ORIGINAL ARTICLE

Comparative anatomy of the knee joint: Effects on the lateral meniscus

C. Javoisa, C. Tardieub, B. Lebelc, R. Seild, C. Hulet", the Société française d’arthroscopie

Introduction

When replaced within the evolutive process of species, humans are primates, hominids sharing a close evolutionary relationship with the great apes (gibbons, orangutans, gorillas and chimpanzees). The chimpanzee (s) delete is our closest living relative with whom we share a recent common ancestor. This common ancestor is neither a chimp nor a gorilla, nor a human. The study of fossil specimens and comparative anatomy helped determine the time of split between the main evolutive species. It is generally believed that the chimpanzee-human split occurred about seven to 10 million years ago [1,2]. More or less preserved fossil specimens were recovered and give us a clearer picture of the human evolutionary line. The Australopithecus afarensis currently name lucy, which lived between two and three million years ago, was discovered within Eastern Africa and is among the most famous and complete fossils ever found.

Despite partial similarities between lateral and medial menisci in human beings, they display differences which better highlight the specific lateral meniscus pathology. We believed it was interesting to go back in time in order to investigate the anatomic and pathophysiological specificity of the lateral meniscus through the study of the comparative anatomy and the embryologic development.

Comparative anatomy and species evolution

The first human ancestors were both of arboreal and terrestrial origin. Humans are the only primates to use a permanent and exclusive bipedal gait [3,4]. A good knowledge of the knee phylogenetic evolution requires proper understanding of the changes induced by the shift from the arboreal to the terrestrial lifestyle and from quadrupedality to bipedalism. The shift toward habitual bipedalism among humans was associated with major anatomical changes [1].

The ‘‘tension’’ pelvis of arboreals evolved toward a ‘‘pressure’’ pelvis with a shorter distance between the sacroiliac and coxofemoral joints and a major widening of the sacrum. These morphological rearrangements of the pelvis had to face the compromise between the child-
birth and bipedalism constraints. The straightening up of the trunk was combined with the acquisition of four spine curves, the lumbar curve being the result of a reverse incurvation of the sacrum. In the hip region, the development of the gluteus maximus contributed to the straightening up of the spine. Primates’ prehensile foot was converted into a weight-bearing and propulsion foot with reduction of the distance between the first and second rays, the appearance of two arches of the foot, the internal longitudinal arch and the anterior transverse arch, and the horizontality of the tibio-talar joint surface. In the knee region, the permanent knee flexion used in non-human arboreal and terrestrial primates was converted into a complete weight-bearing knee flexion and extension specific to humans.

To promote better understanding of the knee joint anatomy in the human species, it appears instructive to make a comparison with other primates and hominid fossils. Lucy’s skeleton combined with pieces from the A. Afarensis (three million years) included well-preserved femurs and tibias with intact meniscal tibial insertions. Lucy is bipedal when walking but also achieves arboreal displacements. Her adaptation to bipedalism included several decisive changes regarding pelvis and inferior limbs. (Fig. 1) [1,3]. Chimpanzees and all non-human primates exhibit abducted knees [4] (Fig. 2). Man is the only one to stand upright with adducted femurs [1,5,6,8–11]. Such evolution was marked by three skeletal modifications, which involved the femoral diaphysis, the femoro-patellar joint and femoral condyles.

The femoral bicondylar angle enabled knee adduction

In chimpanzees and all non-human primates, the femoral diaphysis is straight: The femoral axis is perpendicular to the knee joint line. The acquisition of both knee adduction is linked to the development of a femoral bicondylar angle or femoral obliquity angle [3,5,6,12–14]. It is present in all Australopithecus, which indicates these hominids had bipedal habits. According to anthropologists, it represents one of bipedalism features [7,8]. The femoral bicondylar angle is defined as the angle between the diaphyseal axis and the perpendicular line to the infracondylar plane passing through its middle that is the bottom of the trochlear groove. This angle occasionally differs from the mechanical femoral axis from 1° to 8° (Fig. 3).

Tardieu analyzed the ontogenic development of the human femoral bicondylar angle through a sample of 25 radiographs of the femur of zero to 13 year-old child taken from osteologic collections (Fig. 4) [2,10,11]. This angle is nil (or the angle value is zero) in the newborn child, (Fig. 4 upright insert) the femoral diaphysis remains strictly straight; there is no angle of obliquity. The infradiaphyseal plane, which separates the cartilaginous epiphysis from the diaphysis, is perfectly horizontal (Fig. 4). Femurs of a 7-month foetus (angle of obliquity: 0°) and of four children, respectively six months (1°), three years (5°) and seven years old (9°) suggest that this angle arises in the diaphyseal region independently of growth of the distal epiphysis. A stronger medial metaphyseal appending is thus produced. This morphogenetic phenomenon is a diaphyseal character arising independently of growth of the distal epiphysis. The increase in this angle occurs mostly between one and four years which closely parallels the developmental chronology...
of the acquisition of standing and walking. However, this angle may vary significantly (6° to 14°), the mean values of the studied populations ranging from 8° to 11°. The variability of this angle might depend on each child skeletal loading. Females exhibit a higher angle correlated with a greater interacetabular distance. Conversely, radiographic analysis of nonwalking children shows a perfectly straight femoral diaphysis and a bicondylar angle of 0° (Fig. 5). The oblique positioning of the diaphysis and knee adduction relative to the hip joint are not attributable to the femoral head-neck offset. Therefore, in all mammals, the femoral diaphysis offset is induced by the femoral head and neck while knees are not adducted. Other mammals show no femoral obliquity angle as opposed to humans and their ancestors (Fig. 6) [1–3,13].

The prominence of lateral lip of femoral trochlea prevents any lateral dislocation of the patella

The chimpanzee distal femoral epiphysis has a flat trochlea with similar features to a femoro-patellar dysplasia. This flat surface enables free patellar displacements during repeated knee rotation movements attributed to foot grasping during arboreal displacements. In humans, the trochlea features a groove, the lateral lip being higher and more prominent anteriorly than the medial one. The femoral trochlea adapts itself to act as a stabilizer for the femoro-patellar joint. This feature is linked with the previous one and promotes mediolateral patellar stability in the presence of a high femoral obliquity angle. It is interesting to observe that from fetal development, the cartilaginous structure of the inferior distal epiphysis exhibits a flat trochlea in chimpanzees and a deep trochlear groove with prominence of the lateral lip in humans Fig. 7.

The increased radius of curvature of the lateral femoral condyle and tibial plateau facilitates full extension of the knee joint

The anatomical shape of the lateral compartment bone structures is another significant modification (Fig. 8). In non-human primates, the sagittal aspect of the lateral condyle is circular without any junction or condylotrochlear prominence. This circular shape therefore limits full extension movements of the knee joint. The tibia does not go up over the trochlear surface since there is little or even no knee extension movement.

In humans, the lateral condyle becomes elliptic, which corresponds to an increase in the radius of curvature in its inferior part. According to Kapandji [15], the radius of curvature progressively increases from back to front up to the “t” point and then begins to decrease. The section posterior to the “t” point participates to the lateral femoro-tibial and the anterior section participates to the femoro-patellar. The radius of curvature increases femoro-tibial contact area in full extension [16]. This modification of the condyle shape reduces the stress applied on the knee particularly when almost in extension or in full extension.

In non-human primates, the lateral tibial plateau has a very convex shape, with regard to the lateral condyle. The
combination of a “elliptic” circular lateral condyle with a very convex lateral tibial plateau reduces the contact area between both articular surfaces. The lateral compartment is very mobile and useful for arboreal displacements but less compatible with knee extension under loading conditions. This high convexity of the lateral plateau has diminished in humans: It is slightly convex which increases the femoro-tibial contact surface. The quadrupedal to bipedal transition led to the practice of extension movements of the knee joint associated with reduction of the sustentation polygon, knee adduction, deepening of the trochlear groove and a change from a spherical to an elliptical profile of the lateral condyle, the knee requiring more stability while remaining mobile.

What are the effects of these skeletal changes on the lateral meniscus?

Primate and mammal knee joint has two menisci [17–19]. The medial meniscus is delete identical in all species, is C-shaped and features a double tibial insertion: an anterior and a posterior insertion [1,3,13].

The lateral meniscus is variable in shape according to the type of primate. A crescent-shaped lateral meniscus with one tibial insertion, anterior to the lateral tibial spine occurs in lemuriforms, tarsius and orangutans. In gibbons, gorillas and chimpanzees, the lateral meniscus is ring-shaped and exhibits a single tibial insertion anterior to the lateral tibial spine (Fig. 9). A single notch is seen on the tibial bone sur-
face and the posterior border of the external tibial plateau appears shorter and very abrupt. A crescent-shaped lateral meniscus with two tibial insertions, one anterior and one posterior to the lateral spine, is found in humans.

In humans, there are two tibial insertions of the lateral meniscus. The posterior border of the lateral tibial plateau is long, discontinuous and notched by the posterior insertion of the lateral meniscus. Lucy (A. afarensis) exhibits a single insertion of the lateral meniscus on the tibia, which suggests greater knee mobility and the practice of arboreal locomotion. In arboreal primates with a bent-knee posture, the greater knee mobility and the practice of arboreal locomotion account for the important mobility of the lateral meniscus. Major anteroposterior movements of the lateral meniscus around its single insertion site [1,3,13] are observed. A meniscofemoral ligament is present in all primates.

Conversely, the changes observed in humans restrict the anteroposterior movement of the lateral meniscus and reinforce the knee extension stability necessary for habitual bipedalism. Such posterior insertion in humans contributes to prevent the lateral meniscus from an extreme anterior gliding during frequent extension. The lateral meniscus is pulled strongly anteriorly during medial rotation of the femur on the tibia. As in extension, this posterior attachment of the lateral meniscus limits the anterior movement. This feature is specific to the human species compared to the whole of living mammals. The development of meniscofemoral ligaments also contributes to the stability of the lateral meniscus during flexion, extension and rotational movements of the knee joint. The modification of the tibial insertion of the lateral meniscus caused the appearance in humans of ring or crescent-shaped menisci with single insertion. The clinical entity known as “discoid lateral meniscus” is by far the most common morphological anomaly of the lateral meniscus in humans, which represents 1.5 to 4.6% of the cases. These shapes and insertions are attributable to the evolution of our species and therefore genetically determined. Discoid menisci observed in humans result from the modification of the lateral meniscus and reinforce the knee extension stability necessary for habitual bipedalism.

**Ontogeny of meniscal characters**

The lateral and medial menisci originate from the same mesenchymatous embryologic tissue of the knee. It consists of semilunar fibrocartilage, which appears by the 4th month of the gestational development.

The meniscus has a rich blood supply particularly in the meniscal horn region [20], which evolves during gestational development. It is initially limited to the outer third of the medial or lateral meniscus but progresses up to the peripheral 2/3 of the whole meniscus at birth. The avascular popliteal recess appears at the beginning of the fetal stage.

The histological composition of the menisci is identical (75% water, 20% of type I collagen fibers and 5% de GAG). Macroscopically, it is usually constituted of triangular structures, the medial meniscus is C-shaped and the lateral meniscus is ring shaped. Menisci are 35 mm in diameter, mean length when measured from the peripheral rim is 110.86 ± 13.18 mm for medial meniscus and 111.15 ± 11.07 mm for lateral meniscus [21]. The mean coverage rate of medial meniscus on the tibial articular surface is 64% (51 to 74%) while lateral meniscus shows a higher mean coverage rate of 84% (75 to 98%), such values remain stable during the whole gestational development and growth period [22]. Kohn and Moreno [21] have studied the anatomical meniscal insertions in 46 preserved human cadaver tibias of mean age 35 years. The anterior insertion site surface area of the medial meniscus is 139 ± 43 mm² while the posterior insertion site area is 80 ± 10 mm². Lateral meniscus measurements are different: 93 ± 25 mm² for its anterior insertion and 115 ± 51 mm² for its posterior insertion. Anatomic insertions of both medial menisci were defined from standard lateral and A/P knee radiographs and recently studied by Wilmes et al. [23,24]. He could therefore accurately determine reproducible landmarks for the latitude and longitude of both medial and lateral menisci by focusing on the insertion point of the anatomical horns. Based on 20 cadaver tibias and lateral and A/P views, he could determine the position in the latero-medial axis (X axis) and anteroposterior axis (Y axis) (Fig. 10). These posi-
Insertions remain stable and show a narrow relationship with the intercondylar eminences of the tibia. Insertions of the medial meniscus are closer to the peripheral articular surface whereas the lateral meniscus is narrower, its anterior and posterior insertions being very close together. The anterior insertion of the lateral meniscus is slightly lateralized compared with the posterior insertion in the coronal plane. In the sagittal plane, these insertions are very close together since the anterior insertion is located in the middle of the lateral plateau whereas the posterior insertion is situated at the junction between anterior 3/4, posterior 1/4. Let’s keep in mind the single insertion site of the lateral meniscus in the chimpanzee. Moreover, the lateral meniscus rests on a convex lateral tibial plateau unlike the medial meniscus.

Means of fixation or connection of the lateral meniscus

Besides the meniscal horn insertions on the tibial plateau, other connections have been described.

These connections include the anterior intermeniscal ligament (AIL) of the knee or Winslow’s ligament. It does not present as a constant structure according to the type of study [25,26,27]. In a cadaver study conducted by Marcheix et al. [25], this anterior ligament was present in 100% of the cases and only in 80% of the cases when investigated by MRI examination. It is 31.2 mm long and only 1.8 mm wide. In another cadaver study conducted by Tubbs et al., the Winslow’s ligament was found in only 55% of the cases and demonstrated very similar dimensions (35.4 mm long and 2.5 mm wide). This ligament might be double (3.7% of cases) and various types are described according to their associated insertion on the anterior margin of the meniscal horn and on the anterior capsule [27].

Immediately anterior to the popliteal recess, Bozkurt et al. [28] examined more specifically the presence of the meniscofibular ligament. Based on 50 cadaver dissections, he finds a meniscofibular ligament, which runs between the inferior menisco-synovial junction of the midportion of the lateral meniscus, anterior to the popliteal hiatus up to the artic-
The mechanical properties of these two structures have been well defined [37].

<table>
<thead>
<tr>
<th></th>
<th>Insertion site area (mm²)</th>
<th>Tensile strength (N)</th>
<th>Modulus of elasticity (MPa)</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>aMFL</td>
<td>14.7 ± 14.8</td>
<td>300 ± 155</td>
<td>281 ± 239</td>
<td>20.7 ± 3.9</td>
</tr>
<tr>
<td>pMFL</td>
<td>20.9 ± 11.6</td>
<td>302 ± 158</td>
<td>227 ± 128</td>
<td>23.0 ± 4.3</td>
</tr>
</tbody>
</table>
might reach up to 10 mm for the anterior horn. \cite{41} for the lateral meniscus than for the medial one and posterior meniscal movement during knee flexion is greater proportion and the posterior portion respectively. The natural portion and the posterior portion respectively. The natural meniscofibular ligaments pull the post portion posteriorly and inferiorly whereas the traction exercised by the MFL is located anteriorly and inferiorly and more proximally that is anteriorly in the anteroposterior direction. These meniscofemoral ligaments prevent the natural posterior displacement during knee flexion.

Therefore, during tibial internal rotation in a flexed knee, the MFL pulls the posterior portion anteriorly and inferiorly whereas the meniscofibular ligaments maintain it posteriorly thus protecting it from the lateral femoral condyle. In extension, during axial compression, the stress applied pushes the lateral meniscus outside. The compressive forces change into shearing forces and are transmitted by the MFL to the circumferential fibers of the lateral meniscus. In case of excessive stress, one of the elements from the MFL-meniscal root and post portion chain might disrupt and involve a meniscal or ligamental tear.

These meniscofemoral ligaments are the secondary restraint to posterior tibial translation after the PCL but they also act as an important stabilizer of the horn and the lateral meniscal root when this latter is subjected to compressive stress on the lateral tibial plateau convexity.

Finally, the lateral meniscus is integrated in this anatomo-functional entity, which is the posterolateral corner of the knee. The major structures of the posterolateral corner of the knee include the popliteofibular ligament, the popliteus muscle, the lateral collateral ligament, the biceps femoris and the posterior joint capsule.

**Meniscal kinetics**

Therefore, the whole insertion means and the convexity of the lateral tibial plateau provide better understanding of the meniscal displacements. The lateral meniscus is subjected to greater movements than the medial meniscus.

Up to 90° of knee flexion, \cite{40} have demonstrated that the lateral meniscus displaces 9.5, 3.7 and 5.6 mm posteriorly for the anterior portion, the central portion and the posterior portion respectively. The natural posterior meniscal movement during knee flexion is greater \cite{41} for the lateral meniscus than for the medial one and might reach up to 10 mm for the anterior horn. \cite{41} have recently studied the posterior translation with over 130° of knee flexion. The overall in vivo posterior translation is 8.2 ± 3.2 mm for the lateral meniscus and 3.3 ± 1.5 mm for the medial one. The anterior horns show a greater posterior translation (LM: 10.2 mm, MM: 6.5 mm) than the posterior horns (LM: 6.2 mm, MM: 3.1 mm). There is a significant difference of about 5 mm between the average translations of both menisci.

We conducted a study in five healthy knees; the knee was initially extended then progressively flexed, by increments of 30° up to more than 100° of flexion. For each lateral position, we measured the backward displacement of the anterior and posterior portions regarding the circle representing the posterior femoral radius of curvature corresponding to the higher diameter of the lateral femoral condyle \cite{42}. Movement of the posterior and anterior portion was measured from extension to full knee flexion. The lateral meniscus shows a greater posterior translation than the medial meniscus. The posterior translation is 15 and 16 mm for LM anterior and posterior portions respectively and only 8 and 5 mm for MM anterior and posterior portions (Fig. 14).

These observations are similar in the five studied knees; in all cases, when the knee is placed in over 90° of flexion, the posterior portion of the lateral meniscus moves posteriorly to the tibial plateau whereas the posterior portion of the medial meniscus remains directly above the posterior edge of the medial tibial plateau.

**Reflexion on physiopathology of lateral meniscus lesions**

The lateral meniscus provides good articular congruency in the femoro-tibial compartment, which is hostile because of its opposed convexities. It acts as a knee stabilizer, particularly via the interconnections of the posterolateral corner of the knee, and shows a great capacity to move due to its phylogenetic evolution. The lateral compartment of the knee is commonly presented to be the mobile knee compartment (that of mobility). Stress applied to the lateral meniscus is mostly exerted on the anterior and posterior portions as reported in the work of \cite{43}. Its location and morphology contribute to the transformation of compressive force to shearing force as confirmed by the SFA study in 1996 \cite{43}. The lateral meniscus acts as a shock absorber while distributing compressive stress circumferentially. Its proprioceptive receptors are located in the peripheral 2/3 and in the anterior and posterior portions. The possible mechanisms of injury and their consequences in terms of excessive
load transmission might be anticipated. Stress applied to the medial compartment is thus mainly compressive. Within the lateral compartment, the compressive stress associated with a greater displacement subjects the lateral meniscus to shear forces applied to the lateral tibial plateau convexity. During a traumatism associating valgus, flexion and external rotation, the opposition between the thrust of the lateral condyle reinforced by the anterior traction of the meniscofemoral ligaments and the posterior traction of the meniscofibular ligament and of the capsule result in a posterior subluxation of the lateral tibial plateau, especially in knee flexion. The convexity of the lateral tibial plateau acts as a block on a narrow and mobile meniscus compared to the popliteal recess, which induces a shear movement (Fig. 15).

If the ACL is intact, the translation is not excessive and the shearing force will exert on the central portion compared with the popliteal recess. Such phenomenon has been confirmed by clinical studies on the analysis of meniscal lesions in a stable knee.

In case of torn ACL, the translation is excessive and the block movement associated with high shear force will exert on the posterior portion of the lateral meniscus. In such conditions, the meniscofibular ligaments, the meniscofemoral ligaments — according to the degree of knee flexion — and the root of the lateral meniscus are highly exposed to the risk of injury.

West et al. [44], in 2004, have reported this type of meniscal root injury combined with tear of the ACL. This injury was identified in 12.4% of the cases. Brody et al. [45] well described the MRI features of meniscal roots in T1 and T2. Among 264 MRI performed in patients with torn ACL, 9.8% of lateral meniscal root injuries and only 3% of medial meniscal root injuries were observed. Meniscal extrusion was found in six out of the 26 lateral meniscal injuries (23%). The absence of MFL was commonly found to be associated with meniscal extrusion when there was a lateral meniscal injury. It underlines the difficulty to obtain clear visualization of meniscal roots and meniscofemoral ligaments [46,47,48,49].

De Smet et al. [50] defined MRI criteria using six imaging planes (three coronal and three sagittal projections) (Fig. 16) acquired with fat-saturated T2-weighted MR images to provide proper visualization of the meniscal roots. Three millimetres thick sections should be successively used with 1.5 mm interpolation. This technique combined with thorough analysis of six thin slices proves helpful in the detection of lateral meniscus root injuries. Ahn et al. [51] have shown that these injuries commonly occur in the coronal plane and cause a tear of the posterior portion of the lateral meniscus, which loses its tibial attachment (Fig. 17). This lesion is defined as being situated within 1 cm from the tibial insertion site. The reported prevalence of these injuries in his study is only 6.7% of the 432 ACL grafts. Ahn et al. [51] believe meniscus repair should be performed whenever possible, even in case of lesions in the white-white area. Arthroscopic meniscal healing was
observed in all cases and the lateral meniscus root, due to its two insertions (MFL and tibial insertion) eases the repair procedure compared with a mid-segment vertical lesion. These injuries should be investigated with growing interest.

Conclusion

The use by the Homo sapiens of exclusive bipedalism provides better knowledge of the anatomical differences between both knee compartments. Consequences on the lateral meniscus are greater than those observed on the medial meniscus, which remains identical whatever, the species. The lateral meniscus double insertion is a unique feature of the Homo sapiens. Along with anatomic study and by combining dissections with recent imaging investigations, the use of modern imaging systems, digital radiography, especially in MRI, provides reliable landmarks to facilitate meniscal allografts. Since modern imaging techniques provide good understanding of the functional anatomy, knee kinematics and more particularly that of lateral meniscus might be properly assessed. It provides better understanding of meniscus biomechanics and helps determine its lesion mechanisms. Accurate imaging protocols should be developed to offer better analysis of MFL (especially the posterior one), anterior cruciate ligament injuries (ACL) and meniscus roots in order to quantify the relationships with meniscal extrusion. By defining in a more accurate and comprehensive manner the ACL lesion associated injuries, we will improve our therapeutic indications and techniques of meniscus preservation.

Conflict of interest

The present authors had no conflict of interest regarding this publication.

References

[21] Kohn D, Moreno B. Meniscus insertion anatomy as a basis for meniscus vascularisation supply during foetal development: about 16 cases. KSST A 2008;Suppl. 16:1.
Comparative anatomy of the knee joint


