

The knee in full flexion

AN ANATOMICAL STUDY

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There has been only one limited report dating from 1941 using dissection which has described the tibiofemoral joint between 120° and 160° of flexion despite the relevance of this arc to total knee replacement. We now provide a full description having examined one living and eight cadaver knees using MRI, dissection and previously published cryosections in one knee.

In the range of flexion from 120° to 160° the flexion facet centre of the medial femoral condyle moves back 5 mm and rises up on to the posterior horn of the medial meniscus. At 160° the posterior horn is compressed in a synovial recess between the femoral cortex and the tibia. This limits flexion. The lateral femoral condyle also rolls back with the posterior horn of the lateral meniscus moving with the condyle. Both move down over the posterior tibia at 160° of flexion.

Neither the events between 120° and 160° nor the anatomy at 160° could result from a continuation of the kinematics up to 120°. Therefore hyperflexion is a separate arc. The anatomical and functional features of this arc suggest that it would be difficult to design an implant for total knee replacement giving physiological movement from 0° to 160°.

The arc of flexion of the knee from 120° to 160°, which we term 'hyperflexion' and which is analogous to hyperextension, has two features which distinguish it from lesser degrees of flexion. First, there is cessation of active flexion at 120° because the hamstring muscles lose their mechanical advantage^{1,2} and secondly the medial femoral condyle rolls posteriorly^{3,4} which does not occur up to 120°. ^{3,5,7} The peculiarity of this part of the flexion arc and the relative positions of the femur and tibia in full flexion have been described using radiographs,^{8,9} MRI^{3,4,10} and robotics¹¹ which have shown that in full flexion the femur is externally rotated and moves backwards relative to the tibial plateau. However, there has been only one report based on dissection which in part describes the anatomy at 160° of flexion.¹²

In order to complete a description of this arc, we now describe the posterior compartment of the knee from 120° to full flexion using dissection and MRI. We address four questions: 1) What is the anatomy of the knee in full flexion? 2) How does the femur move between 120° and 160°? 3) What structure limits flexion? and 4) Can the relative position of the tibia and femur at 160° be achieved by a continuation of their movements up to 120° of flexion? The answers to these questions have

implications for the design of total knee prostheses aimed at achieving hyperflexion. If there is a separate arc, it would be difficult to mimic movement in this arc with designs based on lesser degrees of flexion.

Materials and Methods

Dissections were performed on eight knees (five fresh-frozen and three preserved) cadavers. All were skeletally mature, normal Caucasian specimens. Photographs of one cadaver knee were re-examined. This knee had been frozen in full flexion previously at -80°C in liquid nitrogen, sectioned and photographed.⁴ Additionally, MRI was performed on one volunteer with normal knees.

MR scans were obtained of the five fresh-frozen cadaver knees and one living knee using a Gyroscan MRI scanner (Philips Medical Systems, Eindhoven, The Netherlands). The cadaver knees were positioned at various angles up to full flexion on a wooden board as previously described.⁶ Multistack sagittal slices were obtained and reconstructed in the other two planes using various sequence parameters since the signals generated by once-frozen cadaver knees vary among themselves and differ from those generated by the same sequences in living knees.

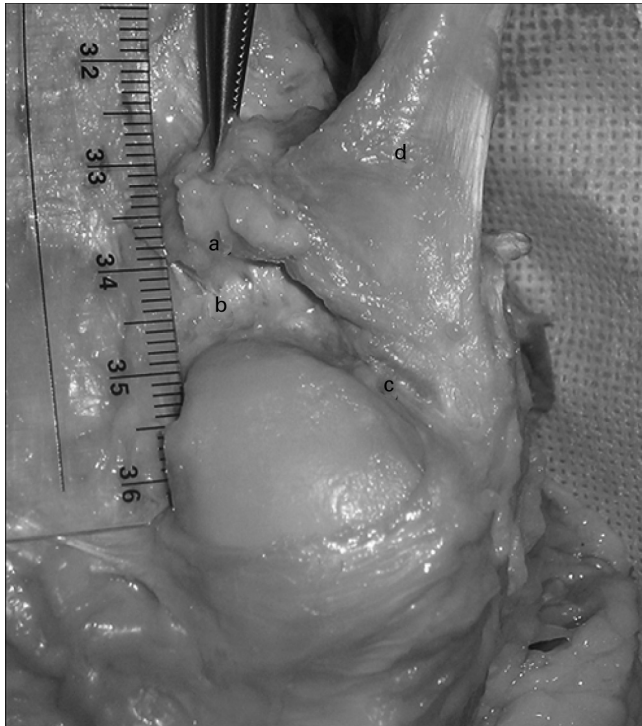


Fig. 1

Photograph of the posterior aspect of the medial femoral condyle (left knee) partially dissected (a, subsynovial fat pad in the retracted/everted lateral half of the capsule; b, the posterior horn space; c, reduced space between the articular cartilage and the medial half of the capsule; and d, fused capsule and the tendon of the medial head of gastrocnemius turned proximally).

Results

The medial tibiofemoral compartment. The medial femoral condyle and its capsular attachment were examined. The posterior edge of the femoral articular cartilage is asymmetrical mediolaterally. The lateral half of the cartilage extends further superiorly and anteriorly than the medial half in the direction of the femoral shaft (Fig. 1).

Towards the intercondylar notch, the capsule is attached to the femur 10 mm from the apex of the articular cartilage forming a synovial pocket beyond the articular surface as illustrated by Pernkopf.¹³ In the fully flexed knee this space contains most of the posterior part of the posterior horn of the medial meniscus. We have therefore called it the posterior horn space. The proximal half of the posterior horn space is filled by a subsynovial fat pad (Fig. 1) which can be seen on MRI. Between the fat pad and the apex of the articular cartilage the femur is covered by a layer of synovium (Fig. 1).

Tibiofemoral movement from 120° to 160° was measured in four cadavers using MRI to determine the position of the medial and lateral flexion facet centres relative to the posterior borders of the tibia.⁶ The mean radius of the medial femoral condyles in these knees was 2 mm less than that in the six cadaver knees previously reported.⁶ The results are shown in Figure 2, with and without adjustment

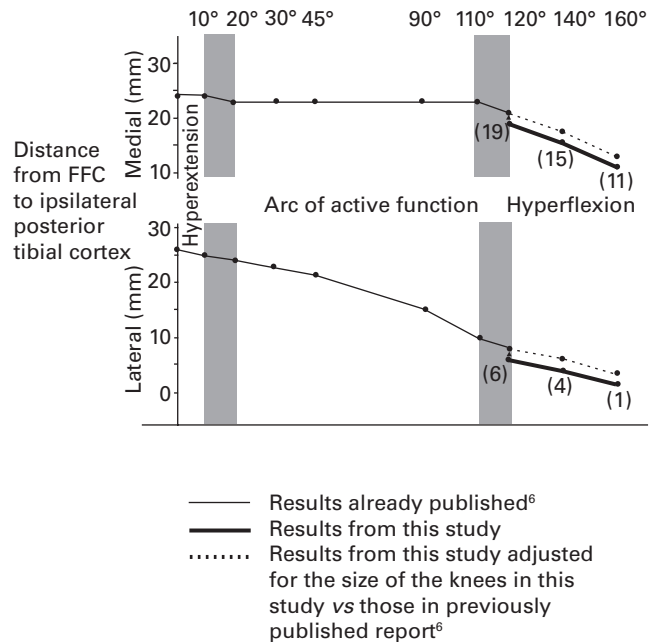


Fig. 2

Graph showing the distance from the flexion facet centre (FFC) to the ipsilateral posterior tibial cortex with increasing degrees of flexion (figures in parentheses show the distance for the six points in this study).

for the size of the femoral radii. The medial femoral condyle moved back 8 mm and the lateral 5 mm resulting in slight femoral internal rotation from 120° to 160°. In one cadaver approximately 5° of tibial longitudinal rotation could be obtained at 160°. As it moved posteriorly, the femur rolled up on to the posterior horn of the medial meniscus and in some knees displaced it until the border was up to 2 mm posterior to the tibia.

Resistance to flexion. This was measured in three cadaver knees by fixing the tibia and then flexing the femur through a digital compressive force meter applied to the femur at a known distance from the axis of rotation to 120°, 140° and 160°. A small flexion moment of 1.3 kg/cm was required to flex one knee to 120°. The other two knees flexed without measurable force. A flexion moment of approximately 6 kg/cm was required to flex the three knees to 140°. No meaningful measurement of resistance could be made at 160° since further flexion was impossible, but up to 60 kg/cm could be applied. Resistance to flexion was probably due to intracapsular structures, rather than to the compression of extracapsular tissues, since no pressure was felt by a finger placed in the popliteal fossa in full flexion with all the musculature present. It is not our contention that the moments could be measured exactly. They were recorded to illustrate that increasing resistance to flexion was encountered between 120° and 160°.

The medial meniscus. At 140° the posterior border reached the posterior extremity of the femoral articular cartilage (Fig. 3). Between 140° and 160° the posterior horn passed

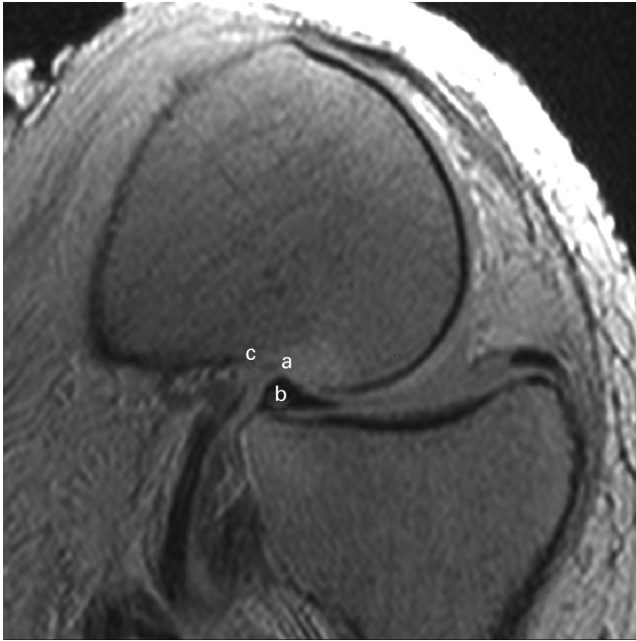


Fig. 3

Sagittal MR scan through the medial compartment at 140° of flexion (a, the posterior extremity of the articular cartilage; b, the posterior horn of the meniscus; and c, the posterior horn space).

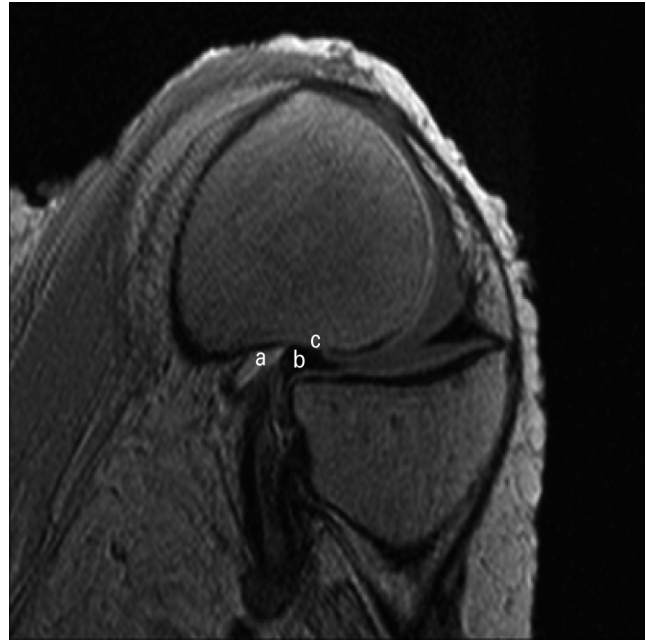


Fig. 4

MR scan through the medial compartment at 160° of flexion (a, subsynovial fat pad (see Fig. 1); b, the posterior horn in contact with the floor of the posterior horn space superiorly; and c, the posterior extremity of the articular cartilage).

over the edge of the articular cartilage to cover an increasing area of the floor of the posterior horn space. At 160° it reached the subsynovial fat pad described above (Fig. 4).

Flexion to 160° has two effects. First, the posterior horn of the medial meniscus is compressed between the tibia and the floor of the posterior horn space by approximately 15% of its height as illustrated previously by Brantigan and Voshell¹² (Fig. 4). Secondly, the femur pivots over the compressed posterior horn so that its distal articular surface lifts about 2 mm away from the tibia (Fig. 4).⁴ The findings on dissecting the ligaments suggested that further separation of the femur from the tibia was limited by the anterior superficial part of the medial collateral ligament (MCL).

In summary, at full flexion the medial femoral condyle did not touch the tibia directly. Posteriorly, the bones were separated by the compressed posterior horn of the medial meniscus in the posterior horn space. Anteriorly, the femur lifted away from the tibia. The capsule was attached 10 mm from the edge of the femoral articular cartilage providing space for the posterior horn and for the synovial fat pad in full flexion.

The lateral tibiofemoral compartment. On the femoral side there are two anatomical differences between the lateral and medial compartments. The posterior edge of the lateral cartilage is symmetrical mediolaterally and the capsule is attached close to its border.

On the tibial side the capsule is attached up to 15 mm distal to the joint line down the posterior and posterolateral tibia. The resulting synovial space (the popliteal recess) is divided

transversely by the popliteal tendon about 5 mm below the tibia plateau. Above this the articular surface is potentially available to the posterior horn of the lateral meniscus which rotates around the posterior border of the tibia at full flexion (Fig. 5). The femoral condyle lies in contact with the tibia immediately above the posterior horn. It was not possible to determine the limitation of downward movement of the posterior horn produced by the tendon of popliteus.

At full flexion the flexion facet centre was 1 mm anterior to the posterior tibial cortex in five cadaver MRIs. (Fig. 2). It also descended 2 mm relative to the tibial plateau in comparison with its level in mid-flexion.³

The ligaments. In full flexion the posterior cruciate ligament (PCL) is orientated approximately as an upward extension of the posterior tibial cortex and its femoral end lies against the roof of the intercondylar notch. The curvature of the PCL as seen in sagittal MR scans is reversed from one which is posteriorly convex in lesser degrees of flexion to one which is about 50° concave posteriorly as the ligament curves around the posterior extremity of the roof of the intercondylar notch.¹⁴

The anterior cruciate ligament (ACL) lies at 60° to the PCL, passing across the tibia between the tibial spines.

The anterior superficial and deep parts of the MCL appeared to be taut when their tensions were tested with traction applied through a thread (Fig. 6). Therefore they would resist the tibiofemoral separation mentioned above. The posterior oblique portion of the MCL and the lateral collateral ligament were slack in full flexion.



Fig. 5

MR scan of the lateral compartment in full flexion in the volunteer (a, contact area; b, the posterior horn; and c, the popliteus tendon; FFC, flexion facet centre).

Valgus-varus movement in full flexion was measured in sagittal MRIs of one volunteer whose knee was fully flexed and stressed manually into tibial valgus and varus. No movement was detected on valgus stress, but the lateral compartment opened 10 mm under varus stress. These findings would be expected from the observed tensions in the collateral ligaments.

Discussion

Standard texts do not describe the anatomy of the knee in full flexion. This description has now been provided by means of dissection and MRI.

From our investigation it was possible to understand how the femur moved relative to the tibia between 120° and 160° of flexion. By 120° the medial femoral condyle starts to roll backwards. This is a distinguishing feature of the arc of hyperflexion. At 140° the femur moves up on to the posterior horn of the medial meniscus. This may be responsible for the resistance to flexion at this point and beyond. By full flexion the medial femoral condyle has moved back approximately 8 mm from its position at 120° to a position 10 mm from the posterior tibial cortex. At this point the superior surface of the posterior horn of the meniscus has moved beyond the posterior border of the femoral articular cartilage to articulate with the femoral cortex in the posterior horn space. In this position it is compressed between the tibia and the femur. In turn, the femoral articular surface is forced away from the tibia anteriorly so that the femur and tibia are not in direct contact. Proximally, the posterior horn impinging against the

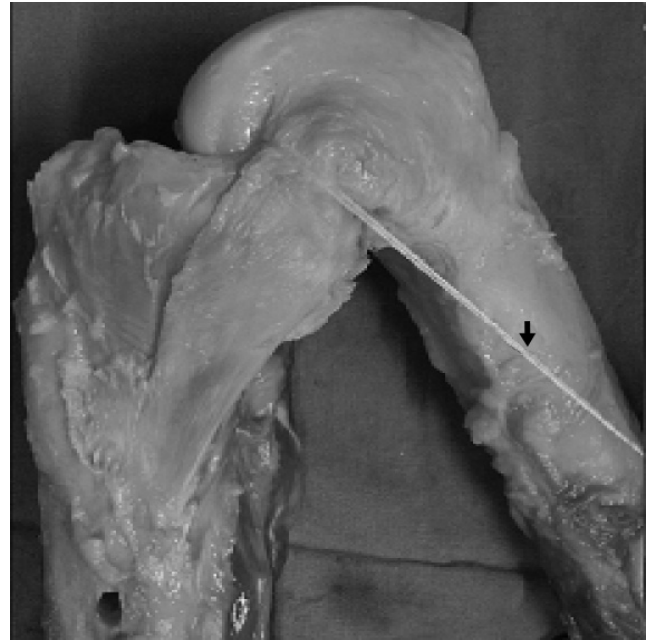


Fig. 6

Photograph showing the medial collateral ligament in full flexion with traction through a thread (arrow) on the superficial and deep portions of the ligament. The ligament is not deflected, demonstrating that it is taut.

synovial fat pad adjacent to the femoral attachment of the capsule. The cause of the posterior movement of the medial femoral condyle from 120° to 160° is not clear. The curvature and attachment separations of the PCL suggest that tension in this ligament is not responsible.¹⁴

Laterally, the femur moves back an additional 5 mm in hyperflexion so that there is little or no tibiofemoral rotation between 120° and 160°. The meniscus moves with the femoral condyle. At 160° the posterior horn of the lateral meniscus comes to lie on the posterior surface of the tibia distal to the femoral condyle. The posterior horn is not compressed and the two bones are in direct contact.

As described, in full flexion the medial femoral condyle lies on the posterior horn of the medial meniscus above the tibia with its flexion facet centre approximately 10 mm anterior to the posterior border of the tibia. The lateral femoral condyle contacts the tibia approximately 1 mm anterior to the posterior tibial border with its flexion facet centre 2 mm lower than in mid-flexion.³ This asymmetry equates to a tibial position of 3° of valgus and 30° of internal rotation compared with full extension. Laterally, the posterior horn of the meniscus is accommodated in a synovial recess on the tibial side and the femur and tibia are in direct contact. Medially, the posterior horn is accommodated in a synovial recess on the femoral side and the femur and tibia are not in direct contact.

The final limit to flexion arises because the posterior horn of the medial meniscus impedes flexion at 140° and limits it absolutely at 160°. It also prevents the medial femoral condyle from moving back beyond a point 10 mm

from the posterior tibial cortex. Thus, the posterior horn of the medial meniscus is a key structure in deep flexion.

Our study showed that the relative position of the bones in full flexion could not occur due to a continuation of their movements up to 120° because this would not result in posterior movement of the medial femoral condyle, separation of the femur and the tibia medially, the displacement of the posterior horn of the medial meniscus to a position beyond the femoral articular cartilage and not the valgus in which the tibia lies in full flexion.

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