



Does the femur roll-back with flexion?

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MRI studies of the knee were performed at intervals between full extension and 120° of flexion in six cadavers and also non-weight-bearing and weight-bearing in five volunteers. At each interval sagittal images were obtained through both compartments on which the position of the femoral condyle, identified by the centre of its posterior circular surface which is termed the flexion facet centre (FFC), and the point of closest approximation between the femoral and tibial subchondral plates, the contact point (CP), were identified relative to the posterior tibial cortex.

The movements of the CP and FFC were essentially the same in the three groups but in all three the medial differed from the lateral compartment and the movement of the FFC differed from that of the CP. Medially from 30° to 120° the FFC and CP coincided and did not move anteroposteriorly. From 30° to 0° the anteroposterior position of the FFC remained unchanged but the CP moved forwards by about 15 mm. Laterally, the FFC and the CP moved backwards together by about 15 mm from 20° to 120°. From 20° to full extension both the FFC and CP moved forwards, but the latter moved more than the former. The differences between the movements of the FFC and the CP could be explained by the sagittal shapes of the bones, especially anteriorly.

The term 'roll-back' can be applied to solid bodies, e.g. the condyles, but not to areas. The lateral femoral condyle does roll-back with flexion but the medial does not, i.e. the femur rotates externally around a medial centre. By contrast, both the medial and lateral contact points move back, roughly in parallel, from 0° to 120° but they cannot 'roll'.

Femoral roll-back with flexion, usually imagined as backward rolling of both condyles, does not occur.

Controversy as to how the femur moves on the tibia during flexion dates back to 1836 when Weber and Weber¹ proposed that the movement was "like a cradle", at least medially. In 1904 Zuppinger² suggested, on the basis of the first radiological study of kinematics of the knee, that the femur rolled back across the tibia with flexion because the cruciate ligaments, in conjunction with the femur and tibia, provided a rigid four-bar link mechanism in the knee. This is probably the most widely held view today and has influenced modern knee replacement. Notwithstanding its general modern acceptance this idea was disputed at the time of its introduction by Fick³ and by Strasser.⁴ More recently, it has been suggested that the medial femoral condyle does not roll back, but that, to a largely optional extent, the lateral condyle does, a combination which equates to femoral external rotation with flexion.⁵⁻⁷

We have therefore studied the relationship between the movement of the tibiofemoral

contact areas and of the femoral condyles between full extension and 120°, the arc under active muscular control, in cadaver and living weight-bearing and non-weight-bearing knees. Our objective was to clarify the way in which the knee moves and to resolve the controversy arising from descriptions based on the condyles as against those based on the contact areas. This controversy is relevant to all clinical areas involving knee movement including total knee replacement.

Materials and Methods

We performed the MRI studies as follows. Six male normal cadaver right knees were examined in Prague, three of which had formed part of previous studies.^{6,7} Five male normal left knees in living subjects were examined non-weight-bearing in London. The same five left knees were also examined during a weight-bearing squat. Other aspects of the second and third groups of knees have been reported in previous studies.⁸

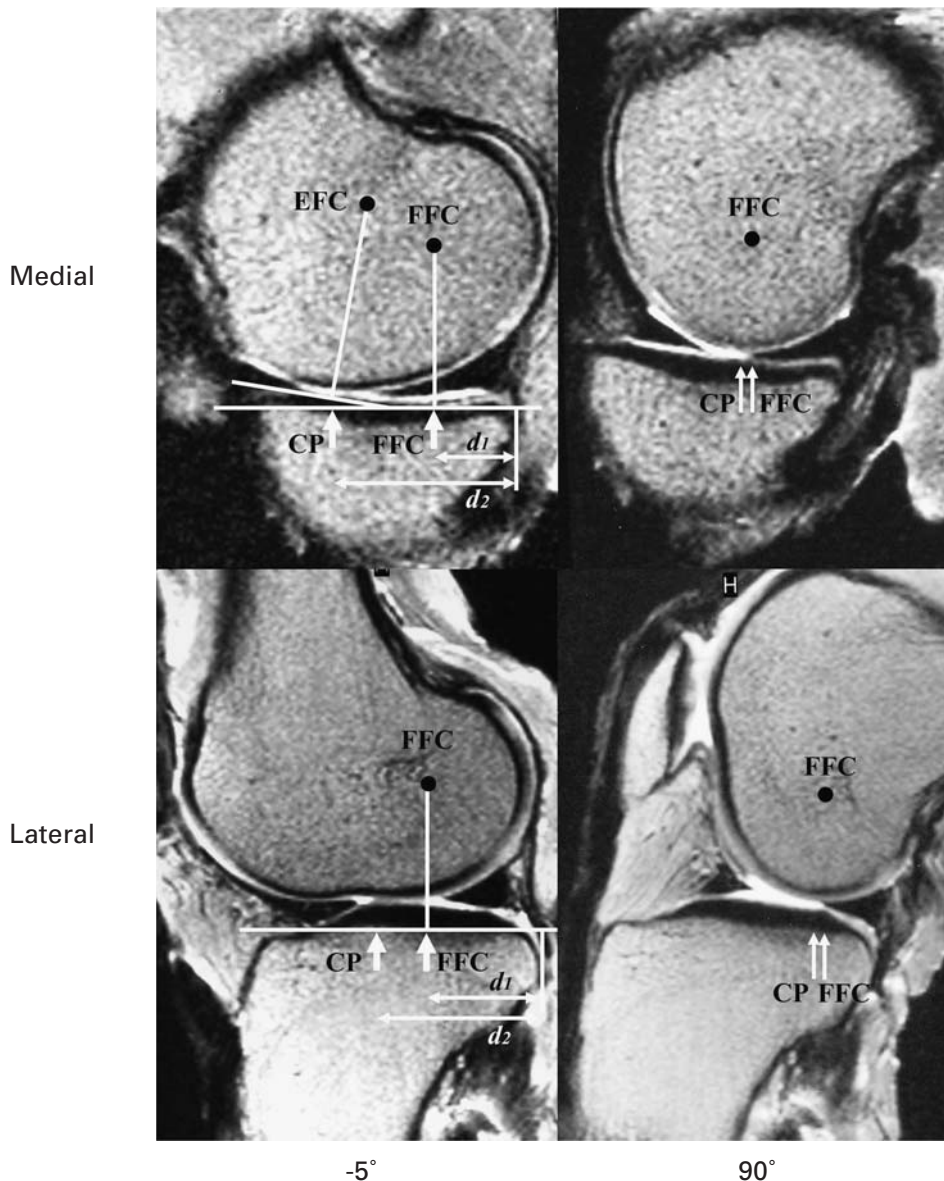


Fig. 1

Sagittal MR scans medially and laterally at -5° and 90° .

The cadaver knees were removed at routine post-mortem leaving the capsule intact. They were attached by pegs to a wooden board^{6,7} in neutral rotation at full extension, termed -5° and at 5° , 10° , 20° , 30° , 45° , 90° , 110° and 120° . Sagittal MR scans were obtained through the centres of the medial and lateral posterior, circular femoral surfaces, which we have elsewhere called the flexion facet centres (FFCs),^{6,7} using a 1.5 Tesla Philips Gyroscan (Philips Medical Systems, Eindhoven, The Netherlands). T2-weighted sequences were employed. The MRI slices used in this study crossed the tibial condyles at their mediolateral centres at all angles of flexion.

MR scans were obtained in the living volunteers as previously described⁸ with a 0.5 Tesla Interventional MR machine (Sigma MR Imaging System; General Electrical Medical Systems, Milwaukee, Wisconsin) using a T1-

weighted sequence. Sagittal sections in the same medio-lateral planes as those in the cadaver were obtained at -5° and at 20° , 45° , 90° and 120° . In one group the subject was seated while the left knee was examined non-weight-bearing. In the other group the same subjects undertook a weight-bearing squat on both legs while the left knee was examined.

Interpretation of the MRI. We identified the FFC on the sagittal MR scan (Fig. 1). Lines were constructed perpendicular to the plane of the tibial flexion facet passing through the medial and lateral FFCs. The distances (d_1 in Figure 1, medial and lateral) between these perpendiculars and the posterior border of the ipsilateral tibia were measured along the plane of the (medial) tibial flexion facet.^{6,7} On medial MR scans the centre of the anterior circular femoral surface, termed the extension facet centre (EFC)^{6,7} was also

Table I. Mean distances (mm) from the ipsilateral posterior tibial cortex to various points in the femur (EFC and FFC) and to the contact points (CP)

	Flexion angle (°)										Flexion angle (°)									
	-5	5	10	20	30	45	90	110	120		-5	5	10	20	30	45	90	110	120	
Cadaver knee																				
Medial																				
EFC	31	30	30	29	28						EFC	Not applicable								
Contact point	39	35	33	28	28	24	23	22	20	Contact point	31	28	27	25	24	22	15	12	10	
FFC	23	23	23	23	23	23	23	22	21	FFC	27	25	25	24	23	22	15	10	6	
Contacting femoral surface	EF	EF and/or FF				FF				Contacting femoral surface	EF	EF and/or FF				FF*				
Contacting tibial surface	EF	EF and/or FF				FF				Contacting tibial surface										
Non-weight-bearing knee																				
Medial																				
EFC	0		20		45		90		120		EFC									
Contact point	32		31		26		24		22		Contact point									
FFC	23		24		24		24		23		FFC									
Contacting femoral surface	EF	EF and/or FF				FF				Contacting femoral surface	EF	EF and/or FF				FF				
Contacting tibial surface	EF	EF and/or FF				FF				Contacting tibial surface										
Weight-bearing knee																				
Medial																				
EFC	0		20		45		90		120		EFC									
Contact point	31		29		24		22		21		Contact point									
FFC	40		29		24		24		22		FFC									
Contacting femoral surface	EF	EF and/or FF				FF				Contacting femoral surface	EF	EF and/or FF				FF				
Contacting tibial surface	EF	EF and/or FF				FF				Contacting tibial surface										
Lateral																				
EFC	Not applicable									EFC	Not applicable									
Contact point	29 27 24 17 12									Contact point	31 18 14 10 9									
FFC	26 26 24 18 12									FFC	26 18 13 10 6									
Contacting femoral surface	EF	EF and/or FF				FF				Contacting femoral surface	EF	EF and/or FF				FF				
Contacting tibial surface										Contacting tibial surface										

found and connected by a perpendicular to the contact point with the tibia (Fig. 1, medial -5°).

The places at which the medial and lateral subchondral plates of the femur and tibia most closely approached each other on the MR scan (Fig. 1) were also found and termed the contact points (CP). The distance (d_2 in Figure 1) between the CP and the posterior border of the tibia was measured as for the FFC. In using the term 'contact point' we are aware that contact is in fact over an area within which the 'contact point' may not be central and the weight-bearing area may extend into the meniscus.

The mean distances from the posterior tibial cortex to the FFC and to the CP at each angle of flexion medially and laterally for each of the three groups of knees were calculated (Table I).

Statistical analysis. The intra- and inter-observer errors with respect to the location of the EFC and FFC have been described elsewhere.^{6,7} The SD was 0.77 mm in cadaver knees with a 95% confidence interval (CI) of ± 1.5 mm.

In this study we estimated the accuracy and reproducibility with respect to the location of the CP. In all images of the three series the distances from the CPs to the ipsilateral posterior tibial cortex were measured twice by one observer (SN) with a minimum interval of one day between measurements. Intra-class correlations were 99.4% in cadaver subjects and 99.3% in living subjects showing the high reproducibility of the method of measurement. The intra-observer errors were 0.08 mm (-1.90 to +1.90) with an SD of 0.87 mm in cadaver subjects and -0.08 mm (-2.78 to +2.08) with an SD of 1.03 mm in living subjects. When one measurement was taken by one observer twice, the 95%

CIs were 1.70 mm in cadaver subjects and 2.01 mm in living subjects.

The distances from the FFC and the CP to the ipsilateral posterior tibial cortex were analysed using one-factor ANOVA and the Bonferrini/Dunn test to compare the difference in the three groups at -5° and at 20°, 45°, 90° and 120° in the medial and lateral compartments separately. The difference between each flexion angle in the same group was calculated by a paired *t*-test. The definition of significant difference was determined as a *p* value of less than 0.05. The statistical analyses were carried out using Statview 4.5 (Abacus Concepts Inc, Berkeley, California).

Results

The mean positions of the FFCs and CPs are given in Table I. MR scans of the medial and lateral compartments at full extension and 90° of flexion in the living weight-bearing knee are shown in Figure 1 and cadaver sagittal sections of the medial compartment in Figure 2.

In the medial compartment the results in all three groups (cadaver, living non-weight-bearing and living weight-bearing) were not significantly different at any flexion angle for any of the three points (FFC, EFC and CP). The last moved backwards between -5° and 30° but the FFC did not. In full extension the point of contact between the tibial and femoral extension facets lay below the EFC, around which the femur was then rotating, on a line perpendicular to the articulating tibial surface, i.e. the tibial extension facet. This is inclined upwards about 11° to the flexion facet (Fig. 1, medial, -5°). Later in flexion the point of contact moved

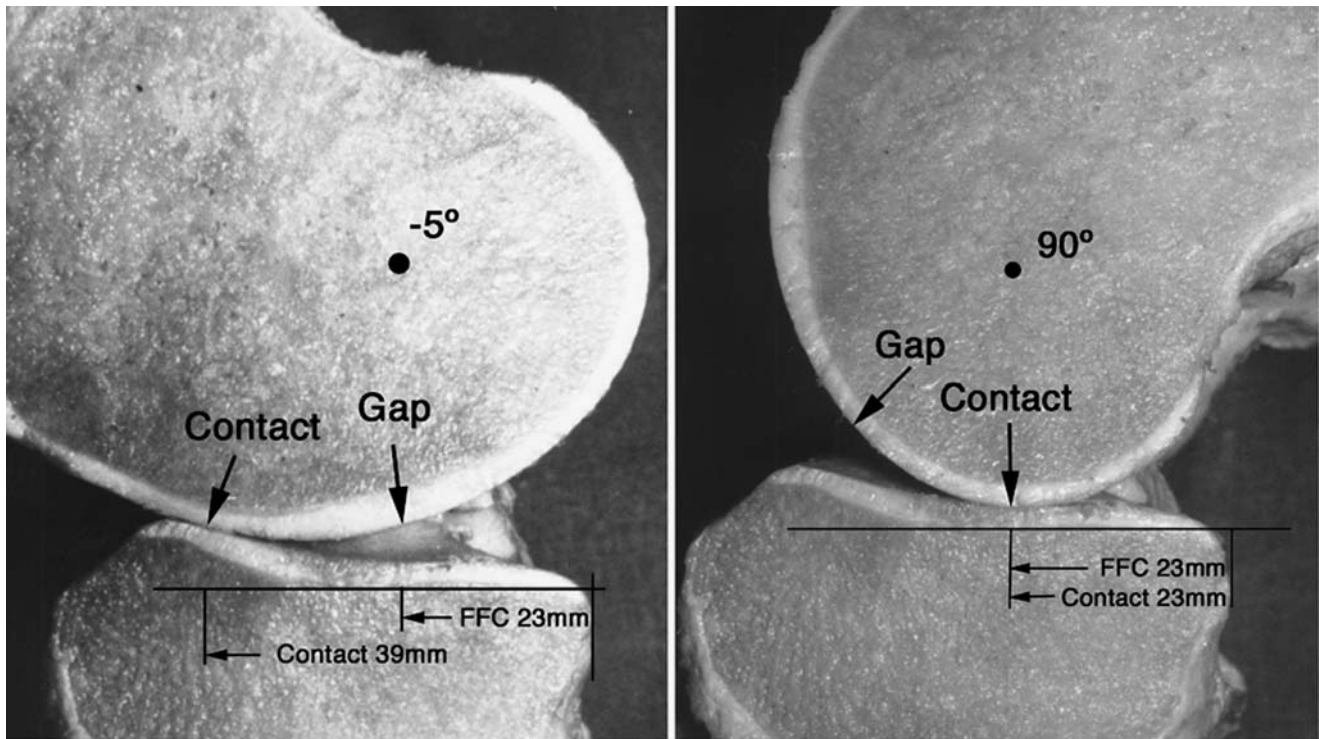


Fig. 2

Sagittal sections through the medial compartment at -5° and 90° . There is backward movement of the CPs but not of the femoral condyle.

back about 15 mm to lie below the FFC, perpendicular to the tibial surface (Fig. 1).

The lateral FFC and CP moved posteriorly in all groups by about 17 mm from 0° to 120° , the backward movement usually taking place between each pair of flexion angles, 80% to 100% of the intervals examined in each group. The movements in the lateral compartment in the two non-weight-bearing groups, cadaver and living knees, were similar to each other but in the weight-bearing knees the FFC and CP moved backwards to a greater extent than in non-weight-bearing knees early in flexion with significant differences in the arcs between 20° , 45° and 90° but not between 90° and 120° .

The mean anteroposterior positions of the femoral condyles, as shown by their FFCs, and the tibiofemoral CPs are shown in each group in Figure 3. In these figures the dotted lines connecting the FFCs denote the position of the femur itself at each flexion angle. The solid lines connecting the medial and lateral CPs show the position of the medial *versus* the lateral CPs at each flexion angle. Medially, the FFCs and the CPs coincide from 45° to 120° but with increasing extension the CP moves anteriorly away from the FFC to lie about 15 mm anterior to it at full extension. Laterally, the FFC and the CP coincide from 20° to 120° and, as on the medial side, the CP moves anteriorly away from the FFC with extension from 10° to 0° . Because of these differences between the positions of the FFC and the

CP, lines connecting the medial and lateral contact points remained approximately parallel throughout flexion and moved back across the tibia by about 20 mm from 0° to 120° . By contrast, lines connecting the condyles (FFCs) showed femoral external rotation around a medial centre, as reported elsewhere.⁶⁻⁸

Discussion

The medial and lateral tibiofemoral CPs were found to move backwards across the tibia by about 20 mm, remaining approximately parallel as they did so, a pattern similar to that reported by Walker and Hajek.⁹ This occurred in the cadaver as well as in the living knees and was not therefore due to muscular action. It also occurred with and without weight-bearing although the pattern was slightly different between the two, as already described for the movement of the condyles.^{8,10} By contrast, in the same knees and in all three conditions, the femoral condyles, (the FFCs), moved differently. The medial condyle hardly moved posteriorly whereas the lateral condyle moved backwards by rolling and sliding, about 20 mm, from 0° to 120° . This pattern has been previously described,^{5-8,10} and has been confirmed using roentgen stereophotogrammetric analysis/CT and 3-D digitisation.¹¹ Thus, there was a discrepancy between the movement of the CPs and of the condyles themselves, especially medially and near extension. How is this paradox to be resolved?

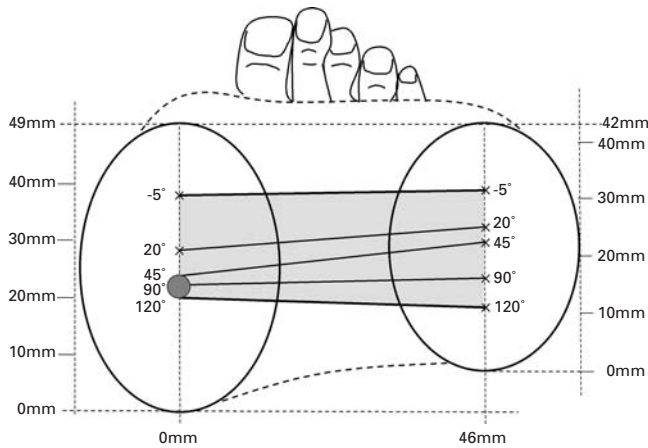


Fig. 3a

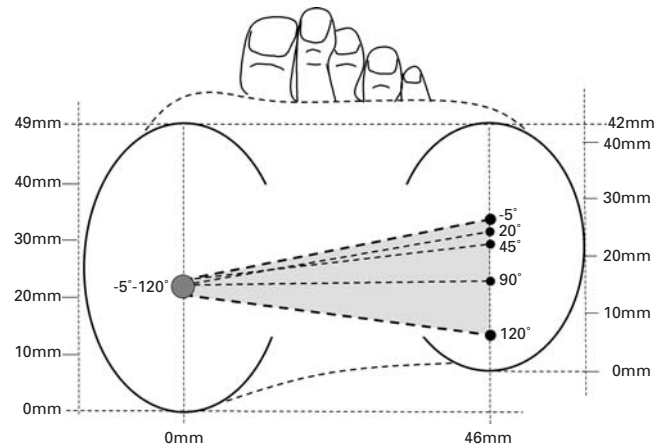


Fig. 3b

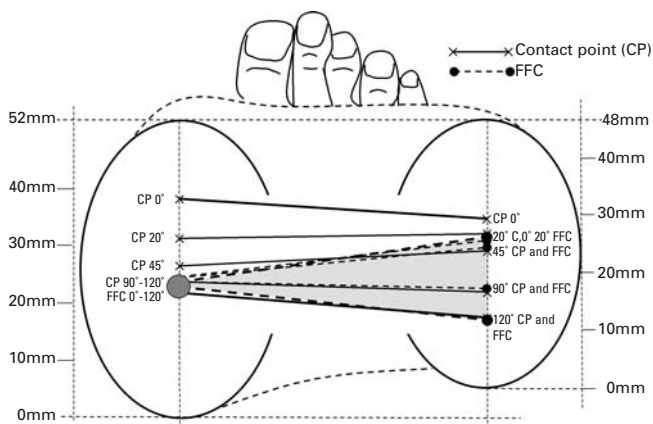


Fig. 3c

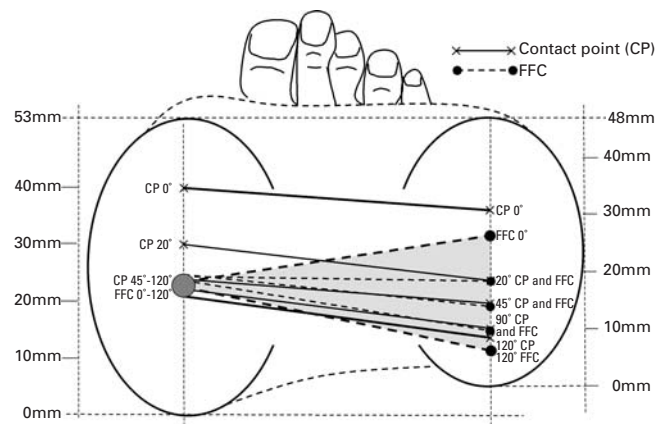


Fig. 3d

Diagram of the tibial condyles showing (a, b) cadaver knees ($n = 6$), (c) non-weight-bearing living knees ($n = 5$) and (d) weight-bearing living knees ($n = 5$). The solid lines connect the centres of the medial and lateral CPs and dotted lines connect the medial and lateral FFCs.

Resolution lies in the fact that the CPs and the FFCs describe different aspects of the condyles. The CPs are not fixed locations on the femur or on the tibia and cannot therefore be used to measure directly the relative positions of the two bones. Having said that, the CP would reflect the relative positions of the bones if, as on the lateral side beyond 10° and the medial side beyond 30° , the femoral surface were to be circular in sagittal section and the tibial surface flat. The situation would then be analogous to the wheel of a car moving on a road. Whether sliding or rolling, the CP would lie on a line perpendicular to the road passing through the centre of the wheel, equating to the FFC. Thus, the CP would always be vertically below the FFC. In the case of the knee, the anterior sagittal shapes, in contrast to the posterior, are not those of a circular wheel on a flat road and it is this which 'uncouples' the movements of the CPs and the condyles towards extension.

In the medial compartment, the anterior femoral surface is composed of an arc of a circle with a radius of about 30

mm, as against 20 mm posteriorly, while the anterior tibial surface inclines upwards by about 11° compared with the posterior part of the surface, the flexion facet.^{6,7} As the knee extends from 120° to about 30° , the tibial and femoral flexion facets are in contact (Fig. 4, line 1). The femoral condyle rotates around its posterior centre, the FFC, and this is vertically above the CP, i.e. up to this point the medial compartment is equivalent to a wheel sliding on a flat road. As the knee extends beyond 30° the anterior surfaces of the tibia and femur, the extension facets (EF), make contact.^{6,7} The femoral surface now has a more proximal and anterior centre with a greater radius and the tibial surface is inclined upwards. As a consequence the CP shifts forwards relative to the FFC (Fig. 4, line 3). This movement has been likened to that of a cradle by Weber and Weber¹ and called 'rocking' by Steindler.¹² Final extension from 10° to -5° can no longer be around the FFC but is instead around the EFC. Thus, the flexion facets lose contact, i.e. the femoral flexion facet lifts off the tibia, the knee 'opens'

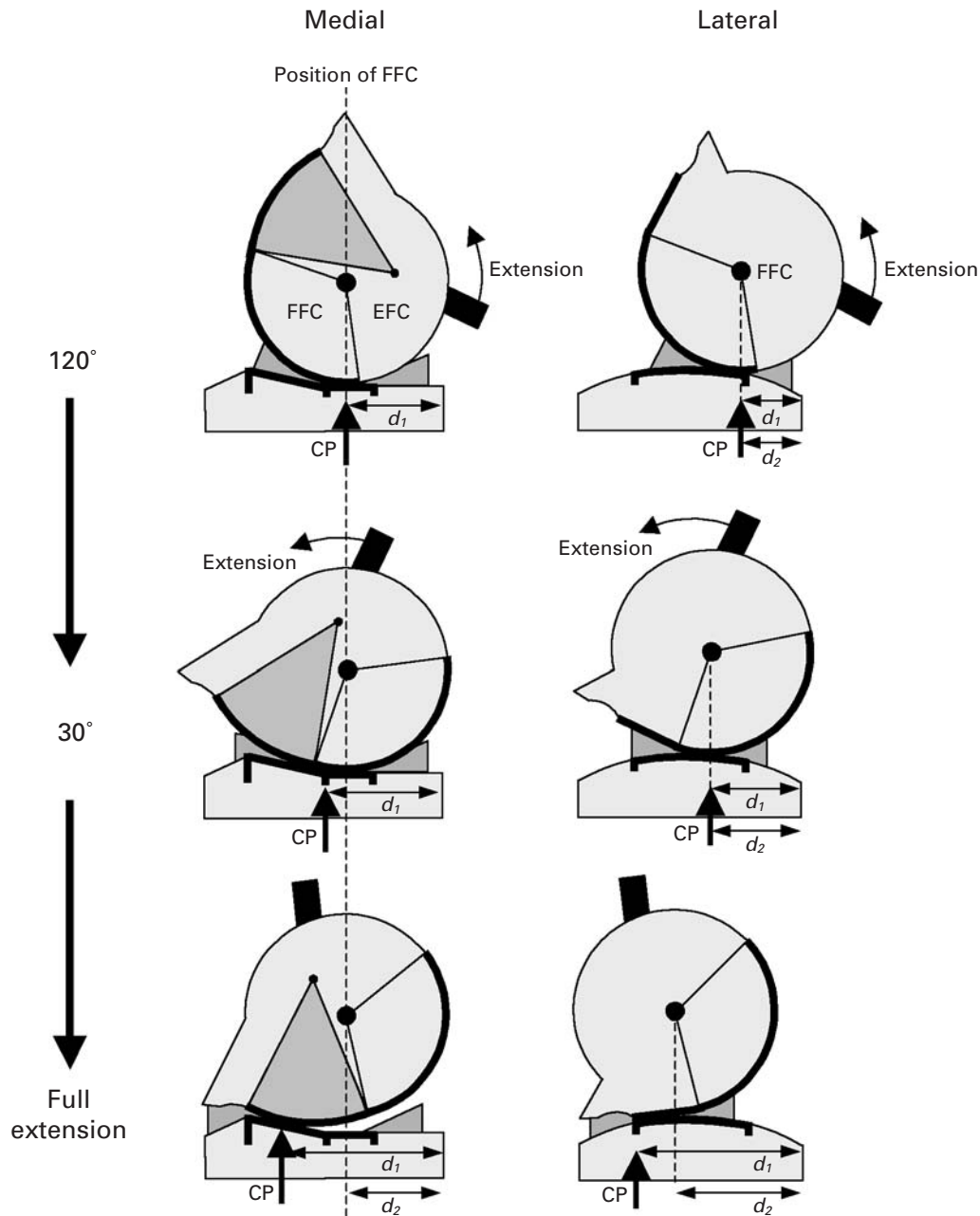


Fig. 4

Diagram representing tibiofemoral movement in both compartments.

posteriorly and the FFC rises relative to the tibia (Fig. 4, line 3).^{5-8,13} The CP now lies anterior to both the FFC and the EFC although the CP and the EFC are on a perpendicular drawn through the anterior tibial facet (Fig. 1, medial -5° and Fig. 4 line 3).

Laterally, the femoral surface is circular from 120° to 10° and contacts an essentially flat tibial surface. Thus, as on the medial side from 120° to 30°, the CP is vertically below the FFC (Fig. 4, lines 1 and 2) and moves forward with the FFC by an amount reflecting the femoral internal

rotation which accompanies extension. With further extension, especially after 10°, the anterior part of the femoral surface rotates down to contact the anterior extremity of the tibial surface (Fig. 4, line 3). This surface of the femur is larger in radius than the flexion facet (FF), indeed it is almost flat, but it is shorter. Having contacted the tibia, it rolls over the anterior edge of the tibial articular surface, seeming to compress the anterior horn as it does so^{6,14} and moving the CP further forwards than the FFC.

In short, the discrepancy between the movements of the femur, as measured by the FFCs, and of the tibiofemoral CPs is due to the differences in shape between the anterior and posterior parts of the surfaces of the joint.

The pattern of movement of the CPs which we have observed with flexion is similar to that which has been termed femoral 'roll-back'. However, only solid bodies, e.g. the femoral condyles, can roll. Areas can move but cannot roll. Thus femoral condylar 'roll-back' can only be said to occur laterally and to account for the movement of the CP, but it does not occur medially, at least up to 120°. Since roll-back of both femoral condyles with flexion does not occur, it is not necessary to seek a mechanism such as a rigid four-bar linkage, to account for it. In turn it is not surprising that the proposed mechanism does not exist because the posterior cruciate ligament is not tense at all times and thus the linkage is not rigid.⁴ Thus, the CPs move back but do not roll. The lateral femoral condyle does tend to roll back but the medial does not, a combination which equates to femoral external rotation with flexion.

It follows that, first, when describing movement of the knee care must be taken to define whether the CPs or the condyles are under investigation since the two move differently and the movement of the bones cannot be deduced solely from the contact areas, and secondly, that while it may be possible to design a total knee replacement implant which could replicate the movement of the condyles or the contact areas, to replicate both, i.e. to produce normality, is probably impossible.

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