Title:

The infrapatellar fat pad is a dynamic and mobile structure which deforms during knee motion and has proximal projections which wrap around the patella

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Abstract (350 words):

Background:

The infrapatellar fat pad (IFP) is a common cause of knee pain and loss of knee flexion and extension. However, its anatomy and behavior are not consistently defined.

Methods:

Thirty-six unpaired fresh frozen knees (mean age: 42 years, range 21-68) were dissected, and IFP attachments and volume measured. The rectus femoris was elevated, suprapatellar pouch opened and videos recorded looking inferiorly along the femoral shaft at the IFP as the knee was flexed. The patellar retinacula were incised and the patella reflected distally. The attachment of the ligamentum mucosum (LMuc) to the intercondylar notch was released from the anterior cruciate ligament (ACL), both menisci and to the tibia via meniscotibial ligaments. IFP strands projecting along both sides of the patella were elevated and the IFP dissected from the inferior patellar pole.

Magnetic resonance imaging (MRI) of one knee at 10 flexion angles was performed and the IFP, patella, tibia and femur segmented.

Results:

In all specimens the IFP attached to the inferior patellar pole, femoral intercondylar notch (via the LMuc), proximal patellar tendon, intermeniscal ligament, both menisci and the anterior tibia via the meniscotibial ligaments. In 30 specimens the IFP attached to the anterior ACL fibers via the LMuc, and in 29 specimens it attached directly to the central anterior tibia. Proximal IFP extensions were identified alongside the patella in all specimens and visible on MRI (medially [100% of specimens], mean length 56mm, laterally [83%], mean length 24mm). Mean IFP volume was 32ml.

The LMuc, attached near the base of the middle IFP lobe, acting as a 'tether' drawing it superiorly during knee extension. The medial lobe consistently had a pedicle superomedially, positioned between the patella and medial trochlea. MRI scans demonstrated how the space between the anterior tibia and patellar tendon ('the anterior interval') narrowed during knee flexion, displacing the IFP superiorly and posteriorly as it conformed to the trochlear and intercondylar notch surfaces.

Conclusion:

Proximal IFP extensions are a novel description. The complex motion of the IFP and its relationship to surrounding structures could have clinical implications. Surgical incisions through the IFP or its resection during arthroscopy could affect these.

Keywords: anatomy, infrapatellar fat pad, Hoffa, structure, knee

What is known about the subject?:

The IFP is the largest soft tissue structure of the knee but little is known about it. Prior reports on IFP anatomy reported small sample sizes, commonly from embalmed specimens, MRI and intra-operatively. The IFP is consistently described to attach directly to the patella, tibia, menisci, inter meniscal ligament and patellar tendon. The anterior interval has previously been defined and measured from MRI scans.

What this study adds to existing knowledge?:

This is the first time that IFP anatomy has been investigated in a large sample of young fresh-frozen cadaveric knees and the IFP motion directly videoed and imaged. Extensions of the IFP proximally around the patella were quantified and its consistent attachment to the intercondylar notch described. A superomedial pedicle between the patella and trochlea was defined for the first time. Furthermore the IFP attachment to the tibia at the anterior interval was not found to be consistently present and its attachment to the anterior tibia was identified to occur via meniscotibial ligaments rather than directly onto the anterior tibial border. These findings have implications for the understanding of this complex structure. A full anatomic understanding of the IFP should aid in the understanding of knee disease and in the management of patients, and suggests that even in simple surgical procedures, such as knee arthroscopy, care to minimize injury to the IFP is merited.

Introduction

The infrapatellar fat pad (IFP) is the largest soft tissue structure in the knee joint, yet reports on it remain sparse and its function is poorly understood. It is situated intracapsularly, between the femoral condyles, tibial plateau and patellar tendon, with its posterior boundary the synovial lined knee joint[15]. Traditionally this deformable pad of adipose tissue was thought to simply occupy unfilled space in the anterior knee, conforming to the changing shape and volume of the articular cavity during joint motion, although it has been speculated that it aidslubrication of the articular surfaces[16, 20]. However, in cases of extreme emaciation when subcutaneous adipose tissue is depleted the IFP is not. Indeed, no relationship between IFP size and body mass has been observed, suggesting a more significant role for the IFP than typical structural adipose tissue[7, 10].

Pressure in the IFP rises significantly near terminal knee flexion and extension, when the volume of the joint cavity is reduced, suggesting that the IFP may have a proprioceptive role[3]. Its excision alters knee joint kinematics and patellar contact pressures, meaning that it may also have a biomechanical role[5]. Studies have found that the IFP is extremely sensitive to pain, and a potent source of stem cells[2, 4, 14, 30]. The former makes it a pain generator, whilst the latter predisposes it to scarring and hence interference with knee motion when it is prevented from deforming normally. Recent research suggests that surgical portals should be modified to help maximize IFP preservation, reduce post-operative pain and minimize scarring during knee arthroscopy[26]. A role in knee osteoarthritis has also been hypothesized[8]. However, the anatomy and behavior of this structure are not fully understood, meaning that interventions for these patients are currently uninformed and therefore often unsuccessful[12].

Prior anatomic descriptions of the IFP were based on small, elderly samples, typically taken from preserved knees, which are static and in extension[1, 15, 17]. In this situation the IFPs are therefore stiff and will not perform as they would in their natural state. Anatomic attachments and characterization of the IFP have also been reported from magnetic resonance imaging (MRI) findings[18, 22, 23] but this method of evaluation does not permit direct visualization and can be impacted by scan parameters. Lastly, it has been visualized directly during arthroscopy[6, 27], however this procedure introduces fluid to the knee, changing the shape of the synovium, again limiting interpretation. The aims of this current work were therefore: to provide a detailed anatomic description for the first time based on dissections from a large sample of young fresh cadavers, and to characterize IFP motion during knee flexion and extension by recording videos down the anterior femoral shaft, alongside segmentation of the fat pad from high quality MRI scans.

Materials and Methods

Following approval from the local Research Ethics Committee, 36 unmatched fresh-frozen cadaveric knees were obtained from a tissue bank. Nineteen were female, eighteen left sided, with a mean age of 42 years (standard deviation=11, range 21-68 years). Specimens with severe patellofemoral osteoarthritis, gross

deformity of the knee or a damaged anterior cruciate ligament (ACL) were excluded. Specimens included 200mm of each of the femur and tibia. The skin and subcutaneous fat were removed, taking care to avoid injury to the medial or lateral retinacula. A method was developed to dissect knees to enable attachments and characteristics of the IFP to be quantified and defined. Where measurements with the IFP in-situ were required photographs were taken and a ruler in the photographs allowed correction of magnification, and ImageJ (National Institutes of Health, Bethesda, Maryland) was used to make photographic measurements.

With the knee in full extension, the superior portion of the rectus femoris (RF) tendon and vastus intermedius (VI) underneath were dissected from adjacent muscles down to the anterior femoral shaft. This incision extended distally to a level 15 mm proximal to the patella. From here incisions 8 mm away from the patella were continued along the proximal half of the patella medially and laterally to partially free the patella (Figure 1). The VI and RF were lifted from the anterior shaft of the femur to expose the complete suprapatellar pouch, which was opened with an incision at its proximal femoral attachment. The patellar retinacula were then incised medially and laterally, maintaining a distance of 8mm from the medial and lateral patellar borders. This allowed reflection of the patella anteriorly and distally, enabling clear visualization of its posterior surface and the IFP. Photographs and videos of the IFP were then recorded looking distally along the femoral shaft as the knee was flexed allowing qualitative characterization of the IFP whilst the quadriceps was manually tensioned.

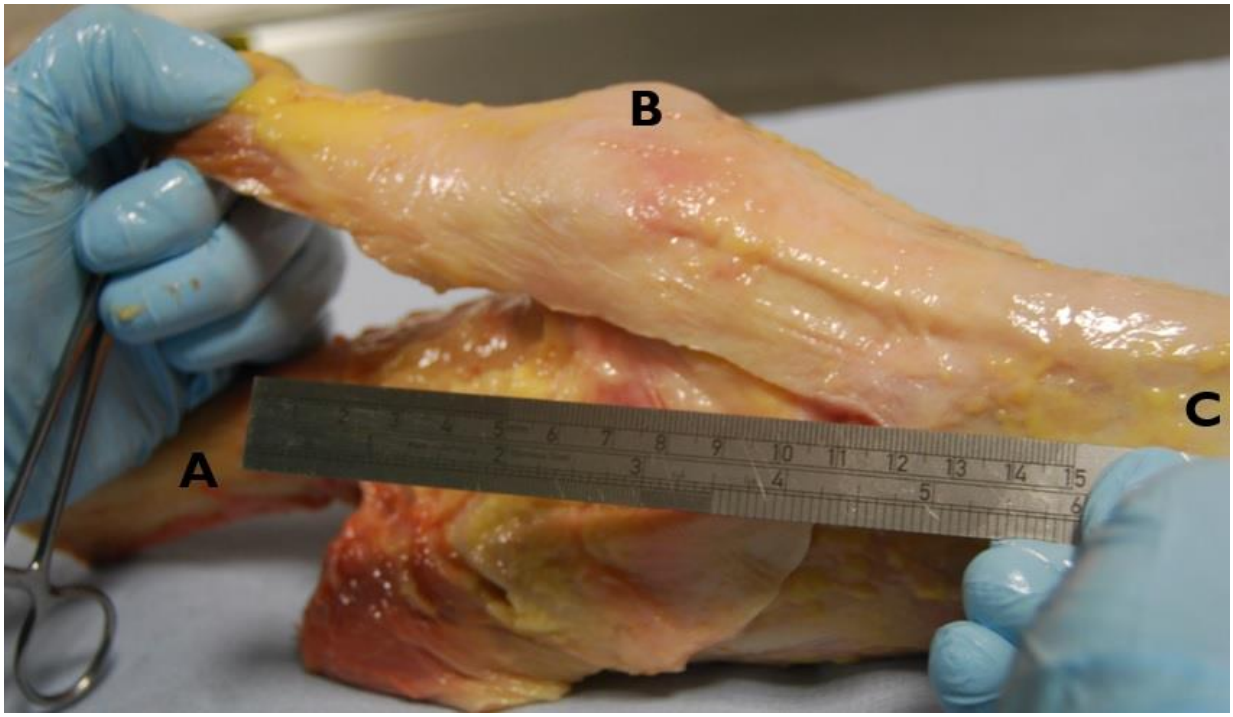


Figure 1: Skin and subcutaneous fat are dissected from the knee and the VI and RF elevated, suprapatellar pouch opened and medial and lateral patellar retinacular incisions enable the patella to be elevated. A: Femur, B: Patella, C: Tibia.

Superficial incisions were made medially and laterally along the length of the patellar tendon, taking care not to damage the anterior IFP below (Figure 2). The total length of the patellar tendon and the length of

IFP adherence to it were recorded. The distal attachment of the patellar tendon was bluntly dissected from the tibial tuberosity and the adherence of the IFP to the posterior proximal patellar tendon carefully released up to the inferior base of the patella. The iliotibial band (ITB) was elevated from Gerdy's tubercle to enable visualization of the lateral IFP. The IFP was observed to extend from lateral (just anterior to the lateral collateral ligament (LCL)) to medial (just anterior to the medial collateral ligament (MCL)) (Figure 3).

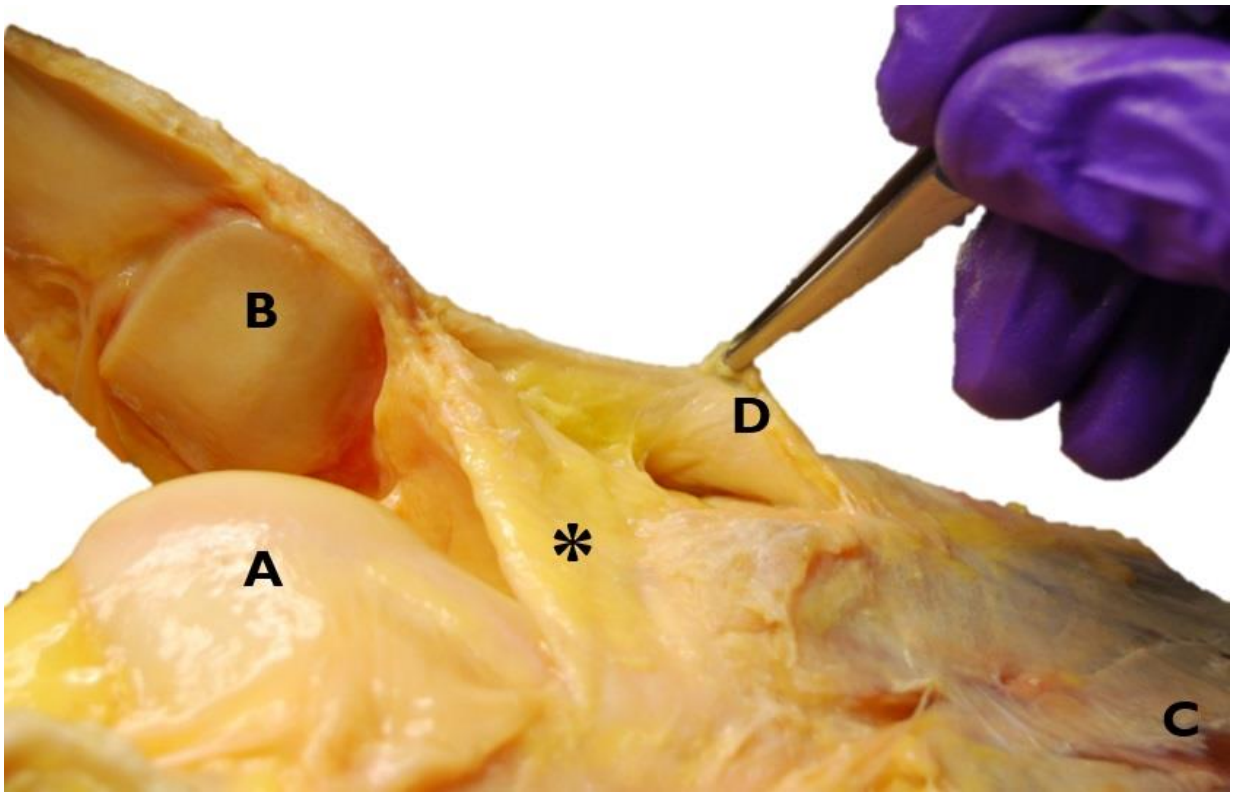


Figure 2: Patellar tendon elevated to expose posterior surface. The IFP was adherent to the proximal part of the tendon but not the distal third. *: IFP, A: Femur, B: Patella, C: Tibia, D: Patellar Tendon

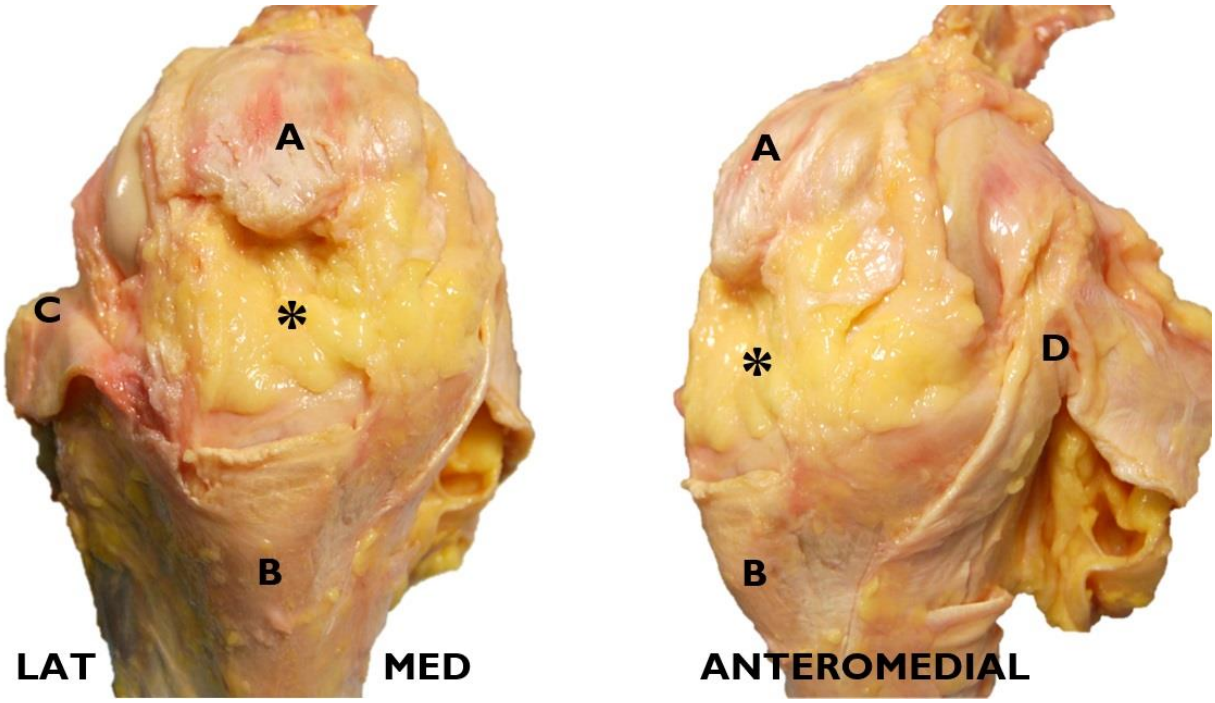


Figure 3: Left: anterior view of the knee in 60 degrees of flexion with the patellar tendon removed and the ITB elevated distally (C) and the medial and lateral retinacula removed, Right: anteromedial view of the same specimen. The IFP can be seen to extend from the MCL medially to the LCL laterally. Proximally it attaches to the inferior pole of the patella. *: IFP, A: Patella, B: Tibia, C: ITB and D: MCL.

Knees were flexed fully and the patella reflected anteriorly and distally. Attachment of the ligamentum mucosum to the femoral intercondylar notch and the anterior fibers of the anterior cruciate ligament (ACL) was recorded and released when present (Figure 4). This enabled full reflexion of the patella to rest anterior to the tibia.

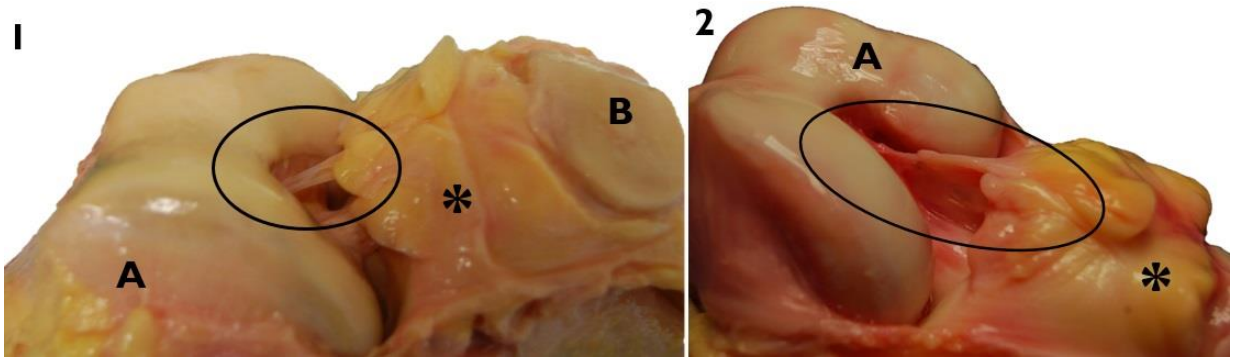


Figure 4: 1: Lateral view showing the IFP attachment to the top of the femoral intercondylar notch. 2: Separate specimen lateral view showing the IFP attached to the femoral intercondylar notch and adhering down the anterior fibers of the ACL. *: IFP, A: Femur, B: Patella.

With the knee in deep flexion, the most posteromedial attachment of the IFP to the medial meniscus was identified and the meniscus incised at this point. The meniscus and IFP were elevated and the IFP remained

indirectly attached to the anterior tibia via the meniscotibial ligaments (Figure 5). The lateral meniscus was similarly incised at the most lateral IFP attachment and the central attachments of the IFP to the anterior horns of both menisci were bluntly released. In some specimens this allowed the patella, IFP and attached medial and lateral menisci and transverse intermeniscal ligament to be completely freed from the femur and tibia. However in some specimens the IFP was adherent to the 'anterior interval' (the space between the patellar tendon anteriorly and the anterior border of the tibia and the transverse intermeniscal ligament posteriorly, which is filled by the IFP close to full knee extension)[27] (Figure 5) and when present this attachment was also released.

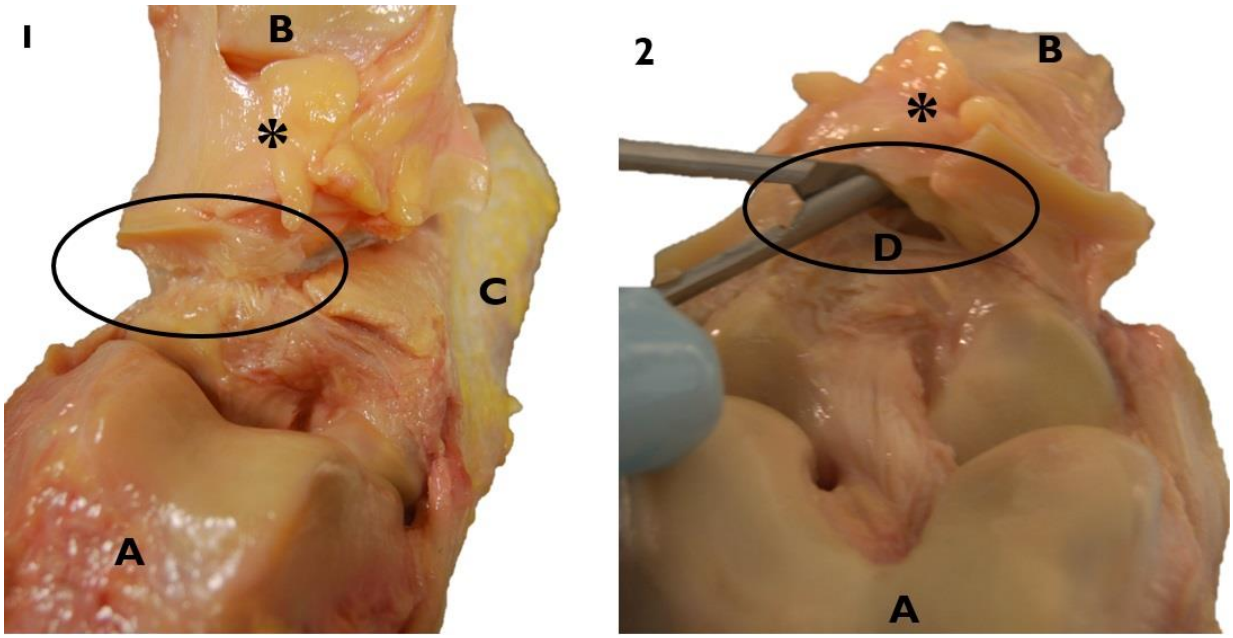


Figure 5: View from proximal to distal looking down the anterior shaft of the femur: 1: Showing the attachment of the IFP to the lateral meniscus and the attachment of the lateral meniscus to the anterior tibia via the meniscotibial ligament. 2: Showing a knee where there was no adherence of the IFP to the anterior tibia centrally at the interval. *: IFP, A: Femur, B: Patella, C: Tibia, D: circled the anterior central tibia where the IFP was not consistently adherent.

The IFP was then inspected to determine the presence of patellar extensions from the IFP projecting along the medial and lateral sides of the patella. These extensions were dissected from the medial and lateral retinacula whilst their distal attachment to the IFP body was maintained (Figure 6). With the IFP placed on the bench with its posterior (inner) surface facing upwards, the width of the fat pad from medial to lateral and the length and width of the patellar extensions were recorded. Where a complete loop of IFP extension was formed around the whole patella, each side was measured from its base to the midpoint of the proximal attachment. The length of direct meniscal attachments to the IFP was measured and the menisci then removed along with the transverse intermeniscal ligament. Finally, the IFP volume was recorded with a 500 ml measuring cylinder containing water using volumetric displacement.



Figure 6: Showing a two dissected IFP from left knees looking from a posterior to anterior view. A clear extension from the main IFP body can be observed which extending up to wrap around the patella. Complete loops of the IFP around the whole patella were identified in 11% of specimens. The IFP was formed into three lobes: 1: lateral lobe, which articulated with the lateral femoral condyle, 2: central lobe, with attachment into the femoral intercondylar notch and 3: medial lobe, which articulated with the medial femoral condyle.

One of the knees was scanned in a 3T MRI scanner (Siemens) in 10˚ increments from 0˚-110˚ knee flexion. A modified Dixon protocol[11] was implemented. Sagittal voxel sizes were set to approximately 0.47mm and slice thicknesses were 3mm. Separate models of the tibia, femur, patella and infrapatellar fat pad (Figure 7) were then generated by semi-automatically segmenting the MRI data using MIMICS® (version 16.0; Materialise NV, Leuven, Belgium). The image segmentation was undertaken by an engineer with prior background in image processing and segmentation of CT and MRI scans, under the supervision of an orthopedic consultant specialized in knee surgery. The software calculated the volume of the segmented IFP, and the angle of the anterior tibia to the posterior aspect of the patellar tendon was recorded to determine the change in the anterior interval angle[13].

Finally one knee was dissected and the medial meniscus removed to enable a medial view of the IFP to be recorded during knee flexion and extension. This enabled direct visualization of the reduction in the anterior interval during knee flexion[13] to be directly observed. Due to the different dissection method this knee was not included in the main findings.

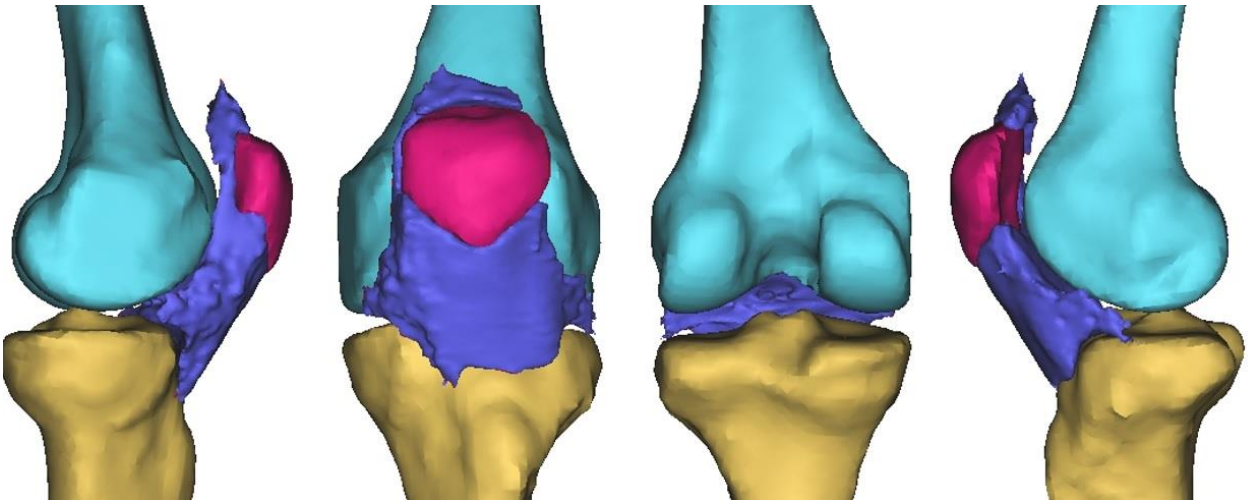


Figure 7: Segmented MRI scan of a left knee in full extension. From left to right: medial view, anterior view, posterior view and on the right, the lateral view. The segmented femur (blue), tibia (yellow), patella (pink) and IFP (purple).

Results

Dissection

All knees met the inclusion criteria and the IFP was present in all knees. At its widest part (distance between its attachment anterior to the MCL to anterior to the LCL) the IFP was 69±10mm (mean±SD), with a volume of 29±6ml. Only one direct bony attachment, to the inferior pole of the patella, was identified in all specimens. The IFP also attached to both the roof of the femoral intercondylar notch via the ligamentum mucosum and the anterior tibia indirectly via the meniscotibial ligament attachments from both menisci in all 36 specimens. Other consistent attachments were the intermeniscal ligament, medial meniscus (mean attachment length = 21mm) and lateral meniscus (mean attachment length=25mm). The IFP was adherent to the proximal 2/3 of the patellar tendon. In 83% of specimens it attached to the anterior ACL fibers via the ligamentum mucosum. It attached to the tibia via the meniscotibial ligaments in all specimens and was found to be adherent to the central anterior tibia, posterior to the patellar tendon, in 80% of specimens, but free in the remaining specimens.

Proximal extensions of the IFP were identified alongside the patella in all specimens and were visible on MRI from the scanned specimen. They were present medially in all specimens with a mean length of 56mm. They were shorter (mean length = 24mm) and only present in 83% of specimens on the lateral side of the patella. IFP extensions, which formed a ring that completely surrounded the patella, were identified in 11% of specimens. Small extensions from the medial lobe of the IFP were identified in all specimens, these were previously defined as pedicles and were positioned between the base of the patella and medial trochlea. They measured 8±2 mm in width and in 39% of specimens the edges were visibly frayed, occurring in specimens over the age of 40 and in all specimens there were some signs of chondral damage.

Videos

Videos were recorded of the superomedial pedicles during knee flexion and demonstrated how they are positioned between the base of the chondral covered patella and the trochlear groove (Video 1).



Video 1.mp4

Video 1: Looking distally along the anterior shaft of the tibia at the IFP from superior to inferior. The tibia is fixed in position on a bench and the femur flexed and extended from 0°-120° with the quadriceps elevated to enable IFP visualization.

A second video demonstrates how the fat pad fills the space between the patellar tendon anteriorly and the anterior border of the tibia and the transverse intermeniscal ligament posteriorly, ('the anterior interval'), during knee extension. The interval is then 'emptied' with the IFP moving into the back of the knee during full knee flexion (Video 2).



Video 2.MOV

Video 2: Viewed from medial to lateral at the IFP with the femur fixed, and the tibia flexed around it. The medial meniscus is removed to improve visualization. The IFP can be seen to fill down behind the patellar tendon in knee extension and move out of the anterior interval during knee flexion.

MRI Imaging

The IFP patellar strands were identified and defined on the MRI scans (Figure 8). The volume of the IFP measured from the dissected IFP was 44ml, and the volumetric from the MRI calculation 41ml, meaning the accuracy of segmenting the IFP had a 6% error.

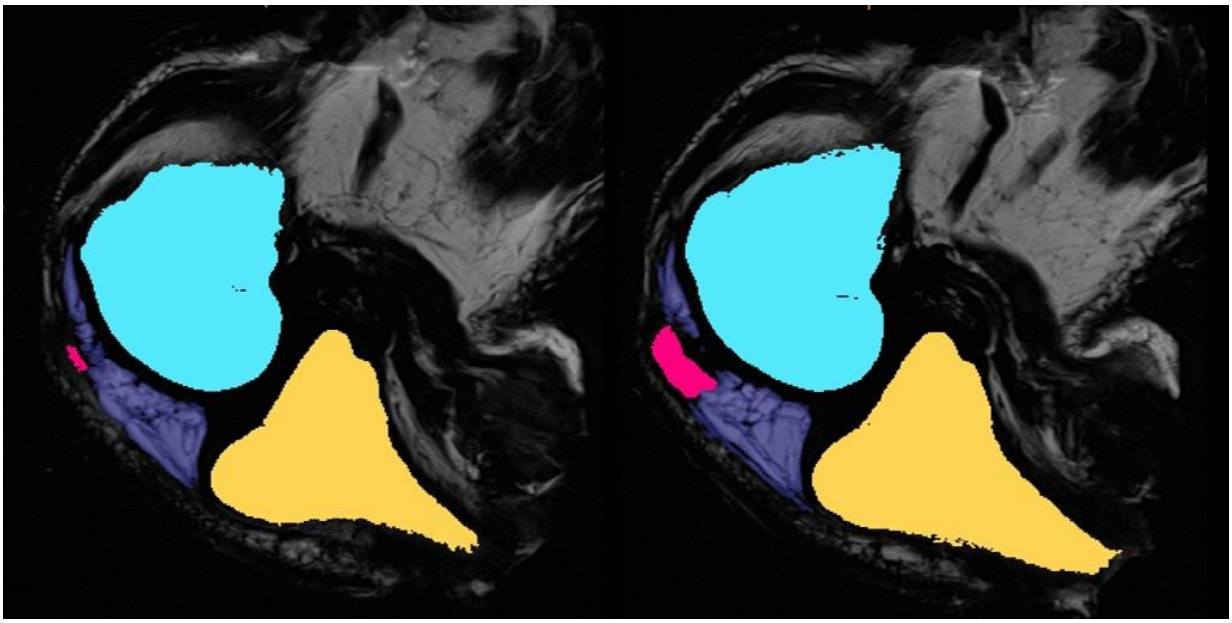


Figure 8: MRI scans from a knee flexed at 120° with the femur (blue), tibia (yellow), patella (pink) and IFP (purple) segmented at different sagittal slices (left most medial slice), to demonstrate the ability to identify the proximal patellar IFP strands medially wrapping round the patella.

At 0° knee flexion the anterior interval was 37°, decreasing to 8° at 120° of knee flexion. The segmented images were made into a movie (Video 3), by taking the same sagittal slice from scans taken at different flexion angles. This further demonstrates the deformation undergone by the IFP during knee motion.

Video 3.wmv

Video 3: An animation showing IFP deformation from the segmented MRI scans during movement through 0°-120° flexion, played on a loop. On the left the IFP has been segmented on its own and on the right, with the tibia (blue), patella (pink), and tibia (yellow).

Discussion

This study has for the first time defined IFP anatomy and behavior in young, fresh cadaveric specimens, with findings conflicting with prior reports from embalmed specimens. Firstly medial and lateral patellar IFP projections were identified and quantified. The presence of a consistent pedicle extending from the medial IFP lobe, positioned between the distal patella and medial femoral condyle during motion, is described. The precise morphology of the IFP was varied, however three consistent lobes were evident (Figure 6)[15]. These related to the anatomic structures against which they contacted during knee motion: the medial and lateral lobes corresponding to the respective femoral condyle, whilst the central lobe is tethered at its base by the ligamentum mucosum to attach proximally into the roof of the intercondylar notch, thereby meaning that it sweeps along and conforms to the changing shape of the central trochlear

groove as the knee extends. The lobes in turn exhibit a range of pedicles. Pedicles have been previously described, although not consistently, in anatomic descriptions[15, 16]. The most consistent of these was a small extension from the lateral border of the medial IFP lobe which extended centrally, which was observed to be positioned between the base of the patella and the trochlea through motion (Video 1). With aging specimens there was a trend to observe fraying at the edges of the pedicles, which could support a recent hypothesis that IFP changes occur with aging and osteoarthritis[8]. This is an area which merits further investigation.

Proximal peripatellar extensions of the IFP have been described previously, but not quantified[21]. Medial extensions were present in all knees in this study, commonly terminating into the suprapatellar fat pad, and on four occasions forming a complete loop around the patella. These were identifiable as fat on the MR images (Figure 8). Medial patellar border pain is a common clinical complaint, with synovial plicae described and often excised to address these symptoms[24]. However, the current findings suggest that pain in this region could actually derive from the IFP extensions, since the IFP is known to be a highly pain sensitive structure[14]. The proximal IFP strands commonly terminated in the suprapatellar fat pad which, inserts into the deep quadriceps muscle, the genu articularis[31]. Thus the deep quadriceps attachment may help to ensure that the IFP is drawn up against the trochlea preventing IFP impingement between the femur and patella during knee motion. This may be one reason why quadriceps strengthening is reported to benefit patients with patellofemoral pain[9]. The intimate and precise relationship of the IFP to its adjacent structures means that it is vulnerable to impingement. This leads to swelling and ever increasing susceptibility to more impingement. This is most frequent with the supero-lateral IFP and especially occurs in knees with abnormally high-riding patellae (patellar alta). An overly tight ilio-tibial band (ITB) may further contribute. A recent report suggests that good symptomatic relief may be obtained with injection of botox into the tensor fascia lata muscle at the hip to de-tension the ITB[28].

The lack of a direct attachment of the IFP to the anterior tibia but instead an indirect link via the meniscotibial ligaments has been described. Adherence of the IFP to the central anterior tibia at the anterior interval[27] was present in most, but not all specimens. The lack of direct attachment between the IFP and anterior tibia presumably aids IFP motion in and out of the anterior interval. The behavior of the anterior interval was captured by MRI to show it filling with IFP in extension, as the patellar tendon (PT) angled anteriorly, and then emptying of IFP during knee flexion as the PT swung back against the anterior aspect of the tibia. Finally, videos and MRI scans demonstrate the impressive and complex IFP deformation which occurs as it is drawn up to run over the femoral condyles during knee extension. The attachment of the ligamentum mucosum from the base of the central IFP lobe extending to the roof of the femoral intercondylar notch guides it up the trochlea during knee extension. This is a complex and dynamic mechanism, which is required to occur frequently and rapidly as the knee extends, for example during walking. It would therefore be vulnerable to interference such as from trauma or repetitive overload induced swelling, or scarring. It is recognized that fibrosis leads to abnormal functioning of adipose tissue[29],

and therefore may inhibit normal IFP functioning. Furthermore increased IFP fibrosis has been linked to degenerative changes in the PFJ following ACL surgery[32]. Given that this trauma is often surgical and in the light of the further knowledge regarding the IFP, it may be appropriate that surgeons should learn to minimize injury to the fat pad at surgery.

Attachment between the IFP and ACL, either via the ligamentum mucosum or directly to the anterior fibers of the ACL, was observed in all knees. This was more consistent than prior reports, likely due to the nature of the fresh tissue making it easier to identify, or it may reflect the younger population examined and that ACL injured specimens were excluded[12, 15]. How important the ligamentum mucosum is can be challenged, as it is frequently noted to be absent at arthroscopic surgery and surgeons will frequently divide it to improve access to the joint in arthroscopy of the knee. A significant correlation between ACL tear and alteration in IFP appearance, most commonly focal edema, has been reported based on MRI observations[1]. Histological analysis in sheep following ACL reconstruction revealed increased cellularity, vascularity and innervation present in the IFP at 2 and 20 weeks post-surgery[25]

The MRI sequence and cadaveric video demonstrate the deformation of the IFP and narrowing of the anterior interval during flexion from 37° to 8°. In extension it is clear that the IFP is compressed by the anterior femur and tibia, the anterior horns of the menisci, and the intermeniscal ligament. A prior report supports this, with the finding of a rise in IFP pressure in knee extension[3]. This may help to explain why patients with fat pad impingement typically dislike standing when the knees need to be straight. Pacinian corpuscles have previously been identified in the IFP, these are nerve endings responsible for detecting pressure, and help affirm the proprioceptive role of the IFP[19]. The lack of adherence of the IFP to the central anterior tibia, previously described, was identified in some specimens, however not all. We hypothesize that scarring and adherence of the IFP at the anterior interval may instead be a pathological change, which is known to result in joint stiffness and often necessitate surgical intervention[27]. Finally the strong investment of the IFP into the medial and lateral menisci was evident. In particular, given the significant posterior motion of the anterior meniscal horns, especially laterally, as the knee is flexed, the IFP is seen to be pulled posteriorly into the joint with the meniscus. Scarring of the fat pad to the anterior meniscal horns will bind the latter and reduce flexion. A more troublesome problem is fixed flexion. A block to extension will arise if the fat pad is scarred to such an extent that it cannot allow normal soft tissue motion in the region of the anterior interval. This may cause loss of motion of the anterior horns of the menisci and / or a physical block to the antero-distal femoral surfaces that close down the anterior soft tissue space in knee extension. In normal knees as a patient undertakes an isometric quadriceps contraction to force the knee into extension two bulges due to IFP prominence are visible, either side of the patellar tendon. As the knee flexes these disappear to be replaced by ‘depressions’ resulting from migration of the IFP out of the anterior interval into the intercondylar region. Deeper flexion will compress the IFP resulting in the recurrence of the bulges either side of the tendon. In those cases with IFP-related loss of knee motion the fat pad will feel hard and stiff to palpate and often the examiner’s ability to push

the patella medially and laterally is abnormally reduced. In these cases the IFP is unable to deform freely and allow change in IFP position and shape, which is essential during knee motion.

This study has some limitations. In order to visualize the IFP it was necessary to open the PFJ superiorly to record videos, and the quadriceps had to be passively tensioned, and the joint opening would have affected joint pressure and therefore possibly IFP behavior. The MRI scans were taken prior to any dissection. However as the knees were sectioned through the mid femoral shaft the quadriceps tension was reduced. The quadriceps muscles were tensioned using bands sutured to the muscles and a screw in the femur during scanning. However it is likely this differed from the knee function which would be observed *in vivo*.

This paper defines the impressive complexity of the IFP structure, quantifies its anatomic attachments in young fresh specimens for the first time, with new findings reported, and performs a preliminary investigation into its dynamic behavior. These findings support a role for it as more than a structure simply to fill dead space in the anterior knee, rather they provide support for it to have a proprioceptive role, its great importance in knee motion, and a possible role in healing. Increased awareness and understanding of this structure may help surgeons to minimize damage to it during routine surgical knee procedures such as knee arthroscopy, ACL reconstruction or menisectomy, when portal placement may be modified to minimize IFP damage and avoid scarring. Further research is required to further investigate and understand this complex and likely underappreciated structure.

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