Summary  The arc of flexion used in almost all the activities of everyday life extends from about $20^\circ \pm 10^\circ$ to $110^\circ/120^\circ$. During this arc, the human knee corresponds to the quadrupedal mammalian knee. Both the femoral surfaces are circular with a similar radius and rotate around their geometrical centres as the knee flexes. The medial femoral condyle does not move antero-posteriorly with flexion, i.e. stability depends on the medial side of the knee. In contrast, the lateral femoral condyle is antero-posteriorly mobile and as it moves it carries the meniscus with it. This AP movement results in longitudinal tibial rotation which is facultative rather than obligatory: if posterior motion occurs, the femur rotates externally around a medial axis with flexion whereas if no AP motion occurs, the knee can flex as would a uniaxial hinge. Rotation first appears in arboreal quadrupeds (apes) and may be becoming vestigial in Man. The axis of longitudinal rotation during flexion, parallel to the tibia and perpendicular to the flexion axis, approximately intersects the latter in the centre of the medial femoral condylar sphere. Varus/valgus rotation, around an AP axis which also passes through the centre of the femoral sphere, permits the lateral femoral condyle to lift away from the tibia because the lateral collateral ligament (LCL) is slack at $90^\circ$ in mid external/internal rotation. Thus, in the arc $20^\circ$–$120^\circ$ the medial femoral condyle resembles the femoral head: it is spherical, it does not translate during flexion and all three axes of rotation intersect at its centre. At $90^\circ$, forced longitudinal rotation does result in AP movement of the medial condyle and on the lateral side in a reciprocal translation which is almost sufficient to abolish the translation accompanying flexion. This movement occurs around a vertical axis which is slightly lateral to that representing longitudinal rotation with flexion.

The arc from $10^\circ$ to full extension is accompanied by the so-called ‘locking’ and ‘screw-home’. It appears to be a feature of bipedal terrestrial gait with an erect stance, i.e. human gait. Although the arc exists, it is rarely used fully in everyday life. The motion is complex and involves asymmetrical articular surfaces other than those used from $20^\circ$ to $120^\circ$. On the medial side, the femur ‘rocks’ forward onto the upward-sloping anterior surface of the tibia and then rotates into extension around an anterior, larger radiused circular surface. On the lateral side, the femur rolls down onto the anterior horn. The result is ‘lift-off’ of the posterior facets used in the arc $20^\circ$–$120^\circ$ and progressive tightening of the structures attached posteriorly to the femur, in particular the ACL. This ligament, as it tightens, may move the lateral femoral condyle anteriorly so that extension is accompanied by about $5^\circ$ of obligatory femoral internal rotation. Flexion and longitudinal rotation occur by rotation around, and translation along, a $20^\circ$ oblique screw axis penetrating medially the epicondyle and, laterally, the region of the tibio-femoral contact surface.

From $120^\circ$ to full flexion, the motion is passive rather than active. Both femoral condyles move backwards and both lose contact with the tibia. Thus, the tibio-femoral joint is strictly speaking subluxed. Medially, the femoral condyle rolls up onto the posterior horn. Laterally, the femoral condyle rolls backwards and downwards, finally to lie posterior to the tibia, resting on the posterior horn.

Although the motion of the knee is complex, it can be (and has been) imaged by MRI in the unloaded cadaveric knee, the unloaded living knee and the loaded living knee. The keys to its understanding are to divide flexion into three arcs and to appreciate that in...
the functional active arc ("20° – 120") the medial femoral condyle, like the femoral head, is spherical, that it does not translate and that it rotates around three axes which intersect at its centre. By contrast, the lateral femoral condyle rolls and slides antero-posteriorly on the tibia to result in longitudinal rotation (a possibly vestigial movement in Man) around a medial axis. © 2002 Elsevier Science Ltd. All rights reserved.

LITERATURE REVIEW

The mechanism of the human knee has been a subject of anatomical and clinical interest for more than 150 years. During this time so much has been written as to make a full review of the literature impossible. Standard textbooks cover the subject, making reference to many points superfluous. The early modern descriptions date from the period 1836, the work of the Weber brothers, to 1917, a textbook by Strasser.1,2 The authors were anatomists, scientists who were then the doyens of the medical schools, and almost without exception they were German-speaking. Today, these works are neither easy to obtain nor to translate. For obvious reasons they are only lightly illustrated and even when translated they are difficult to read. Nevertheless, many of the points made in this article derive originally from the work of this period. The material has been reviewed in English3,4 and in German5 and will not be recapitulated here: those who are interested can obtain the material from the Library of the History of Medicine in Bern, where it has been lodged by recent reviewers.3

In the period 19171 to 19416 little further anatomical work was done and indeed topographical anatomy, like German as the language of science, gradually declined. Relevant references may be found in a recent text-book7 and some are listed at the end of this article.

Since the second World War, particularly since the 1970s, there has been a resurgence of interest in the subject driven by orthopaedic surgeons (particularly those interested in knee replacement and ligament reconstruction) and bio-engineers (taking the place of anatomists). Some relevant publications are cited here and else where7. Unfortunately, bio-engineers use apparatus and terminology which are not always easy for orthopaedic surgeons to understand. Thus, some uncertainty still persists: for example how many orthopaedic surgeons would be able to locate and define the instant helical axis?

In this paper, an orthopaedic surgeon describes the knee on the basis of MR images obtained over the last 5 years of the cadaveric and living knee. Some of this work has been published but some—particularly of the cadaveric knee imaged by MR and two other techniques followed by computer-aided analysis (work in progress 1) and of the living knee (work in progress 2)—is in preparation and is cited as such.

COMPARATIVE ANATOMY

The knees of terrestrial quadrupeds differ from those of man. Firstly, the joint extends only to about 20° (two possible exceptions being the bear and the elephant). Secondly, tibial longitudinal rotation is limited.9 The reader may confirm these facts for himself by examining domestic pets.

The lack of full extension is due to the facts firstly, that in quadrupeds the knee does not fully extend as measured from the epiphyses and secondly, that the proximal tibial epiphysis is retroverted,9 as it is in the human infant.11 In Man, tibial retroversion progressively diminishes over the first 15 years of life, although in societies in which squatting or full kneeling is common some retroversion is said to persist.

Significant longitudinal tibial rotation first appears in arboreal quadrupeds, presumably as a response to the need to grasp the branches of trees both with a prehensile hand and with a prehensile foot: longitudinal rotation is then necessary both at the forearm and at the Shank in order to bring the prehensile extremity perpendicular to the branch.10 Anthropologists have made use of the appearance of longitudinal rotation in arboreal mammals to determine whether a given primate skeleton is arboreal or terrestrial.12 This is done by reference to the Tardieu Index which compares the separation of the walls of the femoral intercondylar notch with the medial-to-lateral width of the tibial spines. The wider the notch in relation to the spines, the more is longitudinal rotation possible at the knee and the more likely is the skeleton to be of an arboreal primate. Man has a more limited range of longitudinal rotation than arboreal great apes and thus skeletons of the knee of early Man can be distinguished from those of his arboreal predecessors. It may be that Man is progressively losing longitudinal rotation as he returns to a mode of gait more similar to that of his terrestrial quadrupedal ancestors: bipedal terrestrial gait would seem to require even more emphasis on stability as against longitudinal rotation than would quadrupedal gait. Is longitudinal rotation becoming vestigial in Man, like the coccyx?

Although to some extent losing the capacity for longitudinal rotation, Man has acquired a range of extension beyond 20° (indeed a range beyond zero into hyper-extension), presumably because of the major energy demands posed by bipedal gait on flexed knees. Hyperextension has come about partly as a result of the
elimination of ‘normal’ quadrupedal tibial retroversion but also, in the author’s view, because the anterior aspect of the original quadrupedal knee appears to have been ‘broken out’ anteriorly to permit full extension between the epiphyses. The resulting anterior anatomy of the human knee differs from that obtaining in the arc 20°–120° and might be likened to the superolateral aspect of the dysplastic acetabulum ‘broken out’ by an oval femoral head. The surfaces of the quadrupedal femoral condyles where they articulate with the tibia are both circular, as are those of Man over the arc from about 20° to 120°. They thus resemble (at least in sagittal section) the normal femoral head. However, over the arc from full extension to 20° the medial, and less obviously the lateral, femoral condyle in Man are made up of a second circle of larger radius to produce a femoral condyle which, overall, is roughly elliptical where it contacts the tibia. As the human knee fully extends from infancy onwards, it is this larger-radiused anterior portion of the femoral condyle which may be thought to ‘break out’ the anterior aspect of the original quadrupedal tibia. The lateral, anterior tibio-femoral articulation is very different from that on the medial side and thus, in a second contrast to the arc 20°–120°, the arc from 20° to full extension is based on strongly asymmetrical articular surfaces.

**THE FLEXION ARC IN MAN**

This may be divided into three segments in each of which the mode of articulation is different: an arc beginning at 20° ± 10° (called here ‘20°’ ) and continuing to 110°/120°, an arc from ‘20°’ to full extension (here referred to as ‘−5°’ although the actual number of degrees of hyperextension varies from knee to knee) and a third arc from 120° to full flexion (i.e. about 145° in Caucasians and 160° in Japanese subjects) (Fig. 1).

![Figure 1](image-url) A diagram to show the three arcs into which flexion may be divided for descriptive purposes.

**The arc ‘20°–120°’: the fundamental active arc**

This arc is entirely under active muscular control. It covers almost all the activities of daily living and may be considered the analog of the normal range in terrestrial quadrupeds as described above.

Throughout this arc both the femoral surfaces, where they make contact with the tibia, are circular in sagittal section, having a radius of about 22 mm.  The articular surface of the medial femoral condyle is not only circular in sagittal section but is also a section of a sphere. Because the surfaces are circular in sagittal section where they contact the tibia, the AP motion of the two condyles during flexion can be measured by tracking the centres of these circles relative to the posterior border of the tibial articular surface. When this is done, it is found that the medial femoral condyle moves neither anteriorly nor posteriorly during flexion in the unloaded cadaveric knee, in the unloaded living knee nor in the loaded living knee (work in progress 2). Thus, it would seem that the essential feature of the medial femoral condyle as it flexes is that it is antero-posteriorly stable. This ‘stability’ is perhaps caused by the facts that the posterior horn of the medial meniscus is firmly attached to the tibia to provide a posterior ‘wall’ to a cup-shaped tibial surface (analogous to the glenoid labrum which provides a cup-shaped surface with flexible ‘lips’ at the shoulder); that (at least) the superficial fibres of the medial collateral ligament (MCL) are tight from ‘20°’ to 90°; and that the bulk of the PCL is tight from 60° to 120° (work in progress 1).

In spite of the fact that the medial femoral condyle does not move antero-posteriorly with flexion (nor with a conventional drawer sign) it can be made to do so by forcibly internally or externally rotating the knee at 90°: its ‘stability’ is therefore not absolute.

In contrast to the AP immobility of the medial femoral condyle, the lateral femoral condyle tends to move backwards (by rolling and/or sliding) during flexion and during tibial internal rotation at (for example) 90°. The opposite, forward motion accompanies extension and tibial external rotation. AP motion of the condyle is accompanied by movement of the lateral meniscus, i.e. the meniscus moves with the femur relative to the tibia as the knee flexes and rotates. This contrasts with the fact that on the medial side the posterior (but not the anterior) horn is fixed to the tibia.

The combination during flexion of an antero-posteriorly immobile medial femoral condyle and backward motion of the lateral femoral condyle results in femoral external rotation (tibial internal rotation) with flexion. However, because longitudinal rotation and flexion can take place to some extent independently, the tibial internal rotation which accompanies flexion is almost fully reversible over the arc ‘20°–120°’ if internal rotation is applied to the femur (or external rotation to the tibia)
as the knee flexes.\textsuperscript{13,16} The mechanism responsible for this rotation, i.e. for posterior motion of the lateral femoral condyle with flexion, is unclear (especially when it is appreciated that it occurs even during a squat in which the foot is fixed to the ground)\textsuperscript{16} (work in progress 2). The possible mechanisms include increasing PCL tension with flexion beyond 60°, the tendency for both condyles to roll-back because of friction, however slight, which is not resisted laterally but is resisted medially by the posterior horn, and the geometrical effect of transposing the femoral valgus angle from the frontal to the transverse plane as the knee flexes from 0° to 90°.

Because the two femoral condyles are circular where they contact the tibia during flexion from ‘20°’ to 120°, the flexion axis over this arc can be located as a line passing through the centres of the circular contacting surfaces. Projected laterally this axis passes through the epicondyle and thus the attachment of the lateral collateral ligament. Projected medially, however, it passes about 13 mm posterior and distal to the medial epicondyle (in the extended knee) and thus does not pass through the attachment of the MCL. In the mid-line it passes between the femoral attachments of the two cruciate ligaments (Fig. 2). The behaviour of the ligaments during flexion can be explained on the basis of these anatomical facts but is outside the scope of this paper.

The axis of longitudinal rotation during flexion, perpendicular to the flexion axis and parallel to the tibial long axis, approximately intersects the flexion axis at the centre of the femoral sphere, penetrating the medial tibial condyle roughly at its mediolateral centre and at the junction of its posterior and central thirds (Fig. 3)\textsuperscript{7,13,16} (work in progress 1). [At extreme internal and external tibial rotation at 90° the axis may pass slightly more laterally, because of AP movement of the medial femoral condyles]\textsuperscript{7,13} (work in progress 1). The third axis, perpendicular to the other two, through which the tibia can rotate into varus or valgus, also passes through the centre of the medial condylar sphere (work in progress 1). This rotation occurs in two circumstances. Firstly, the surface of the lateral tibial condyle, which contacts the femur from 30° to 90° is roughly on the same horizontal plane as the contact area medially so that little if any varus/vaugh motion accompanies normal flexion over this arc. More posteriorly however, the tibial surface curves distally so that the femoral condyles also moves distally—the equivalent of tibial valgus rotation—at 120°. Secondly, the normal tibia can be stressed into varus (Fig. 4) by separating the lateral surfaces, a separation which is possible because of the facts that the LCL is slack at 90° in mid-ER/IR (were it not to be so, longitudinal rotation would be impossible), and that both the medial femoral condyle and the lateral surface of the intercondylar eminence are circular in frontal section.\textsuperscript{7,14}

Thus, over the arc ‘20°–120°’ the knee may be thought of as a medial sphere which rotates around all three axes.
but which translates little if at all during flexion, although it does in forced rotation at 90°. In so far as longitudinal rotation accompanies flexion, the lateral femoral condyle rolls and/or slides backwards or forwards across the top of the tibia carrying the meniscus with it. The three axes (of flexion, longitudinal rotation and of valgus/varus) approximately intersect in the middle of the medial femoral sphere, a situation comparable to that obtaining at the femoral head in the hip.

The arc ‘20°’ to full extension: ‘screw-home’ or ‘terminal extension’

This arc equates to the phase of knee movement referred to as ‘screw-home’, a phenomenon which has been of great interest to anatomists although it may have little importance in the activities of daily living, being used only in such activities as one leg stance and certain sports e.g. the back-swing in golf (Fig. 5). The outstanding anatomical feature of the tibio-femoral joint during this arc is the marked asymmetry between the medial and lateral sides. This asymmetry and indeed this arc of movement, is not seen in other mammals.

Medially, the femoral condyle ‘rocks’ between 30° and 10° from its posterior circular surface (already described) to an anterior circular surface, having a larger radius (≥ 30 mm) and an arc of about 40°. The term ‘rocking’ to describe this movement was implied by the Weber brothers in 1836 and used by Steindler in 1956. As the medial condyle ‘rocks’, two factors cause the posterior circular femoral surface to rise 1–2 mm with extension and thus to lose contact with the tibia. These are, firstly, that the anterior femoral surface contacts the upwardly sloping anterior tibial surface and secondly, that as contact is made anteriorly and lost posteriorly, the axis of rotation of the femur transfers from the centre of the posterior circle to the centre of the anterior circle: rotation about the latter causes the posterior femoral condyle to rise. However, the motion at the anterior interface remains one of pure sliding. Thus, medially there is no AP movement of the femur as a whole.
between ‘20°’ and full extension although there is an anterior transfer of the contact area, contact being lost posteriorly.

On the lateral side the larger radiused anterior facet, which is present on the medial side, is represented only by the posterior part of the flattened distal aspect of the femoral condyle. This contacts the tibia over so small an arc to make the extent and radius of this section difficult to define (and for this reason the whole of the articular surface of the lateral femoral condyle is about 7 mm shorter than the medial). As the lateral femoral condyle rotates into extension, the flattened distal segment appears on MRI to ‘roll’ down over the anterior edge of the tibial articular surface to engage and compress the anterior horn in a recess in the femoral condyle (Fig. 5).

As on the medial side, the posterior surface rises away from the tibia. Since the lateral femoral condyle rolls forwards whilst the medial femoral condyle slides between ‘20°’ and full extension: (1) the distal femur continues to rotate internally as it extends; (2) the axis of rotation over this arc would be expected to penetrate the lateral compartment in the vicinity of the contact area, whilst (3) as explained, the axis penetrates the medial femur through the centre of its anterior circular surface. The centre of this anterior surface coincides with the medial epicondyle to which the MCL, tight from ‘−5°’ to 90°, is attached (work in progress I). Such an axis is oblique, downwards (≈ 20°) laterally and forwards (≈ 10°) (work in progress I).

In computer simulations based on CT and RSA of the cadaver knee, rotation around this oblique axis, combined with about 3 mm lateral femoral translation along it, reproduces the tibio-femoral displacement seen between full extension and 10° flexion, an arc the magnitude of which depends upon the presence and degree of hyperextension (work in progress I). The ratio of the longitudinal rotation to flexion predicted by such a screw axis is about 0.5:1, a ratio which corresponds to that observed in practice. In contrast to the arc ‘20°’−120°, this rotation may be obligatory, since little or no rotation can be sensed manually or seen on MRI when attempts are made to rotate the cadaveric or living knee over this arc, (work in progress 2). Hallen and Lindahl however have challenged this view, reporting that although screw-home usually occurs, it is not obligatory because some rotation is still possible in full extension. If the association of flexion and longitudinal rotation is almost or totally obligatory, the two rotations can most economically be represented as occurring around a single oblique axis (as above), not around two orthogonal axes as described for the arc ‘20°’−120°.

This description of the arcs from full extension to ‘20°’ as compared with the arc ‘20°’−120°, suggests that the medial and lateral compartments differ greatly with respect to their shapes, their relative movements and their axes of rotation and that posteriorly the ‘normal’ mammalian facets, which contact from ‘20°’ to 120°, do not make contact from ‘20°’ to extension, i.e. the ‘normal’ mammalian knee is strictly speaking subluxed. These findings correspond to the evolution of the arc from 0° to ‘20°’ in Man suggested above.

The knee progressively resists extension over the last 10° before reaching an ‘absolute’ sense of resistance, at least to manual examination, at full hyperextension, i.e. it ‘locks’. This resistance is due to tightening of the posterior capsule, of a few posterior fibres of the PCL, of the collateral ligaments which would become tight were the knee to be forced into extension beyond its natural limit, perhaps to compression of the anterior horns of both menisci which seem to act like ‘chocks’ beneath a wheel on a road and finally (perhaps most importantly) to the ACL (work in progress I). This ligament is attached to the femur posterior to the screw axis described above and thus its femoral attachment tends to rise away from its tibial attachment as the knee extends. However, the ACL (in particular the posterolateral fibres) appears to be fully elongated at about 10° flexion, so that further elongation of the ligament is impossible. In order to permit the further vertical separation of its attachments which would occur from 10° to full extension, the attachments of the ligament are therefore forced to approach each other in the horizontal plane over this arc, i.e. the lateral femoral condyle is forced to move forwards in terminal extension. Such forward movement of the lateral femoral condyle would result in the femoral internal rotation that accompanies terminal extension, i.e. it would produce ‘screw home’ (work in progress I). As the lateral femoral condyle moves forwards, the LCL which is inclined upwards and forwards becomes tighter, finally limiting forward movement. At this point the knee is locked.

110°/120° to 145°/160°: the passive arc

This arc can only be used passively: the thigh muscles can flex the tibia to about 120° but thereafter have no effective moment arm. It therefore requires an external force, for example the body weight, to carry the tibia into further flexion. For this reason the arc is only used in squatting and full kneeling. The maximum arc that can be achieved is limited by the posterior soft tissues and the extent of tibial retroversion. It appears to be greater in Japanese and other societies who use full kneeling or squatting in everyday life, a functional habit which may be associated with greater residual infantile retroversion of the proximal tibia and greater forward bowing of the femoral shaft.

On the medial side, the femoral condyle rolls upwards and posteriorly onto the posterior horn of the medial meniscus (work in progress 2) and in extreme flexion the most distal part of the non-articular portion of the
femur appears to compress the meniscus so that the femoral condyle is in effect ‘hinged away’ from the tibia. Since the articular surface of the femur is in contact with the posterior horn, not with the articular surface of the tibia, the medial tibio-femoral joint is strictly speaking subluxed.

On the lateral side, the femoral condyle continues to move posteriorly beyond 120° until it comes to lie posterior to the tibia, resting upon the posterior horn of the lateral meniscus.24 The latter drops over the posterior extremity of the horizontal tibial surface, onto the tibial posterior articular surface. Thus, as on the medial side, the tibio-femoral joint is, strictly speaking, subluxed.

In Caucasians no significant longitudinal rotation occurs during a squat to 145° since both femoral condyles move back about equally (work in progress 2). However, in the Japanese mode of kneeling, in which the buttock rests on the feet, there is strong tibial internal rotation between 90° and 160°.24

Because the medial femoral condyle rises about 2 mm as it rolls up onto the posterior horn, whilst the lateral femoral condyle drops about 2 mm, the tibia moves into slight valgus as the knee flexes fully.

REFERENCES


This paper should be read in conjunction with the Journal of Bone and Joint Surgery, vol. 82B; 8 (November 2000) in which there were 5 papers (and a list of 98 further works consulted) and Chapter 10 in John Insall’s Surgery of the Knee, with special reference to the illustrations.

WORK IN PROGRESS

1. Johal et al. The movement of the weight-bearing and nonweight-bearing living knee imaged by MRI.