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Tibio-femoral movement in the living knee. A study of weight bearing and non-weight bearing knee kinematics using 'interventional' MRI

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Abstract

The aim of this study was to image tibio-femoral movement during flexion in the living knee. Ten loaded male Caucasian knees were initially studied using MRI, and the relative tibio-femoral motions, through the full flexion arc in neutral tibial rotation, were measured. On knee flexion from hyperextension to 120°, the lateral femoral condyle moved posteriorly 22 mm. From 120° to full squatting there was another 10 mm of posterior translation, with the lateral femoral condyle appearing almost to sublux posteriorly. The medial femoral condyle demonstrated minimal posterior translation until 120°. Thereafter, it moved 9 mm posteriorly to lie on the superior surface of the medial meniscal posterior horn. Thus, during flexion of the knee to 120°, the femur rotated externally through an angle of 20°. However, on flexion beyond 120°, both femoral condyles moved posteriorly to a similar degree. The second part of this study investigated the effect of gender, side, load and longitudinal rotation. The pattern of relative tibio-femoral movement during knee flexion appears to be independent of gender and side. Femoral external rotation (or tibial internal rotation) occurs with knee flexion under loaded and unloaded conditions, but the magnitude of rotation is greater and occurs earlier on weight bearing. With flexion plus tibial internal rotation, the pattern of movement follows that in neutral. With flexion in tibial external rotation, the lateral femoral condyle adopts a more anterior position relative to the tibia and, particularly in the non-weight bearing knee, much of the femoral external rotation that occurs with flexion is reversed.

Keywords: Tibiofemoral movement; Knee kinematics; Magnetic resonance imaging; Interventional MRI

1. Introduction

There has already been extensive work on the kinematics of the tibio-femoral joint, but no previous study has imaged the internal anatomy of the living weight-bearing knee throughout the range of movement. Recent work using MRI in unloaded cadaveric and living knees has permitted descriptions of the femoral and tibial articular surfaces, and has imaged the movements of the medial and lateral femoral condyles during various arcs of knee flexion (Niitsu et al., 1990; Ando et al., 1994; Todo et al., 1999; Iwaki et al., 2000; Pinskerova et al., 2000; Hill et al., 2000; Nakagawa et al., 2000; Wretenberg et al., 2002). The validity of this method of employing MRI to study tibio-femoral movement has been confirmed by comparing it with RSA (Karrholm, 2000), RSA combined with CT and with a 3D digitiser (Martelli and Pinskerova, 2002; McPherson et al., 2002, 2004) carried out on the same 3 cadaveric knees.

A preliminary study to test the feasibility of using open MRI to image the weight-bearing living knee was published in Hill et al. (2000). Only 7 knees in male subjects were imaged in 4 positions from 0° to 90°. Non-weight bearing images were also obtained but not in the same subjects. Thus feasibility was demonstrated but the data was limited. The results obtained were comparable to the cadaveric experience (Iwaki et al., 2000). The object of the present study was to provide a definitive description over the whole flexion range based on Hill et al.'s preliminary work. We sought data points every 10° flexion from full extension to full flexion weight-bearing in 10 males. We also extended data on the effect of non-weight bearing vs. weight-bearing and of tibial rotation, and we compared males with females and left with right knees.

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2. Volunteers and methods

Ten male volunteers with no known abnormalities of the knee were recruited. The subjects were Caucasians with a mean age of 25 years (20–30 years). MR images of the right knees were obtained using a 0.5 T superconducting open magnet scanner (Signa SPIO; General Electrical Medical Systems, Milwaukee, Wisconsin) as described by Vedi et al. (1999). The vertical open configuration of the scanner allows the subject to be positioned weight-bearing standing and squatting, whilst the knee is scanned. The overhead gantry prevents a fully vertical position and thus the subjects stand with their backs against a board that is inclined at 10°. Sagittal images (5 mm thick, 0 mm spacing; pulse sequence: fast-spoiled gradient recalled echo in the steady state (FSPGR)) were obtained with the knee positioned in hyperextension (noted here as '−5°'), 10° increments from 0° to 120° (the limit of active flexion) and full deep squatting flexion (called here '140°', although some knees flexed further). It should be noted that the subjects maintained each increment whilst the knee was scanned and then flexed to the next angle, that is the activity is more quasi-static than dynamic. This procedure took a minimum of 10 min.

The volunteers positioned their feet shoulder width apart, with the longitudinal axis of the right foot approximately in the sagittal plane. The angle of knee flexion was measured by eye with a goniometer. 'MR tracking' was employed to maintain these sagittal planes despite incremental changes in knee position. The MR signal in a 'MR tracking' procedure is detected by a small receiver coil, which in this study was positioned anteriorly in the mid-line over the tibial tuberosity. This coil has a limited sensitive volume, and when the received magnetic resonance signal is subjected to frequency analysis a peak is seen in the power spectrum. This indicates the location of the coil (Dumoulin, 1998) and images can then be obtained in reference to this fixed point. It should be noted that the sagittal plane is specific to the magnetic field and not to the tibia. Multiple images were obtained across the knee and thus the optimal images could be selected.

The right knees of two female Caucasian volunteers (ages 26 and 32 years) were scanned as were the males.

In five of the 10 male volunteers the left knees were imaged at increments of flexion weight bearing as a squat in neutral rotation (0°, 20°, 45°, 90°, 120° and full deep flexion), and then flexing with both knees in full tibial internal and then in external rotation (0°, 20°, 45° and 90°). Following this, both knees were scanned non-weight bearing seated in neutral (0°, 20°, 45°, 90° and 120°) and in tibial external and internal rotation (0°, 20°, 45° and 90°). When non-weight bearing, the volunteer's foot was supported by the observer and a manual force applied to obtain full longitudinal rotation of the tibia. 'Flashpoint' (not MR) tracking (Gedroyc, 2000; Vedi et al., 1999) was used to maintain the same sagittal mid-medial or mid-lateral compartment plane of imaging despite changes in flexion angle or longitudinal rotation.

The posterior femoral condyles have been shown to have closely circular surfaces in the sagittal plane and the centres of these circles, elsewhere called the 'flexion facet centre' (Iwaki et al., 2000; Pinskerova et al., 2000) can therefore be used as reliable reference points for the position of the femoral condyles in reference to the tibia (Kurosawa et al., 1985; Elias et al., 1990). The movements of the posterior femoral condyles relative to the tibia were measured according to the method described by Iwaki et al. The centres of the posterior circular surfaces of the femoral condyles ('flexion facet centres') were identified by placing acetate overlays with circles of varying diameters over the mid-medial and mid-lateral compartment sagittal images. The distance between this centre and the ipsilateral posterior tibial cortex was measured for each position with a digital Vernier calliper, and corrected for magnification (Fig. 1). There was slight distortion of some of the images due to peripheral magnetic field inhomogeneity, but these have been included in the measurements taken.

In addition, the height of the flexion facet centre above the tibia was measured for each increment of flexion, both medially and laterally, for the 10 weight bearing male volunteers in neutral rotation.

In order to estimate intra-observer variation, twenty randomly selected images were measured twice by one observer, with a minimum interval of 24 h between measurements, and analysed according to the method

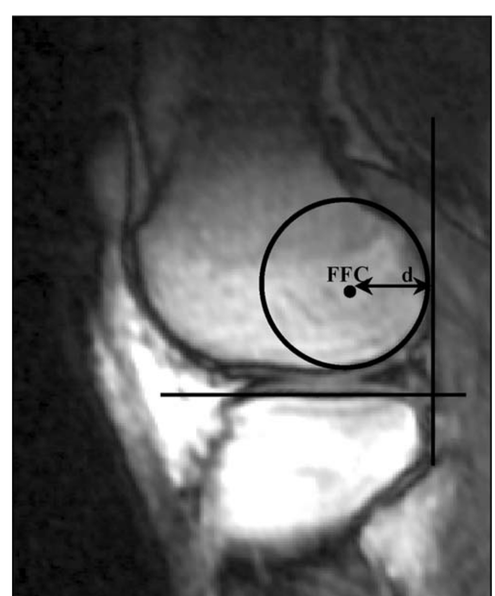

Fig. 1. Measurement technique. (FFC—flexion facet centre; d—measured distance to ipsilateral posterior tibial cortex).

described by Bland and Altman (1986). This suggested a mean difference ± standard deviation of 0.60 ± 0.78 mm (coefficient of variance of 2%).

3. Results

3.1. The male weight bearing knee from full extension to full flexion in neutral tibial rotation

On flexion from hyperextension ('−5°') to 120°, the lateral femoral condyle (measured by the lateral flexion facet centre) translates backward 21.1 mm ± 4.7 mm (mean ± standard deviation) relative to the tibia. From 120° to full deep flexion (140°), there is another 9.8 mm (±2.1 mm) posterior movement such that the lateral condyle almost subluxes posteriorly relative to the tibia (Fig. 2).

In contrast, the medial condyle (medial flexion facet centre) moves forwards 1.7 mm ± 1.3 mm between −5° and 30° (2.2 mm ± 1.5 between −5° and 90°) and 3.6 mm ± 2.0 mm posteriorly from 90° to 120°; a net posterior movement of 1.4 mm ± 3.3 mm from hyper-extension to 120°. Thereafter, it translates backward 8.4 mm (±2.1 mm) to full flexion (Fig. 2).

Between 10° and 30° the contact area transfers from the 'extension facet' to the more posterior 'flexion facet' (Iwaki et al., 2000; Pinskerova et al.,

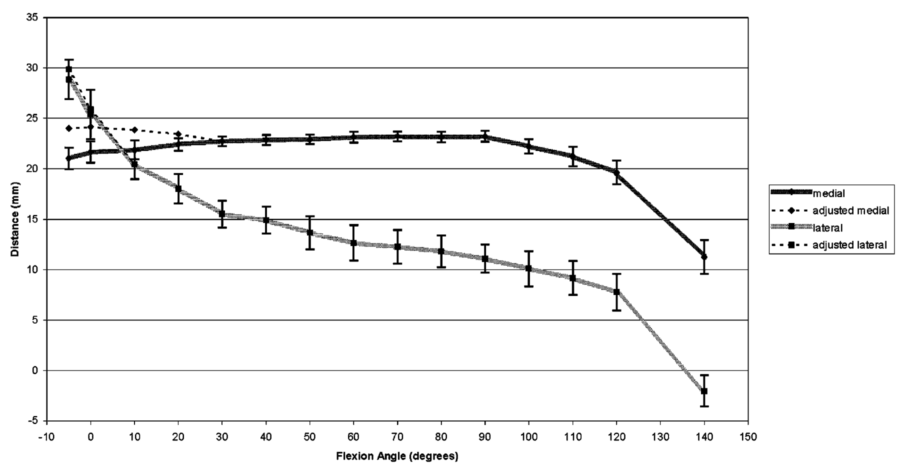

Fig. 2. Anteroposterior translation of medial and lateral femoral condyles: right knee, weight-bearing males, neutral rotation; mean ± 95% CI. The broken lines depict adjusted values for rotation around a more anterior extension facet centre (see text).

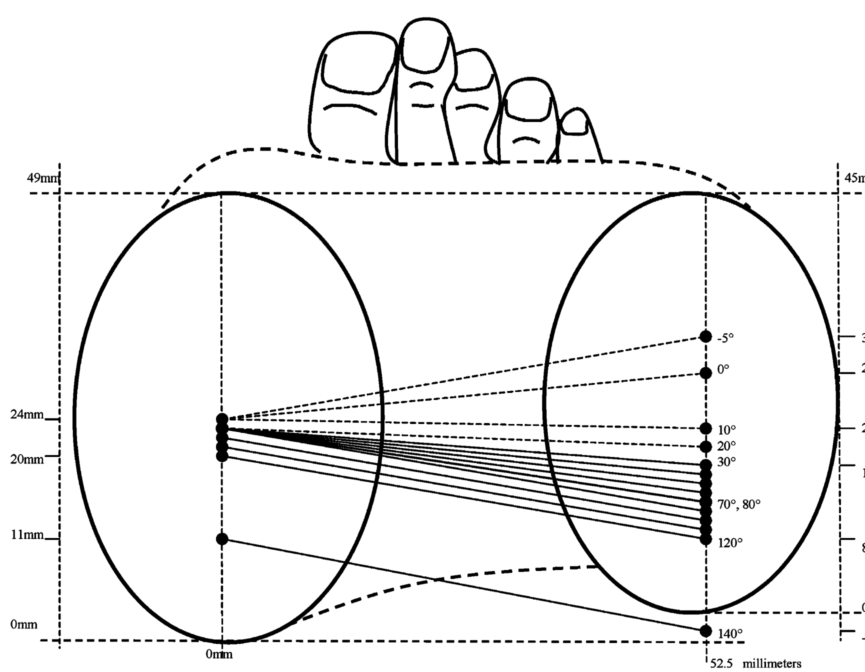

Fig. 3. Movements of medial and lateral femoral condyles relative to tibia: right knee; weight bearing males; neutral tibial rotation. The broken lines depict adjusted values for transfer from the flexion facet centre (FFC) to the more anterior extension facet (EFC).

2000). As a consequence of rotation around the extension facet axis from 0° to 30°, the flexion facet moves upwards and also backwards as the femur rotates to full extension. In Figs. 2–5 the broken lines depict suitably adjusted positions for the femoral condyle. The medial femoral condyle now demonstrates minimal anteroposterior movement between hyperextension and 90°.

The mean movements of both femoral condyles are in Fig. 3. The femur externally rotates (or tibia internally) through approximately 20° on weight bearing knee flexion from −5° to 120°, with the majority of this rotation occurring early in the flexion range and around a medially positioned axis. The 'flexion facet centre' of the lateral femoral condyle lies 2.0 mm (±2.5 mm) posterior to the posterior tibial cortex in full flexion.

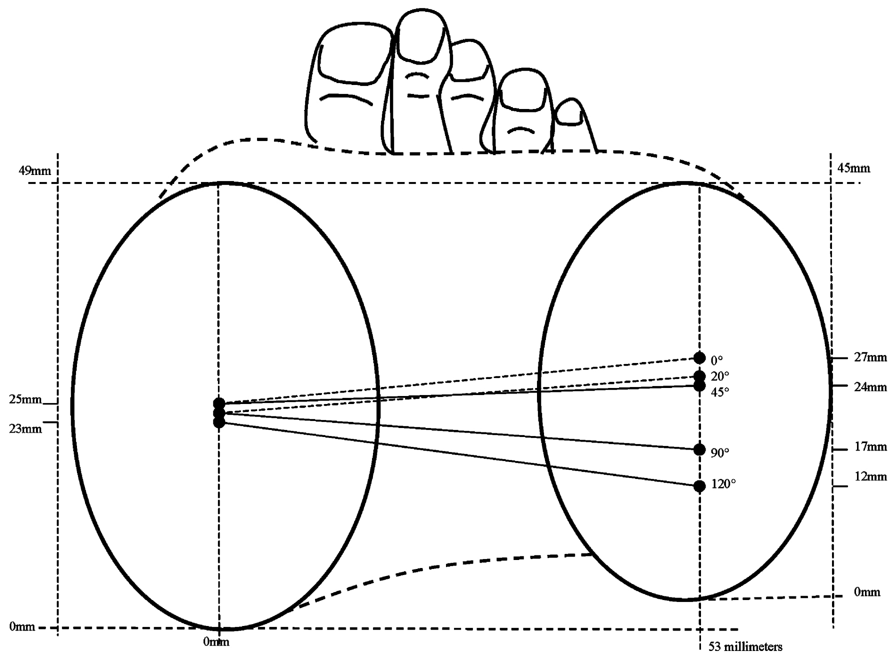

Fig. 4. Movements of medial and lateral femoral condyles: average of 5 right and 5 left knees; non-weight bearing males; neutral tibial rotation.

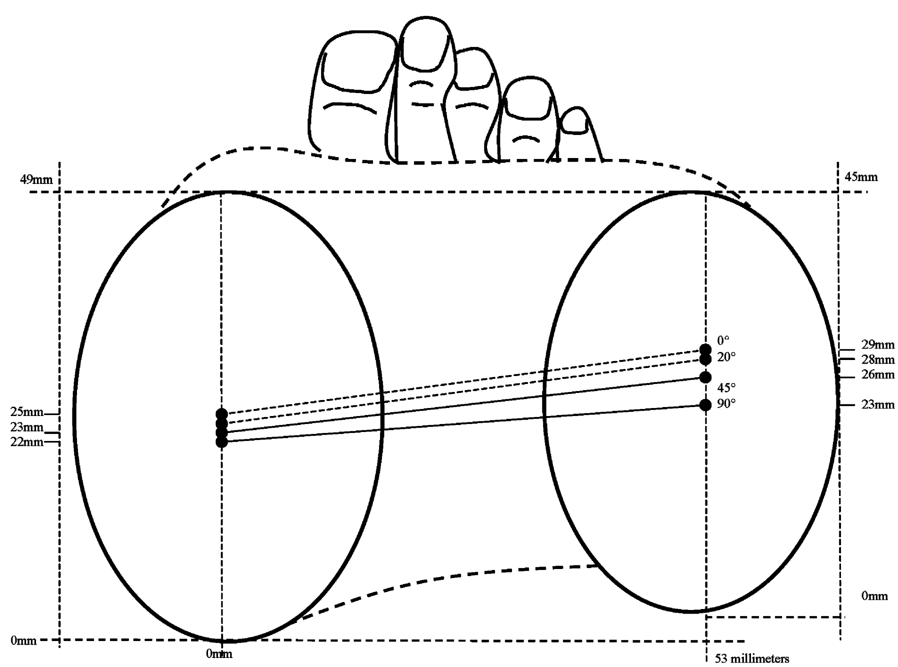

Fig. 5. Movements of medial and lateral femoral condyles: average of 5 right and 5 left knees; non-weight bearing males; tibial external rotation.

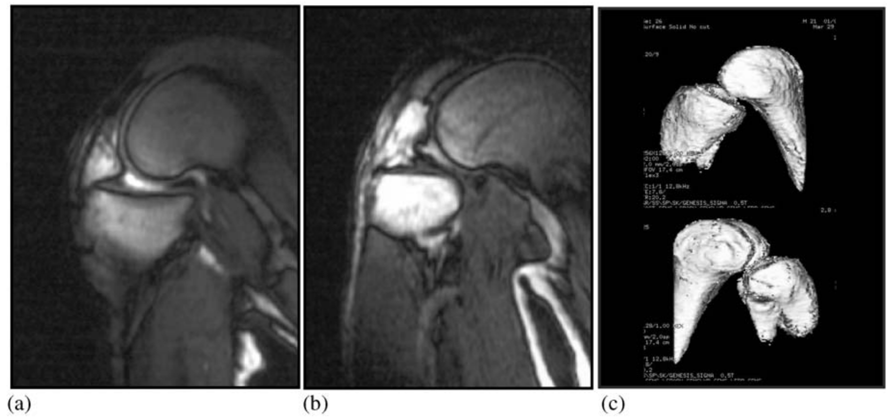

Fig. 6. The weight-bearing knee in full flexion: 'a'—medial sagittal image; 'b'—lateral sagittal image; 'c'—medial (above) and lateral (below) 3D images.

From 120° to full flexion the lateral flexion facet centre dropped 1.9 mm (±0.8 mm), as the femoral condyle rolled over the posterior corner of the tibia ($p<0.001$, paired t-test). Conversely, the medial condyle flexion facet centre lifted away from the tibial surface by a mean distance of 1.7 mm (±0.45 mm) compared with its position at 120° active flexion ($p<0.001$, paired t-test). Lift off medially was due to the fact that the femoral condyle rolls up onto the posterior horn of the meniscus. The medial meniscus does not move backwards with flexion, in contrast to the lateral meniscus, which does. It is therefore caught between the non-articular posterior (superior) surface of the femoral condyle and the tibia. The femoral condyle therefore rolls up onto the meniscus and lifts away from the tibia (Fig. 6).

On extension from 30° to −5°, the medial flexion facet centre lifts off the tibia by 1.1 mm (±0.79 mm), ($p<0.001$, paired t-test) as tibio-femoral contact transfers anteriorly. This is consistent with Iwaki et al.'s findings of the transfer of the contact area onto a more anterior 'extension facet' causing the posterior flexion facet to rise in non-weight bearing cadaver knees. The lateral flexion facet centre lifts little if at all.

3.2. The female knees

The results for the 2 female volunteers are similar to the previously described male knees. The lateral femoral condyle moves 20.7 mm ± 3.5 mm (mean ± standard deviation) posteriorly on flexion from −5° to 120°, whereas the medial condyle shows minimal anteroposterior translation. Beyond 120° both condyles move a similar distance into deep flexion (6.2 mm ± 2.2 mm laterally, 6.8 mm ± 1.9 mm medially). The limited resources and availability of the open MRI scanner prohibited scanning of more than 2 female knees, and thus they have not been subjected to statistical comparison to the 10 males.

3.3. The left vs. the right knee

The weight-bearing left knee in neutral rotation shows the same pattern of movement as previously described for the right knee. The medial flexion facet centre moves forwards 2.5 mm ± 0.2 mm between 0° and 20° (3.5 mm ± 1.1 mm between 0° and 90°). However, once the values from 20° to hyperextension have been adjusted for the transfer of contact from the flexion facet to the more anterior extension facet, there is little anteroposterior movement of the medial condyle. The lateral condyle 'rolls back' with flexion as before. (The differences between left and right scans were compared using a paired t-test: there was no significant difference.)

3.4. Non-weight bearing

The movement of the non-weight bearing knees in neutral rotation differs slightly from that of the same knees weight-bearing (Fig. 4). The femur externally rotates through 14° on flexion from 0° to 120°, with the majority of this occurring after 45° of flexion. This contrasts with the weight-bearing knee, where there are 16° of femoral rotation over this flexion arc, with most of this (approximately 11°) occurring between 0° and 45° of flexion.

3.5. Tibial rotation during flexion

In tibial internal rotation, the knee behaves approximately as in neutral rotation. The medial femoral condyle moves forwards slightly with flexion from 0° to 90° (1.6 mm weight bearing; 0.6 mm non-weight bearing). However, in tibial external rotation, both under weight bearing and non-weight bearing conditions, the lateral femoral condyle lies more anteriorly relative to the tibia at corresponding degrees of flexion. Thus, particularly in the unloaded knee, much of the femoral external rotation that is seen in neutral is reversed (Fig. 5).

4. Discussion

The first part of this study differs from that of Hill et al. (2000) in that more subjects were involved; more points in the flexion arc were examined, a greater range of flexion was studied, and imaging protocols and tracking methods were improved. Indeed, so far as we aware, this study is the first in which the soft tissues and bones of the weight bearing living knee have been imaged over small increments throughout the range. It therefore represents baseline data for other studies of movement of the bones and for comparison in due course with movements of the contact area and, for example, the PCL.

Our findings over the arc 0–90° differ only slightly from those of Hill et al. they stated that the weight-bearing medial femoral condyle moved 4 mm forward in flexion to 90°, whereas we found that there was minimal movement if adjustment is made for rotation around the extension facet centre from 20° to −5° (Iwaki et al., 2000; Pinskerova et al., 2001). The two studies reinforce each other and conform with previous cadaveric descriptions (Iwaki et al., 2000; Pinskerova et al., 2001). The medial femoral condyle does not 'roll-back' at least from hyper-extension to 90°, but the lateral condyle does. In spite of the fact that the medial femoral condyle does not move backwards from 0° to 30°, the contact area does do so because of the shapes of the femoral and tibial articular surfaces, a subject outside the scope of this paper.

During flexion from full extension to 20°, there were 10° of femoral external (tibial internal) rotation, a finding consistent with the rotation:flexion ratio of 1:2 first described by Braune and Fischer (1891). Full passive flexion (120–140°) is accompanied by 9.2 mm roll-back (8.4 mm medially and 9.8 mm laterally) i.e. there was little net longitudinal rotation in this arc, in contrast to the finding of Nakagawa et al. (2000) who did observe rotation in non-weight bearing Japanese knees flexing to 160°. At full deep flexion (140°), the lateral condyle has almost subluxed posteriorly off the tibia and the medial has rolled up onto the posterior horn (Fig. 6), findings which are consistent with Nakagawa et al.'s study of deep flexion in the unloaded Japanese knee and Hefzy et al.'s (1998) radiographic study.

Others have also imaged the movement of the normal living knee. Ramsey and Wretenberg (1999) reviewed the use of cortical pins to measure three-dimensional kinematics, discussing the work, in particular of Levens et al. (1948), Lafortune et al. (1992) and Reinschmidt (1997). Cortical pins permit direct measurement of skeletal movement, but are invasive and do not image the internal anatomy of the knee. Shapeero et al. (1988) used ultrafast, cine CT in cadaver knees and found that the lateral femoral condyle moved 2.3 times further on the tibial plateau than the medial condyle. More recently, Asano et al. (2001) used computed tomography to study the knees of six living subjects and described a femoral medial pivoting motion relative to the tibia similar to that described here. The disadvantage of radiographs or CT in living subjects is irradiation. RSA (Karrholm, 2000) also necessitates the insertion of tantalum markers. MRI is a safe and non-invasive tool and has been used in the living knee by others. Niitsu et al. (1990) described a technique for imaging of the knee joint during movement, and Sheehan et al. (1998) found cine phase contrast magnetic imaging a valuable technique for measuring in vivo patello-femoral movement. Wretenberg et al. (2002), using MRI to study tibiofemoral contact points in the non-weight bearing right knee of 16 subjects at 0°, 30° and 60° flexion, observed larger displacements of the contact area laterally than medially. However, in an earlier MRI study of knee flexion to 90° of 23 healthy knees in the lateral position, Ando et al. (1994) stated that the medial side moved more than the lateral.

Our findings in full passive flexion (Fig. 6) question the ability of total knee replacement prostheses of the condylar type to achieve ranges of flexion above 120° in a physiological manner. In particular, on the lateral side of the human knee there is extreme posterior displacement of the lateral femoral condyle on the tibia. With man-made materials, such as metal and polyethylene, it is doubtful if this could be achieved without causing the tibial component to lift-off anteriorly and/or the femur to sublux posteriorly. The medial posterior displacement onto the posterior horn, combined with tibio-femoral compression, might also over-stress the posterior lip of a polyethylene bearing and may account for the occurrence of posterior horn tears of the medial meniscus in deep flexion.

The results in the second part of the study suggest (but do not prove because of our small numbers) that, as one might expect, the pattern of relative tibio-femoral movement during knee flexion is independent of gender and side. They also show that femoral external rotation (or tibial internal rotation) occurs with flexion under loaded and unloaded conditions, but that the magnitude of rotation is greater and occurs earlier on weight bearing. The medial femoral condyle is essentially stable whether weight bearing or non-weight-bearing, in internal or external rotation, with minimal movement in an anteroposterior direction relative to the tibia from hyperextension to 120°.

During flexion from 0° to 90° in neutral tibial rotation, or in combination with tibial internal rotation, the lateral femoral condyle translates backwards, by a

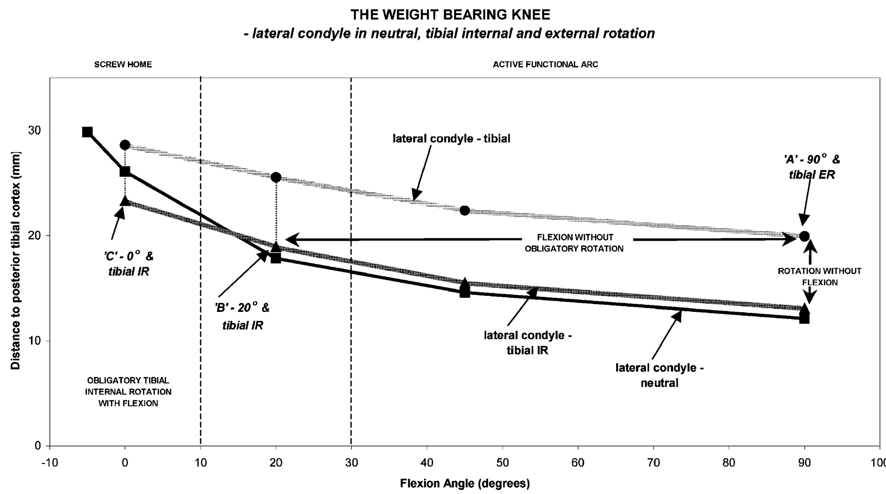

Fig. 7. The weight-bearing knee: points 'A', 'B' and 'C'—see text.

combination of sliding and/or rolling. This femoral external rotation with flexion is largely reversible at 90° if an external rotation force is applied to the tibia, particularly in the unloaded knee. Thus, if a volunteer stands with his knee at 90° of flexion in full tibial external rotation (Fig. 7, position 'A'), it would be possible for him to extend his knee to 20° (position 'B') without moving the lateral condyle antero-posteriorly. Thus, to a large degree, tibial rotation is 'facultative' rather than 'obligatory' over this arc (20–90°). However at position 'B' the tibia would be at the limit of internal rotation at that point in the flexion arc. Therefore to extend the knee from 20° in full internal rotation (Fig. 7, position 'B') to extension (position 'C', 0° flexion and full internal tibial rotation) the knee must rotate longitudinally. Some rotation is possible at 0° flexion (Hallen and Lindahl, 1966), and therefore flexion over the arc of terminal extension is accompanied by obligatory longitudinal rotation and, in addition, some optional rotation.

These results define the kinematics of the tibio-femoral joint by direct imaging. There may be biomechanical implications of the near vertical as opposed to full upright loading in the weight-bearing knees, and whilst some caution would also be appropriate in extrapolating these results to activities such as walking or running, the motions studied encompass the envelope (Blankevoort et al., 1988) within which knee motion can occur.

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References

Ando, Y., Fukatsu, H., Ishigaki, T., Aoki, I., Yamada, T., 1994. Analysis of knee movement with low-field MR equipment—a normal volunteer study. Radiation Medicine 12 (4), 153–160.

Asano, T., Akagi, M., Tanaka, K., Tamura, J., Nakamura, T., 2001. In vivo three-dimensional kinematics using a biplanar image matching technique. Clinical Orthopaedics and Related Research 388, 157–166.

Bland, J.M., Altman, D.G., 1986. Statistical method for assessing agreement between two methods of clinical measurement. The Lancet i, 307–310.

Blankevoort, L., Huiskes, R., De Lange, A., 1988. The envelope of passive knee joint movement. Journal of Biomechanics 21, 705–720.

Braune, W., Fischer, O., 1891. Die bewegungen des Kniegelenks nach einer neuer Methode am lebenden Menschen gemessen. Leipzig, S. Hirtzel.

Dumoulin, C.L., 1998. Active visualisation—MR tracking. In: Debatin, J.F., Adam, G. (Eds.), Interventional Magnetic Resonance Imaging. Springer, Berlin, pp. 66.

Elias, S.G., Freeman, M.A.R., Gockay, E.I., 1990. A correlative study of the geometry and anatomy of the distal femur. Clinical Orthopaedics and Related Research 280, 98–103.

Gedroyc, W.M.W., 2000. Interventional magnetic resonance imaging. BJU International Suppl. 1 86, 174–180.

Hallen, L.F., Lindahl, O., 1966. The 'screw home' movement in the knee joint. Acta Orthopaedica Scandinavica 37, 97–106.

Hefzy, S.M., Kelly, B.P., Derek, T., Cooke, V., 1998. Kinematics of the knee joint in deep flexion: a radiographic assessment. Medical Engineering & Physics 20, 302–307.

Hill, P.F., Vedi, V., Williams, A., Iwaki, H., Pinskerova, V., Freeman, M.A.R., 2000. Tibiofemoral movement 2: the loaded and unloaded living knee studied by MRI. Journal of Bone and Joint Surgery (Br) 82-B, 1196–1198.

Iwaki, H., Pinskerova, V., Freeman, M.A.R., 2000. Tibiofemoral movement 1: the shapes and relative movements of the femur and the tibia in the unloaded cadaver knee. Journal of Bone and Joint Surgery (Br) 82-B, 1189–1195.

Karrholm, J., Brandsson, S., Freeman, M.A., 2000. Tibiofemoral movement 4: changes of axial tibial rotation caused by forced rotation at the weight-bearing knee studied by RSA. Journal of Bone and Joint Surgery (Br) 82 (8), 1201–1203.

Kurosawa, H., Walker, P.S., Abe, S., Garg, A., Hunter, T., 1985. Geometry and motion of the knee for implant and orthotic design. Journal of Biomechanics 18 (7), 487–499.

Lafortune, M.A., Cavanagh, P.R., Sommer 3rd, H.J., Kalenak, A., 1992. Three-dimensional kinematics of the human knee during walking. Journal of Biomechanics 25 (4), 347–357.

Levens, A.S., Inman, V.T., Blosser, J.A., 1948. Transverse rotation of the segments of the lower extremity in locomotion. Journal of Bone and Joint Surgery 30A, 859–872.

Martelli, S., Pinskerova, V., 2002. The shapes of the tibial and femoral articular surfaces in relation to tibio-femoral movement. Journal of Bone and Joint Surgery (Br) 84 (4), 607–613.

McPherson, A., Pinskerova, V., Karrholm, J., Martelli, S., Freeman, M., 2002. How does the knee move? Possible methods of investigation. Poster. 10th Congress European Society of Sports, Traumatology, Knee Surgery, Knee Surgery and Arthroscopy, Rome.

McPherson, A., Karrholm, J., Pinskerova, V., Sosna, A., Martelli, S., 2004. Imaging knee motion using MRI, RSA/CT and 3D digitisation. Journal of Biomechanics. PII:S0021-9290(04)00084-3.

Nakagawa, S., Kadoya, Y., Todo, S., Kobayashi, A., Sakomoto, H., Freeman, M.A.R., Yamano, Y., 2000. Tibiofemoral movement 3: full flexion in the living knee studied by MRI. Journal of Bone and Joint Surgery (Br) 82-B, 1199–2000.

Niitsu, M., Akisada, M., Anno, I., Miyakawa, S., 1990. Moving knee joint: technique for kinematic MR imaging. Radiology 174 (2), 569–570.

Pinskerova, V., Maquet, P., Freeman, M.A.R., 2000. Writings on the knee between 1836 and 1917. Journal of Bone and Joint Surgery (Br) 82-B, 1100–1102.

Pinskerova, V., Iwaki, H., Freeman, M.A.R., 2001. The shapes and relative movements of the femur and tibia in the unloaded cadaveric knee: a study using MRI as an anatomical tool. In: Insall, J.N., Scott, W.N. (Eds.), 3rd Edition. WB Saunders Co., Philadelphia.

Ramsey, D.K., Wretenberg, P., 1999. Biomechanics of the knee: methodological considerations in the in vivo kinematic analysis of the tibiofemoral and patellofemoral joint. Clinical Biomechanics 14, 595–611.

Reinschmidt, C., van den Bogert, A.J., Nigg, B.M., Lundberg, A., Murphy, N., 1997. Effect of skin movement on analysis of skeletal knee joint motion during running. Journal of Biomechanics 30, 729–732.

Shapeero, L.G., Dye, S.F., Lipton, M.J., Gould, R.G., Galvin, E.G., Genant, H.K., 1988. Functional dynamics of the knee joint by ultrafast, cine-CT. Investigative Radiology 23 (2), 118–123.

Sheehan, F.T., Zajac, F.E., Drace, J.E., 1998. Using cine phase contrast magnetic resonance imaging to non-invasively study in vivo knee dynamics. Journal of Biomechanics 31 (1), 21–26.

Todo, S., Kadoya, Y., Miolanen, T., Kobayashi, A., Yamano, Y., Iwaki, H., Freeman, M.A.R., 1999. Anteroposterior and rotational movement of femur during knee flexion. Clinical Orthopaedics and Related Research 362, 162–170.

Vedi, V., Williams, A., Tennant, S.J., Spouse, E., Hunt, D.M., Gedroyc, W.M.W., 1999. Meniscal movement. An in-vivo study using dynamic MRI. Journal of Bone and Joint Surgery (Br) 81-B, 37–41.

Wretenberg, P., Ramsey, D.K., Nemeth, G., 2002. Tibiofemoral contact points relative to flexion angle measured with MRI. Clinical Biomechanics 17 (6), 477–485.