionally, to preserve equilibrium, the elements representing the QT and PT were fixed and no forces were applied through them. Furthermore, the same LR length changes were assumed as for the MPFL. Another important limitation of this study is the fact that the patellofemoral pressure values that predict the development of a symptomatic PFOA are not known. We have extrapolated the well-known values that would lead to the development of a symptomatic tibiofemoral osteoarthrosis. It has also been 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 (Segal et al. 2009). For that reason, we speculate that a higher pressure would be necessary to cause damage. Using the FEM allows to reliably predict the clinical evolution of an MPFL-graft. Logically, in a condition with multifactorial etiopathogeny such as lateral patellar instability, the model fails in some cases 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. This is a major limitation of this study. The abovementioned anatomic additional factors are often associated in patients requiring MPFLr and can change the pressures at the PFJ and lead to different outcomes. Although it has not been addressed in the present work, the conditions in which the graft would not prevent post-operative instability could be incorporated (Farahmand et al. 1998; Hautamaa et al. 1998; Sanchis-Alfonso 2014).

Conclusion

The main finding of this study is that the use of a parametric 3D finite element model of the PFJ allows the evaluation of different types of surgical techniques for MPFLr with regard to the effect on the patellofemoral contact pressure. That also goes for the kinematic behaviour of the MPFL-graft with flexion-extension of the knee and the maximum MPFL-graft stress based on a previous study which has shown that the graft length variation differs in each type of MPFLr. In this way, from diagnostic images like a CT, for example, it is possible to simulate different surgical treatments and customize the treatment for individual patients.

Additional file

Additional file 1: Figure S1. Patellar cartilage contact pressure (MPa) obtained for different values of friction coefficient (μ) (0.01, 0.02, 0.025, 0.03) in the 30º knee flexion angle for the native knee model. **Figure S2.** Patellar cartilage contact pressure (MPa) obtained for different patellar-femoral cartilages combinations in the 30º knee flexion angle for the intact knee model. PCT=Patellar Cartilage Thickness, FCT=Femoral Cartilage Thickness. (DOCX 387 kb)

Abbreviations

CT: Computerized Tomography; FEM: Finite element methodology; LR: Lateral retinaculum; MPa: Megapascal; MPFL: Medial patellofemoral ligament; MPFLr: Medial patellofemoral ligament reconstruction; MR: Magnetic resonance; PFJ: Patelofemoral joint; PFOA: Patellofemoral osteoarthritis; PT: Patellar tendon; QT: Quadriceps tendon; RF: Rectus femoris; VI: Vastus intermedius; VL: Vastus lateralis; VM: Vastus medialis

Authors' contributions

(I) Conception and design: V.S-A; (II) Provision of patients: V.S-A; (III) Adquisition of the images to reconstruct the FE models: C.R-F and F.G-C; (IV) Creation of the parametric model and FE simulations: D.A-L; (V) Data analysis and interpretation: All authors; (VI) Manuscript writing: All authors. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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Publisher's Note

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Evaluation of Patellar Contact Pressure Changes after Static versus Dynamic Medial Patellofemoral Ligament Reconstructions Using a Finite Element Model

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Abstract: Objectives: To evaluate the effect of various medial patellofemoral ligament (MPFL) fixation techniques on patellar pressure compared with the native knee. Methods: A finite element model of the patellofemoral joint consisting of approximately 30,700 nodes and 22,200 elements was created from computed tomography scans of 24 knees with chronic lateral patellar instability. Patellar contact pressures and maximum MPFL graft stress at five positions of flexion (0°, 30°, 60°, 90°, and 120°) were analyzed in three types of MPFL reconstruction (MPFLr): (1) static/anatomic, (2) dynamic, using the adductor magnus tendon (AMT) as the femoral fixation, and (3) dynamic, using the quadriceps tendon as the attachment (medial quadriceps tendon-femoral ligament (MQTFL) reconstruction). Results: In the static/anatomic technique, the patellar contact pressures at 0° and 30° were greater than in the native knee. As in a native knee, the contact pressures at 60°, 90°, and 120° were very low. The maximum MPFL graft stress at 0° and 30° was greater than in a native knee. However, the MPFL graft was loose at 60°, 90°, and 120°, meaning it had no tension. In the dynamic MPFLr using the AMT as a pulley, the patellar contact pressures were like those of a native knee throughout the entire range of motion. However, the maximum stress of the MPFL graft at 0° was less than that of a native ligament. Yet, the maximum MPFL graft stress was greater at 30° than in a native ligament. After 30° of flexion, the MPFL graft loosened, similarly to a native knee. In the dynamic MQTFL reconstruction, the maximum patellar contact pressure was slightly greater than in a normal knee. The maximum stress of the MPFL graft was much greater at 0° and 30° than that of a native MPFL. After 30° of flexion, the MQPFL graft loosened just as in the native knee. Conclusions: The patellar contact pressures after the dynamic MPFLr were like those of the native

Keywords: MPFL reconstruction; finite element model; patellar contact pressure; patellar cartilage degeneration after MPFL reconstruction

1. Introduction

Chronic lateral patellar instability (CLPI) is a common finding of knee surgeons in their daily clinical practice. Although its etiology is multifactorial, the most important structure in the development of this instability is medial patellofemoral ligament (MPFL) deficiency [1,2]. Over the last 10 years, MPFL reconstruction (MPFLr) has become a standard surgical technique for the treatment of CLPI, either as an isolated technique or combined with other surgical techniques [1–6]. Many surgical techniques using various types of grafts (autografts, allografts, or synthetic) and fixation techniques have so far been described. Based on the fixation technique used, there are two types of MPFLr, static and dynamic [1,7–12]. A static MPFLr, which involves an anatomic femoral bone attachment and a patellar bone attachment, is currently more common [1]. In the less used dynamic reconstruction, only one of the graft's extremities is fixed to bone, while the other one is fixed to soft tissues. This type of reconstruction is therefore a less rigid reconstruction [7–12]. Static and dynamic reconstructions show MPFL isometry between 0° and 90° [9,13]. In a static/anatomic MPFLr, the graft is isometric in all the cases between 0° and 30° of knee flexion [13]. In 83% of cases, the graft is isometric from 0° to 60° [13]. Beyond 60° of knee flexion, the MPFL becomes progressively lax and isometry is lost [13]. Regarding isometry, a ligament is considered isometric when there is less than 5 mm of length change throughout the entire range of motion [14].

Both static and dynamic reconstruction techniques have been shown to yield satisfactory clinical results in the short and intermediate terms [1,7,8,12]. However, what is not known is whether one type of MPFLr is more likely than the other to lead to the development of patellofemoral osteoarthritis (PF OA) in the long term. We hypothesized that a static anatomic reconstruction might generate greater patellar contact pressure than a dynamic reconstruction and would therefore increase the risk of PF OA in the long term. Nevertheless, from a functional standpoint, a dynamic reconstruction would enable behavior that is more like that of a native MPFL than a static reconstruction. In a dynamic MPFLr, the fixation point gives a bit before the graft starts to stretch when the patella moves laterally. Therefore, the dynamic MPFLr allows for patellar contact pressures that are closer to those generated in a native knee. After the fixation of the MPFLr, it is important to verify that the patella can still be manually lateralized in full extension some 10 mm, to avoid any over-constraint, but with a firm endpoint. To avoid excessive tension on the graft when we perform an anatomic/static MPFLr, we have to fix the graft at 30° of knee flexion as it is at this angle that the distance between the femoral and patellar attachments points is greatest [13].

Cadaveric experiments have been conducted that show the achievement of physiological patellofemoral biomechanics, like that of the native knee with static MPFL reconstructions [15–17]. Cartilage degeneration after a static MPFLr has been related to graft overtension or an incorrect femoral attachment point [16,17]. Several biomechanical studies based on the finite element (FE) method have evaluated the MPFLr [18–24]. Previous studies were mainly based on a single FE model of the knee. Sanchis-Alfonso et al. [18] recently created a 3D parametric FE model of the patellofemoral joint (PFJ) that allowed for the evaluation of different types of MPFL reconstructions through the full range of motion of the knee. Additionally, the model is patient-specific. The objective of this paper was to evaluate the effect of different MPFL fixation techniques on patellar pressures compared with the native knee. High patellar pressures would be a risk factor for patellofemoral cartilage degeneration in the long term. This evaluation used a clinically-validated 3D parametric FE model of the PFJ [18].

2. Methods

Investigation performed at the Department of Mechanical Engineering, University of Zaragoza, Zaragoza, Spain.

2.1. Parametric FE Model of the PFJ

A parametric FE model of the PFJ was previously developed [18] based on the geometrical average of 24 knees acquired with a 64-detector multidetector computer tomography (CT) system (Philips, Best, The Netherlands) at the highest spatial resolution, without slice interpolation (0.255 × 0.255 × 0.672 mm^3) [13]. The knee geometry was simplified (Figure 1). The main parts of the PFJ were the femoral condyle and patella bones, considered as rigid parts, and the femoral and patellar cartilages, considered as deformable components. A cartilage thickness of 3 mm was assumed [18,25]. Tendon and ligaments were also included to stabilize the patella and support the distribution of the patellar contact pressures better. The quadriceps tendon (QT), which consists of the vastus medialis (VM), vastus lateralis (VL), vastus intermedius (VI), and rectus femoris (RF) tendons, and the patellar tendon (PT) were modelled as a group of four and two truss elements, respectively (Figure 1), while the MPFL and the lateral retinaculum (LR) were defined as beam elements. The QT was oriented from the insertion site on the patella to the muscle origin or the most distal wrapping point on the femur, while the PT was oriented from the distal patella to the tibia [19,20]. The tendon and ligament properties were taken from previous studies and are summarized in Table 1 [21,26,27]. The cartilages were modelled with an elastic modulus of 10 MPa and a Poisson's ratio of 0.45 [22,28,29]. A contact between both cartilage surfaces was defined with a friction coefficient of 0.02 [30]. Finally, the FE model of the PFJ consisted of around 30,700 nodes and 22,200 elements.

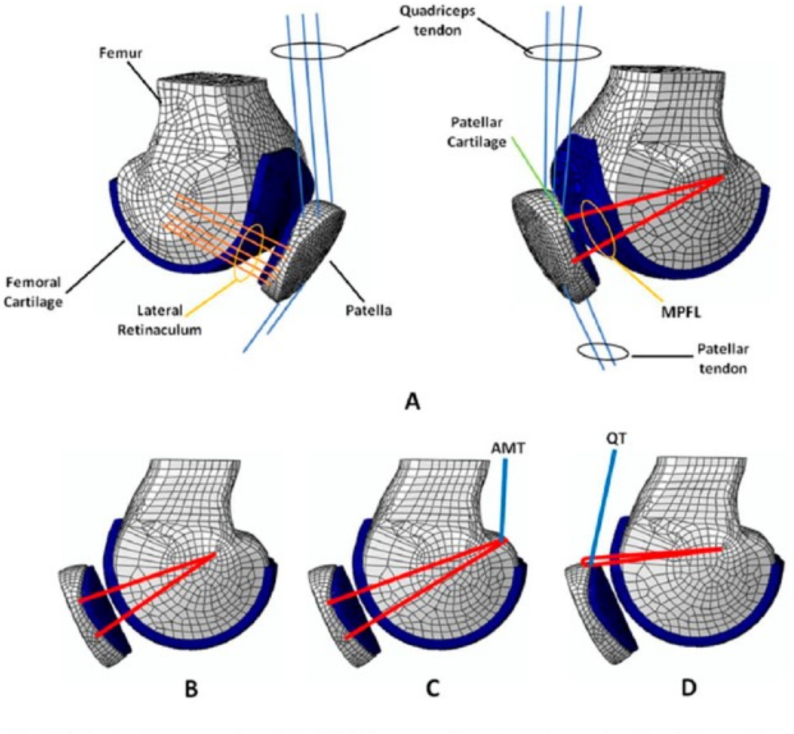

Figure 1. (**A**) Parametric geometry of the PFJ (femur, patella, and femoral and patella cartilages), (**B**) static/anatomic reconstruction, (**C**) dynamic reconstruction using AMT as the femoral fixation, and (**D**) dynamic reconstruction using the quadriceps tendon (QT) as one of the attachment points.

Table 1. Material properties considered for the FEM (Finite Element Model) simulation (from references [21,26,27]).

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 Autograft)	100	0.3
MPFL Reconstruction (Gracilis Autograft)	80	0.3
MQTFL Reconstruction (Semitendinosus Autograft)	100	0.3
MQTFL Reconstruction (Posterior Tibial Allograft)	513	0.3

2.2. *MPFLr Techniques*

Three types of MPFLr were simulated: (a) static/anatomic reconstruction, meaning a reconstruction with a femoral anatomic fixation point and 2 patellar fixation points (Figure 1B); (b) dynamic reconstruction using the adductor magnus tendon (AMT) as the femoral fixation (Figure 1C); and (c) dynamic reconstruction using the quadriceps tendon as the attachment point (medial quadriceps tendon-femoral ligament (MQTFL) reconstruction) (Figure 1D). For the static reconstruction, the native ligament was simulated (intact knee). Two types of grafts were used for both the static and dynamic reconstructions using the AMT as a pulley. They were the semitendinosus autograft and gracilis autograft. These are the most frequently used grafts during MPFLr surgery. Two types of grafts were also used in the original MQTFL reconstruction (MQTFLr) technique described by Fulkerson and Edgar [12]. Those were the semitendinosus autograft and posterior tibial tendon allograft. For that reason, we performed two simulations during MQTFLr, using a semitendinosus autograft in one of them and a posterior tibial tendon allograft in the other.

2.3. *Simulation of the Different Surgical Techniques*

The three surgical techniques were analyzed for 5 knee flexion positions: 0°, 30°, 60°, 90°, and 120°, as in a previous dynamic Computed Tomography (CT) scan study [13]. Table 2 summarizes the mean distance between the patella and femoral insertions points for the different MPFL reconstructions. Based on this data, the insertion nodes for each technique and the elongations suffered by the ligaments were determined. The reference position, where the ligaments did not experience any strain, was considered to be 40° of knee flexion. In some knee flexion positions, the distance between the femur and the patella insertion points was smaller than the reference distance (40°), which meant that the ligament was not experiencing any type of stress (Table 2, cases indicated by *). In other cases, the MPFL underwent an elongation (Table 2, cases indicated by +), which was simulated by applying a pretension force, $\Delta L \times K$, where ΔL is the length increment and K is the stiffness of the ligament (Table 1). LR lengths were assumed to be the same as the MPFL length to preserve the equilibrium on both sides of the joint. The average MPFL lengths were used in this part of the study to compare the performance of the static/dynamic reconstructions over the mean parametric FE model of the PFJ.

Table 2. Intact MPFL and different types of MPFL reconstruction (MPFLr) data (* ligaments under no tension, + ligaments under tension).

	Anatomic MPFLr (STATIC)	**MPFLr Using the AMT as a Pulley (Superior Bundle) (DYNAMIC)**	**MPFLr Using the AMT as a Pulley (Inferior Bundle) (DYNAMIC)**	**MQFTLr (DYNAMIC)**
Flexion Angle (°)	Length (mm)	Length (mm)	Length (mm)	Length (mm)
0	60.2 +	61.1 +	58.3 +	65 +
30	57.9 +	60.9 +	60.1 +	63 +
40	57.7	60.8	60.8	62,7
60	57.3 *	60.7 *	62.1 *	62 *
90	55.6 *	60.4 *	62.2 *	62 *
120	50.7 *	55.8 *	57 *	62 *

AMT = Adductor Magnus Tendon.

The parametric FE model and the simulations were carried out using the software Abaqus/CAE v.6.14 (Dassault Systèmes, Velizy-Villacoublay, France). Models were generated for each degree of knee flexion. First, the patella was brought closer to the femur to generate the contact. Then, the ligaments were incorporated. Subsequently, a previously calculated pretension force was applied to the ligaments little by little according to the length variation of the graft during the knee flexion (Table 2). It has been demonstrated that length variation of the graft during knee flexion differs in each type of MPFLr [13]. This way, the pressure of contact is generated. The initial contact pressures were removed to compare the different surgical techniques under the same conditions. Therefore, the results are presented as relative contact pressures. Maximum patellar contact pressures at each degree of knee flexion were evaluated. Maximum MPFL graft stress at each degree of knee flexion was then evaluated for the different positions of the knee.

3. Results

3.1. Static Anatomical Technique

With the static anatomical technique, the patellar contact pressures at 0° and 30° of knee flexion were greater than those of the native knee regardless of whether semitendinosus or gracilis autografts were used (Figure 2A–C). As in a native knee, the patellar contact pressures at 60°, 90°, and 120° were very low. The maximum patellar cartilage contact pressures are displayed in Figure 2B, C. The maximum MPFL graft stress at 0° and 30° was greater than in a native knee regardless of whether semitendinosus or gracilis autografts were used (Table 3). As in a native knee, at 60°, 90°, and 120° the MPFL graft was loose, meaning that it had no tension (Figure 2A–C). The MPFL and LR maximum stresses are displayed in Table 3.

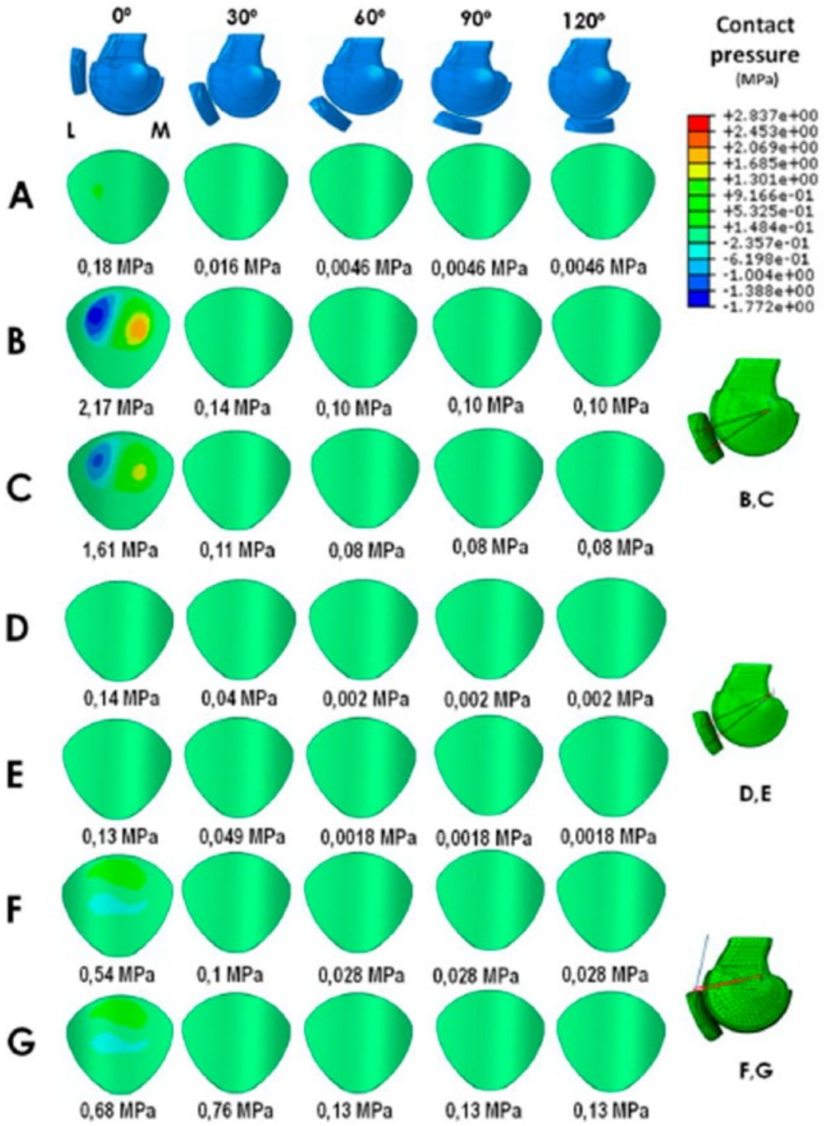

Figure 2. Contact pressure (MPa) on the patellar cartilage: (**A**) intact knee, (**B**) anatomic MPFLr with semitendinosus autograft, (**C**) anatomic MPFLr with gracilis autograft, (**D**) MPFLr with semitendinosus autograft using the AMT as a pulley, (**E**) MPFLr with gracilis autograft using the AMT as a pulley, (**F**) MQTFLr with semitendinosus autograft, and (**G**) MQTFLr with posterior tibial tendon allograft (M: Medial; L: Lateral).

3.2. Dynamic MPFLr Techniques

In the dynamic MPFLr using the AMT as a pulley (Figure 2D–E), the patellar contact pressures were very similar to those of a native knee through the entire range of knee motion regardless of whether semitendinosus or gracilis autografts were used. The maximum patellar cartilage contact pressures are displayed in Figure 2D–E. The maximum MPFL graft stress was less at 0° than that of a

Table 3. MPFL and LR maximum stress (MPa) values for each case analyzed.

Ligament Status	Flexion Angle (°)	Maximum MPFL Stress (MPa)	Maximum LR Stress (MPa)
INTACT MPFL	0	8.85	1.52
	30	0.78	0.15
ANATOMIC MPFLr	0	74.72	1.51
Semitendinosus autograft	30	6.55	0.14
ANATOMIC MPFLr	0	58.78	1.51
Gracilis autograft	30	5.12	0.14
MPFLr with AMT as a Pulley	0	7.11	0.15
Semitendinosus autograft	30	2.53	0.05
MPFLr with AMT as a Pulley	0	6.35	0.15
Gracilis autograft	30	2.10	0.05
MQTFLr	0	66.70	1.42
Semitendinosus autograft	30	9.36	0.23
MQTFLr	0	100.80	1.42
Posterior Tibial allograft	30	49.76	0.23

3.2. Dynamic MPFLr Techniques

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In the dynamic MQTFLr, using either a semitendinosus autograft or posterior tibial tendon allograft, the maximum patellar contact pressure was slightly greater than in a normal knee but lower than with the static anatomical technique (Figure 2F,G). The maximum patellar cartilage contact pressures are displayed in Figure 2F,G. The maximum stress of the MPFL graft using a semitendinosus autograft was much greater at 0° and 30° than that of a native MPFL (Table 3). With a posterior tibial tendon allograft, the maximum MPFL graft stress was greater than with a semitendinosus autograft. In all cases, after 30° of flexion, the MQPFL graft loosened like the native ligament. The MPFL and LR maximum stresses are displayed in Table 3.

4. Discussion

The most important finding of this study was that the patellar contact pressure from 0° to 30° of knee flexion, the range in which the patella is usually unstable [1,2], was lower in the dynamic reconstructions compared to the static anatomic reconstructions. In addition, the pressure was similar in dynamic reconstructions compared with an intact knee. This was consistent with our hypothesis. Our results, using a clinically validated FE parametric model [18], are different from those found by Rood et al. [31] in a controlled laboratory study using Tekscan pressure-sensitive films. According to these authors, the static MPFLr resulted in greater peak and mean pressures from 60° to 110° of flexion when compared to dynamic reconstructions. Moreover, these authors showed that the static MPFLr results in greater patellofemoral pressures and thus increases the risk of PF OA in the long term. On the other hand, the dynamic reconstruction results in more normal pressures.

In the most commonly used dynamic MPFLr, the femoral attachment site uses the AMT as a pulley [7,8,10,11]. Some authors have tested the validity of this surgical technique, both clinically and radiologically, and found very satisfactory clinical results in the short term [7,8]. Fulkerson and Edgar [12] described the MQTFLr, another dynamic reconstruction technique. While the soft tissue technique using AMT is considered to be a non-anatomic technique, the soft tissue technique using the quadriceps tendon as the soft tissue fixation point is an anatomic technique as it reconstructs the MQTFL [32,33]. This technique also has good clinical results in the short term, like that of the static anatomic MPFL reconstructions with a patellar attachment point [12]. Moreover, this surgical technique essentially avoids the risk of patella fracture, which is a serious complication after MPFLr [34,35]. Both dynamic techniques restore the medial patella stabilizer, preventing lateral patella dislocation. Nevertheless, uncertainty currently exists relative to the long-term outcomes associated with these dynamic techniques, particularly with the development of PF OA. MPFLr evaluation by means of the FE parametric model, as done in the present study, is more sensitive than evaluations using clinical and radiological tests alone. It allows for the evaluation of patellar compression forces whose increment has been associated with the appearance of osteoarthritis in the tibiofemoral joint [36].

In the present study, we have shown that the dynamic technique using the AMT as a pulley with a gracilis tendon autograft (i.e., the most used graft) [8] not only does not increase the patellar contact pressure compared to an intact knee, but also shows a slightly lower resistance to rupture of the graft compared to a native ligament at 0° (Figure 2D–E, Table 3). In an ideal MPFLr, the graft should be more resistant than the native ligament to compensate for other instability predisposing factors [1]. Moreover, it is logical to think that if the reconstruction uses a graft with the same or lower maximum stress as the torn ligament, we are risking a new rupture. If the maximum stress is greater, then a repeat tear is less likely. Therefore, the aim is a stronger graft that will not tear again. However, this increment of the graft's resistance should never be achieved by increasing the patellar contact pressure. Using a graft with the same or lower maximum stress as the ligament that has just tore could explain this technique´s failure when performed as an isolated MPFLr in patients with a severe trochlear dysplasia. Lind et al. [11] found that the outcomes after MPFLr with the gracilis tendon looped around the AMT insertion in pediatric patients were inferior to MPFLr using bony femoral fixation in adult patients (20% of the pediatric patients experienced redislocation within the first postoperative year compared with 5% of the adult patients). In this series, 20 out of 24 patients had some degree of trochlear dysplasia (10 cases were grade B and 10 cases were grade C or D, 42%) [11]. However, there was no correlation between high degree of trochlea dysplasia (grade C and D) and redislocations. Of the five redislocations, only two were seen in the 10 high-dysplasia knees. This uncorrected factor may have contributed to the high degree of redislocation observed in this series. Alm et al. [10] also found an elevated redislocation rate after MPFLr in children and adolescents when the adductor sling technique was used. The authors concluded that the adductor sling technique could only be recommended in the absence of additional patellofemoral maltracking, caused by an elevated tibial TT-TG distance (>15 mm), patella alta, or especially severe trochlear dysplasia. However, our clinical approach was to treat the associated predisposing factors for CLPI, and MPFLr was associated with realignment surgery in 56% of our cases. This approach could explain our satisfactory clinical results [8]. In our series of isolated MPFLr using the AMT as a pulley, the percentage of trochlear dysplasia grade C or D was only 8.5% (unpublished data). The fact that this type of reconstruction does not increase patellar contact pressure is very important because it indicates that it will not be predisposed to the development of a patellar chondropathy or PF OA in the long term.

Our study showed that MQTFLr, from a biomechanical point of view, behaves like an anatomic static MPFLr (Figure 2F,G). The MQTFL graft was under tension during the first 30° of knee flexion, but it loosened after 30° and the already low patellar contact pressure decreased considerably during the first 30° (Table 3). MQTFLr significantly increased the resistance of the reconstruction without significantly increasing patellar contact pressure. This finding is very important because it indicates that this type of reconstruction is unlikely to contribute to the development of patellar chondropathy or PF OA in the long term. MQTFLr fulfills all the criteria for an ideal MPFLr from a biomechanical point of view. It combines a perfect balance between an optimal patellar contact pressure with the maximum graft stress, making a new tear less likely.

Importantly, from a biomechanical standpoint, a dynamic reconstruction is better than a static one because it enables patellar contact pressure that is like that of an intact knee. To be able to definitely answer the question as to which reconstruction technique is better, the clinical results regarding the percentage of redislocations and functional results need to be considered. However, there are few clinical studies, and those that exist are of low quality with respect to the scientific evidence. We need well-designed, long-term prospective studies with many patients to answer these questions.

4.1. Clinical Relevance

Our findings have important clinical relevance because they validated the use of MPFLr using the AMT as a pulley. The results are relevant not only for adults with a CLPI as a primary surgery, but also in certain situations, such as in revision surgeries with multiple bone tunnels or in children. In children, this method avoids injury to the distal femur growth plate and subsequent risk of developing a deformity of the knee [37]. Moreover, our study validated the use of MQTFLr not only as a primary surgery but also in the revision setting to avoid patellar problems.

Another interesting finding of our study was that the type of graft does matter, at least from a biomechanical point of view (Figure 2, Table 3). Numerous MPFLr surgical techniques, using autografts as well as allografts, have been described. From a clinical point of view, there seems to be no significant differences between the various types of grafts [38,39]. However, our FE parametric model study showed significant differences in terms of patellar contact pressure and the maximum MPFL graft stress. For example, the gracilis autograft has been recommended [8] in the MPFLr using the AMT as a pulley because the gracilis tendon appears to be long and strong enough to duplicate the MPFL function [40,41]. However, according to the results found using the FE method, the semitendinosus tendon has greater stress to failure relative to the gracilis, without significantly increasing the patellar contact pressure. In theory, a new tear is therefore less likely with a semitendinosus tendon autograft (Figure 2D,E, Table 3).

4.2. Limitations

This study has several limitations. First, the PFJ was reconstructed from CT scans in which soft tissues cannot be clearly distinguished and cartilage thickness was estimated by taking a fixed measure into account. The inclusion of magnetic resonance (MR) data from the same patients and the use of image registration techniques to merge MR and CT data would not only allow for measuring cartilage thickness accurately but also for patient-specific matrix properties, such as the T1 or T2 relaxation time, related to proteoglycan and collagen matrix integrity, respectively. Various material models have been developed to describe the mechanical behaviour of articular cartilage [42–46]. Due to computational costs and time-consuming nature associated with 3D FE modelling of more complex models, cartilage has been considered to be a homogenous, isotropic, and linearly elastic material, and interstitial fluid flow has been neglected. Second, ligament material properties were taken from the literature [21,26,27]. In the future, patient-specific material properties could be considered. Third, greater patellar contact pressure is an important risk factor for developing PF OA in the long term. However, the pressure values that will produce symptomatic PF OA are unknown. Segal et al. [36] observed that a threshold of 3.42 to 3.61 MPa had 73.3% sensitivity, with specificity from 46.7% to 66.7%, regarding 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. However, it is logical to think that the pressures causing a symptomatic PF OA would be greater. Several experimental studies have included a certain amount of the quadriceps force applied to the patella [21,31] to determine the patella femoral spatial relationship and contact pressure. Our model did not incorporate this force. It was not necessary because the model itself has stability and because we were only comparing three techniques.

5. Conclusion

The patellar contact pressures after dynamic MPFLr were like those of the native knee, whereas static reconstruction resulted in greater pressures and, thus, could eventually increase the risk of PF OA in the long term. Therefore, dynamic MPFLr might be a safer option than static reconstruction from a biomechanical point of view. We need long-term clinical studies with both dynamic and static techniques to corroborate the conclusions that were obtained with our biomechanical study using an FE parametric model.

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Isolated reconstruction of medial patellofemoral ligament with an elastic femoral fixation leads to excellent clinical results

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Abstract

Purpose The primary objective was to compare the functional outcomes after an isolated MPFL reconstruction using either a quasi-anatomical technique (group A) or an anatomical MPFL reconstruction (group B). The secondary objectives were to compare the rates of redislocation, range-of-motion and subjective patellar instability (Smillie test).

Methods A multicenter longitudinal prospective comparative study was performed. Group A had 29 patients and 28 were included in Group B. Patients with trochlear dysplasia types C and D and patients who had undergone a trochleoplasty, a distal realignment or patella distalization concurrently with MPFL reconstruction were excluded. The main evaluation criterion was the Kujala functional score.

Results The mean postoperative Kujala was 90.4 (89.4 in group A and 92.1 in group B). Upon comparing the mean difference between pre- and post-operative values, no differences were detected between the two groups (n.s).

Conclusions Isolated quasi-anatomical MPFL reconstruction using a gracilis tendon autograft for recurrent patellar dislocation provides outcomes as good as the isolated anatomical MPFL reconstruction in patients with no trochlear dysplasia up to those with trochlear dysplasia type A and B at the 2–5 years follow-up.

Level of evidence Level IV.

Keywords Medial patellofemoral ligament reconstruction · Quasi-anatomic reconstruction · Recurrent patellar instability

Introduction

Lateral patellar dislocation is a significant cause of knee injuries [2]. In this pathology, medial patellofemoral ligament (MPFL) reconstruction has a high rate of success for patients with patellofemoral instability. However, the complication rate associated with this procedure is 26.1% [28]. A frequently reported complication after MPFL reconstruction is the loss of knee flexion (13.4% of all complications), often associated with medial knee pain

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[28]. Enderlein et al., in a prospective study, found the incidence of medial knee pain after MPFL reconstruction in around 30% of the cases [5]. The fact that overtensioning of the MPFL can cause an overload of the medial portion of the patella with a subsequent medial pain syndrome is well known [4, 6, 30]. The stiffness of the surgical construct may be one of the causes of that overload. In the Chassaing technique, the proper tension of the graft is determined after moving the knee through flexion and extension movements to assess the resulting patellar stability [3]. In the Schottle technique, the graft tension is deemed satisfactory when the lateral edge of the patella is aligned with the lateral edge of the trochlea [25].

Many MPFL reconstruction techniques have been described. Alm et al. [1] studied a surgical technique in which the gracilis or semitendinosus tendons are left intact in their insertion, looped around the adductor magnus tendon and attached at the medial facet of the patella in children and adolescents. They reported elevated redislocation rates due to maltracking of the patella in patients with patella alta, trochlear dysplasia or an elevated tibial tuberosity to trochlear groove distance (TT–TG) [1]. A modification of that technique was later described [17, 19]. This is a quasi-anatomical MPFL reconstruction technique that uses a gracilis tendon autograft attached to the patella at the anatomical ligament footprint and passed underneath the adductor magnus tendon, which is used as a pulley for femoral fixation. It has been shown that this technique provides good results in association with distal realignment (in cases of a preoperative TT–TG distance exceeding 20 mm), and/or patella distalization (in cases of patella alta as defined by a Caton–Deschamps index ˃ 1.2) [17]. Several biomechanical, anatomical and finite elements studies supporting the use of a non-anatomical technique have already been published [16, 18, 21]. No mention has been made relative to the results of this kind of patellofemoral ligament reconstruction when carried out on mature knees as an isolated surgical procedure.

The primary objective of the present study was to compare the functional outcomes after an isolated MPFL reconstruction using either a quasi-anatomical technique or an anatomical MPFL reconstruction. The secondary objectives were to compare the rates of redislocation, range-of-motion and subjective patellar instability in accordance with the Smillie test of those same patients.

The hypothesis was that an isolated quasi-anatomical MPFL reconstruction using a gracilis tendon autograft for recurrent patellar dislocation provides outcomes as good as a traditional anatomical technique in patients with no trochlear dysplasia up to those with moderate trochlear dysplasia at 2–5 years of follow-up.

Materials and methods

The study was intended to be a non-inferiority study with respect to a standard validated technique.

IRB approval

The study was approved by the ethics committee of ICATME—Institut Universitari Dexeus (2/2014).

Patients

The following inclusion criteria were used: (1) patients with objective recurrent (minimum two episodes of dislocation) patellar instability operated on from 2014 to 2016, (2) a patient agreement to return for a minimum 2-year follow-up period and (3) patient consent to participate in the study.

The following exclusion criteria were used: (1) patients with TT–TG realignment or patella distalization during the surgery (TT–TG > 20 mm and Caton–Deschamps index > 1.2), (2) patients who had undergone a trochleoplasty concurrently with MPFL reconstruction, (3) patients with grade C or D trochlear dysplasia, (4) subjects who could not fill out the questionnaires by themselves.

At the end of the study, 31 patients were consecutively operated on with an isolated quasi-anatomical MPFL reconstruction (group A) and 28 patients were consecutively operated on with an isolated anatomical MPFL reconstruction (group B). Two patients were lost during follow-up in the study group and none in the control group.

Finally, 29 and 28 patients were included in each group, respectively. The two groups were analyzed and considered homogenous and comparable. A complete description of the baseline characteristics is provided in Table 1.

Surgical procedure

Group A The homolateral gracilis tendon (GT) autograft was always the graft of choice. A 2-cm vertical skin incision 1 cm

Table 1 Baseline characteristic of the two groups

	Group A	Group B
Sex	37.9% M, 62.1% F	32.1 M, 67.9% F
Mean age	22.8 yo	24.6 yo
Dysplasia type A	58.5%	60.7%
Dysplasia type B	35.3%	31.3%
Mean CDI	1.15	1.17
Mean TT–TG	14.8 mm	15.1 mm

F female, *M* male, *yo* years old, *CDI* Caton–Deschamp Index, TT–TG tibial tuberosity–trochlear groove distance medial to the anterior tibial tuberosity was used to approach the gracilis tendon (GT). After exposing the sartorial fascia, it was horizontally incised in line with the palpable GT. It is important not to go any deeper so as to prevent injury to the underlying superficial medial collateral ligament. Both the gracilis (proximal) and semitendinosus (distal) were identified and separated. After freeing the tibial attachment of the GT, a #2 high-strength suture (Hi-Fi, ConMed, Largo, FL) with a Krackow mattress was placed at its distal end. The GT was harvested using a closed tendon stripper and another similar suture was placed at the proximal end. The tendon was sized both in length and diameter and stored wrapped in vancomycin-soaked gauze. The doubled graft should be at least 90 mm in length (total graft length 180 mm) to properly reconstruct the MPFL. The diameter was checked just to be sure that the tendon could easily be passed through the patellar tunnels. The tendon was sized and stored in gauze soaked in vancomycin [20]. A 2-cm vertical skin incision was then made over the superior medial border of the patella to expose its proximal third. Two convergent drill holes (usually 4.5 mm in size) approximately 10 mm in depth were created leaving a bone bridge of 10 mm, thereby obtaining a V-shaped tunnel. Another 2–3-cm skin incision was made along the adductor magnus (AM) tendon, slightly proximal to the medial femoral epicondyle. The tendon of the AM was identified and dissected so as to be used as a pulley for the graft. The graft was then passed through the patella, then under the fascia and finally looped around the AM tendon back to the patella. The knee was cycled several times through full range-of-motion while keeping the graft under slight tension. Finally, both graft ends were sutured together at 30° of flexion with #0 high-resistance non-absorbable sutures. Tension was calculated on the basis that the patella could still be lateralized manually some 10 mm to prevent over-constraint. The lower limb was finally immobilized in a brace locked at full extension. No lateral retinacular release was performed in the present series.

Group B An anatomic double-bundle static MPFL reconstruction using homolateral semitendinosus autograft was always carried out. A 2-cm vertical skin incision was then made centered over the junction of the medial and middle thirds of the patella to expose its proximal third. Two convergent drill holes (usually 4.5 mm in size) approximately 10 mm deep were created leaving a bone bridge of 10 mm, thereby obtaining a V-shaped tunnel. Another 3-cm skin incision was made over the femoral insertion of the MPFL. The anatomic femoral insertion of the MPFL is always located between the medial femoral epicondyle (MFE) and the adductor tubercle (AT), usually 10 mm distally from the latter. The graft was then passed through the patella, then under the fascia and finally inserted to the anatomic footprint point without fluoroscopy at 30° of flexion by a suture anchor with enough tension to make the graft taut but without pulling. No lateral retinacular release was performed in the present series. The lower limb was finally immobilized in a brace locked at full extension.

Partial weightbearing was allowed immediately after surgery as tolerated, with a knee brace locked at full extension. Range-of-motion exercises were encouraged after 2 weeks and progressed to full range of motion by the sixth week. The brace was discarded at approximately 3 weeks depending on the status of the quadriceps. The protocol was the same for both groups and all the patients followed.

End points

The main evaluation criterion was the Kujala functional score [11]. Secondary evaluation criteria were functional scores consisting of the IKDC subjective [8], Tegner [29] and VAS, the rate of redislocation of the patella, subjective patellar instability in accordance with the Smillie test (apprehension when the patella is lateralized by the examiner) and range-of-motion measured with a goniometer.

The functional scores were collected by a single independent surgeon with a computerized questionnaire. The clinical examination data were collected by each surgeon in a prospective clinical evaluation.

Statistical analysis

Because a sample size calculation was not made, it was decided to carry out a posteriori power sample analysis at the end of the study. We conducted the analysis to determine if there was at least 80% power and a 95% confidence interval in our sample size to test the primary outcome of our study to confirm our hypothesis. Therefore, we performed a retrospective noninferiority power calculation using the Kujala knee score as a primary endpoint. A10-point lower Kujala score was considered a clinically relevant inferior clinical outcome. Based on previous studies, the standard deviation (SD) for the Kujala score was assumed to be 15 [5]. As result of our post hoc power analysis, the calculation resulted in a sample size of 28 or less subjects per group. This confirms the validity of the sample analyzed in the present study. Previous studies comparing the clinical results of two different MPFL reconstruction techniques described the same sample size when the noninferiority power calculation using the Kujala knee score as primary endpoint was calculated at the beginning of the study [12].

Categorical variables are expressed as frequencies and percentages, while continuous variables were described with mean and standard deviation. The differences between pre- and post-surgery were assessed with the Student's *t* test for paired data and the comparison between groups was performed with Student's *t* test for independent data. Person's correlation coefficient was also used to assess the relationship between the ICD and TA-GT along with other continuous variables. For all the analyses, two-sided *p* values of less than 0.05 were considered as statistically significant. The statistical analysis was performed using the SPSS 23 (SPSS, Chicago, IL) package.

Results

133 patients were operated on for recurrent patellar dislocation in the two institutions. 31 of them had an anterior tuberosity distalization and/or medialization, 11 had atrochleoplasty and 32 were excluded for having a grade C or D trochlear dysplasia. The baseline characteristics of the two groups are detailed in Table 1.

The mean postoperative Kujala was 90.4 ± 8.6, being 89.3 ± 8.5 in group A and 92.1 ± 9 in group B. No statistical differences were found between the two groups with regard to the improvement in the Kujala score, the improvement in the IKDC subjective score, the mean post-operative Tegner score, and the mean VAS decrease (Table 2).

With a linear regression, the influence of the CDI and type of trochlear dysplasia on the postoperative score and postoperative VAS were evaluated without identifying any correlation or any difference between the two groups. The evaluation of the influence of the TT–TG score highlighted a statistical correlation ($p = 0.042$) between increased TT–TG values and a decreased postoperative Kujala score. No differences were detected between the two groups.

A group comparison between patients with no trochlear dysplasia, Type A and type B dysplasia were done. No differences between the groups in terms of postoperative Kujala (n.s), postoperative IKDC (n.s) or postoperative VAS (n.s) were observed.

Only one postoperative patellar dislocation occurred. It was in group A and it happened at 8 months postoperative due to a traumatic accident during sport activities. The baseline characteristics of this patient were: dysplasia type A, TT–TG distance of 16 mm and a CDI of 1.2.

The mean postoperative range-of-motion was 133° ± 7 in group A and 134° ± 9 in group B. There was no statistical difference between the two groups (n.s). Neither were there any differences in terms of the preoperative values (n.s).

Subjective patellar instability was present in only two cases postoperatively, one in each group. In both cases, no further patellar dislocation occurred, and the patients were pain free.

Discussion

The most important finding of the present study was that an isolated quasi-anatomical MPFL reconstruction using a gracilis tendon autograft for recurrent patellar dislocation provides outcomes as good as the classical anatomical technique at 2–5 years follow-up in patients with no trochlear dysplasia up to those with moderate trochlear dysplasia.

Our results were verified by comparing the values found in our study with those found in previous published studies. In a meta-analysis, a mean postoperative Kujala score of 85.8 (95% CI 81.6–90.0) was found by Schneider et al. [24]. The pooled estimated mean postoperative Tegner score was 5.7, with 84.1% (95% CI 71.1–97.1%) of the patients returning to sports after surgery. The pooled total risk of recurrent instability after surgery was 1.2% (95% CI 0.3–2.1%), with a positive apprehension sign risk of 3.6% (95% CI 0–7.2%) and a reoperation risk of 3.1% (95% CI 1.1–5.0%). The studies were included without regard to the type of fixation. Furthermore, the grafts used were a semi-tendinosus autograft, a gracilis autograft, a quadriceps tendon or an autologous patellar tendon autograft. In a systematic review of 14 articles, Longo et al. [14] found that the most frequently used score was the Kujala score with a mean value of 83.26. Functional failures ranged from 0% to 8.8%. Major complications were not described. Minor complications ranged from 0 to 40%. Reoperations ranged from 4.5% to 17.7%. In another systematic review of isolated patellofemoral reconstruction, McNeilan et al. [15] described a mean Kujala score improvement for all the included patients ranging from 59.9 preoperatively to 89.1 postoperatively. The overall complication rate identified in that study was only 5.8%. The most commonly reported complication in adults was persistent subjective patellar instability in accordance with the Smillie test, without luxation in 1.8% of the cases.

There are several arguments that have advocated for the use of the adductor magnus tendon as a pulley for the graft instead of inserting it in the traditional Schottle point. According to Sanchis-Alfonso et al. [22, 23], the radiographic method described by Schottle et al. [26] does not ensure a precise location of the femoral fixation point in

Table 2 Functional score results

	Group A	Group B	*p* value
Improvement of Kujala score	27.3 (SD 15.6)	30.4 (SD 17.4)	n.s
Improvement of IKDC subjective score	34.1 (SD 15)	41.0 (SD 21.7)	n.s
Mean postoperative Tegner score	5	4.91	n.s
Mean VAS decrease	−4.2	−4.3	n.s

MPFL reconstruction surgery, from an anatomic standpoint. A mispositioned femoral tunnel occurs in between 31 and 71% of MPFL reconstructions [32]. The study done by Servien et al. also highlights the difficulty of a reproducible MPFL reconstruction with only 65–69% of the femoral tunnels well positioned [27]. Another study demonstrates that radiographic localization of the MPFL femoral tunnel results in inaccurate tunnel placement on a true lateral radiograph. This happens when there is deviation from a true lateral fluoroscopic image, which can be difficult to obtain intraoperatively [33]. For Melegari et al. [16], the use of the non-isometric attachment point of the adductor tubercle in medial patellofemoral ligament reconstruction does not alter the knee contact area or contact pressures as compared with isometric femoral attachment at the posterior medial epicondyle. For Tischer et al. [31], in the case of a patella alta, a slightly more proximal femoral insertion is beneficial for the biomechanical behaviour of the reconstructed MPFL, which due to the greater lengthening of the MPFL occurs for the first 20° of knee flexion in comparison to a normal patella height.

One of the strengths of this study is that patients with an isolated reconstruction of the MPFL were compared to avoid the bias generated by the other surgical techniques like distalization of the patella or medialization of the tibial tuberosity. The results of MPFL reconstruction using the present technique in association with a distal realignment procedure have been already shown [17].

Using an isolated reconstruction of the MPFL in patients with trochlear dysplasia could be criticized. A study associates trochlear dysplasia with poorer MPFL reconstruction clinical outcomes [9]. Furthermore, severe trochlear dysplasia is the most important predictor of residual patellofemoral instability after isolated MPFL reconstruction [10]. For these reasons, patients with dysplasia type C or D have been excluded from the present series.

TT–TG realignment or patella distalization was not performed in four young patients without closed growth plates, despite having an elevated TT–TG or a patella alta to prevent growth deviations. This was also the case for six patients with a TT–TG or a CDI at the upper edge of the accepted range of values (20 and 1.2, respectively). Even so, the subgroup of patients with a TT–TG $\geq$ 20 and the subgroup of patients with a CDI $\geq$ 1.2 did not show worse clinical outcomes or a higher percentage of re-dislocation.

The quasi-anatomical technique provides several advantages. It is an inexpensive procedure as no implants are used. The femoral physeal plate of young patients is not affected as no tunnel needs to be drilled and no hardware is needed to fix the graft to the bone. Moreover, no irradiation is called for as no intraoperative fluoroscopy is called for during surgery. Finally, the elastic fixation may provide better control over the possibility of medial patellofemoral over-constraint compared to the bone fixation of the graft, which seem to be more rigid than the "elastic fixation" [22].

This study had several limitations. The patients in the two groups were not operated on by the same surgeon, which can introduce a performance bias. A gracilis tendon was used in group A, while a semi-tendinosus tendon was used in group B. No radiographic analysis of the residual patellar tilt was done, but some studies claim that MPFL reconstruction produces no improvement in patellar tilt [7, 13]. Additionally, the patients were not randomized, but the two groups were homogeneous in terms of preoperative characteristics.

Conclusions

Isolated quasi-anatomical MPFL reconstruction using a gracilis tendon autograft for recurrent patellar dislocation provides outcomes as good as the isolated anatomical MPFL reconstruction in patients with no trochlear dysplasia or trochlear dysplasia type A and B at 2–5 years follow-up.

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Compliance with ethical Standards

Conflict of interest The author(s) declare that they have no competing interests.

Ethical approval The study was approved by the ethics committee of ICATME—Institut Universitari Dexeus (2/2014).

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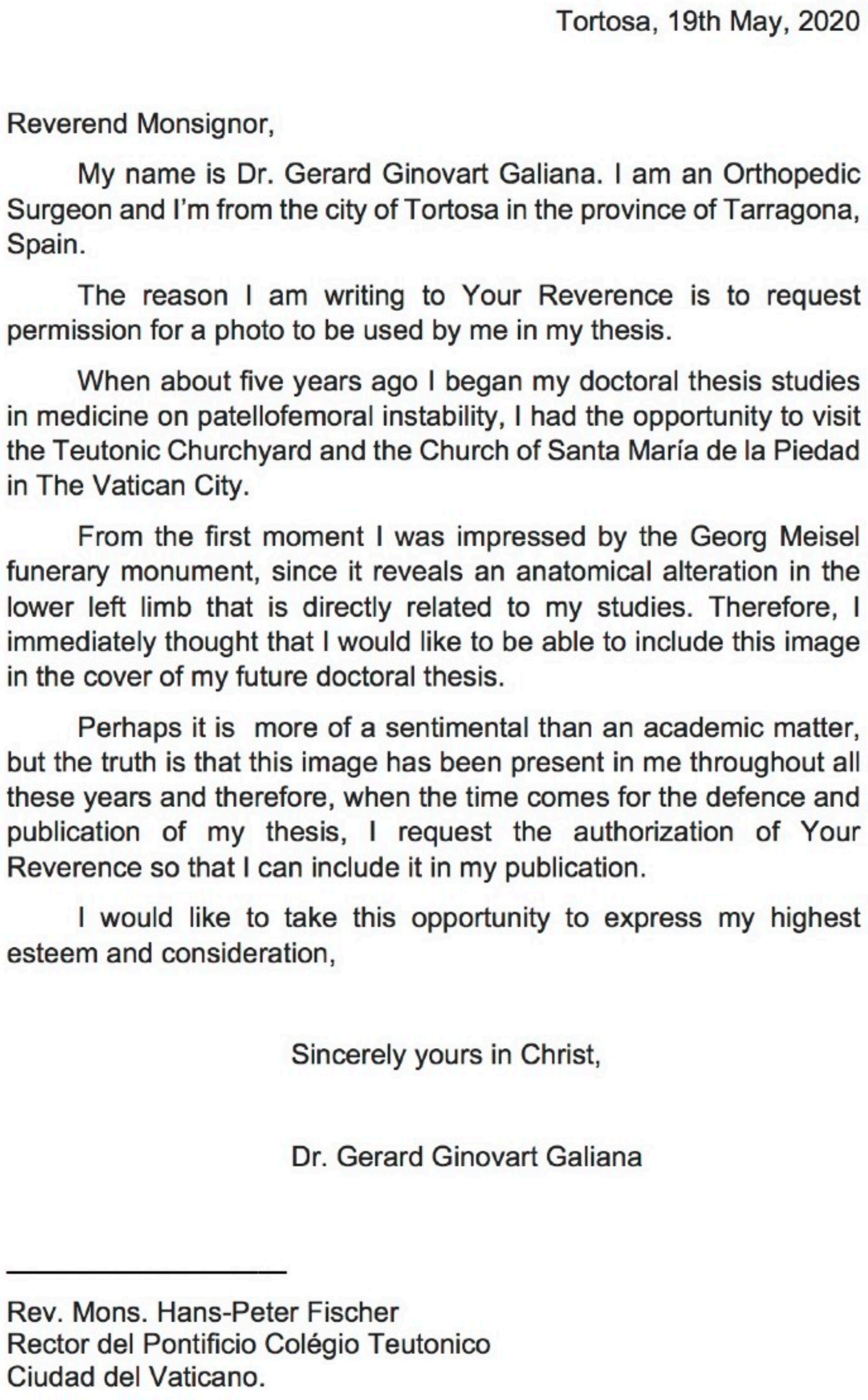
ADDENDUM



Tortosa, 19th May, 2020

Reverend Monsignor,

My name is Dr. Gerard Ginovart Galiana. I am an Orthopedic Surgeon and I'm from the city of Tortosa in the province of Tarragona, Spain.

The reason I am writing to Your Reverence is to request permission for a photo to be used by me in my thesis.

When about five years ago I began my doctoral thesis studies in medicine on patellofemoral instability, I had the opportunity to visit the Teutonic Churchyard and the Church of Santa María de la Piedad in The Vatican City.

From the first moment I was impressed by the Georg Meisel funerary monument, since it reveals an anatomical alteration in the lower left limb that is directly related to my studies. Therefore, I immediately thought that I would like to be able to include this image in the cover of my future doctoral thesis.

Perhaps it is more of a sentimental than an academic matter, but the truth is that this image has been present in me throughout all these years and therefore, when the time comes for the defence and publication of my thesis, I request the authorization of Your Reverence so that I can include it in my publication.

I would like to take this opportunity to express my highest esteem and consideration,

Sincerely yours in Christ,

Dr. Gerard Ginovart Galiana

Rev. Mons. Hans-Peter Fischer
Rector del Pontificio Colégio Teutonico
Ciudad del Vaticano.

Pontificio Collegio Teutonico

Mons. Hans-Peter Fischer
Rettore

Vatican City, 19th May 2020

Dear Dr. Galiana,

let me first thank you for your kind request. I am happy to allow you to use the image of the funerary monument of Georg Meisel for the purpose you told me in your previous letter.

Wish you all the best in your future career.

Best Regards

Hans-Peter Fischer

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Quantitative and Qualitative Analysis of the Medial Patellar Ligaments: An Anatomic and Radiographic Study

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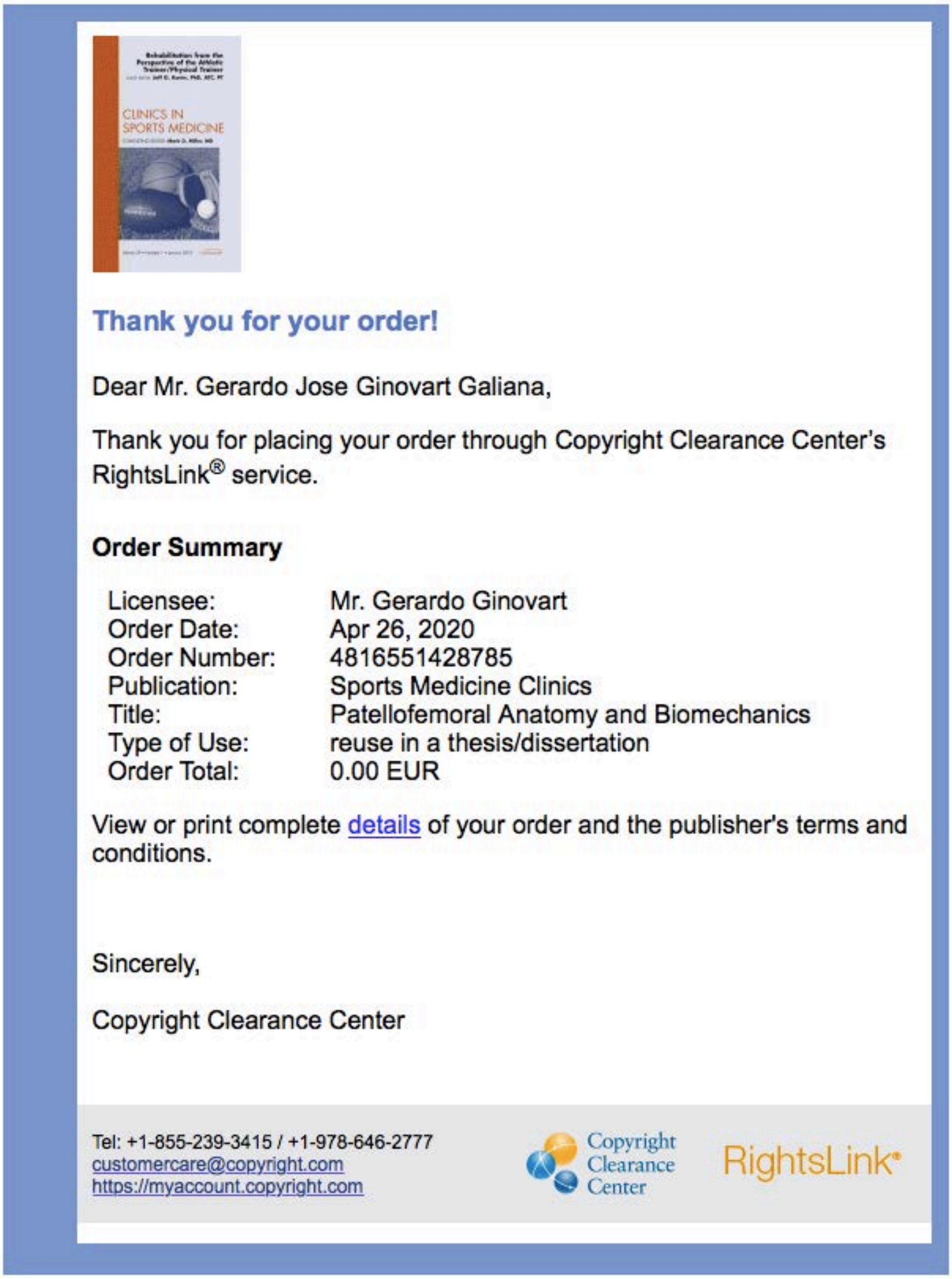

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