The flexion gap in normal knees
AN MRI STUDY

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Varus and valgus joint laxity of the normal living knee in flexion was assessed using MRI. Twenty knees were flexed to 90° and were imaged in neutral and under a varus-valgus stress in an open MRI system. The configuration of the tibiofemoral joint gap was studied in slices which crossed the epicondyles of the femur.

When a varus stress was applied, the lateral joint gap opened by 6.7 ± 1.9 mm (mean ± SD; 2.1 to 9.2) whereas the medial joint gap opened by only by a mean of 2.1 ± 1.1 mm (0.2 to 4.2). These discrepancies indicate that the tibiofemoral flexion gap in the normal knee is not rectangular and that the lateral joint gap is significantly lax. These results may be useful for adequate soft-tissue balancing and bone resection in total knee arthroplasty and reconstruction surgery on ligaments.

A knowledge of the kinematics of the knee is important for understanding the pathogenesis and treatment of disease, particularly when treatment involves surgical reconstruction. Recent studies, using modern techniques, have challenged some traditional concepts, such as the four-bar link model of movement of the human knee and obligatory femoral rollback.1-3

One such established concept is the preparation of a rectangular joint gap in total knee arthroplasty (TKA). This has been regarded as an important goal in achieving restriction of function of the knee.4-6 It has, however, been empirically recognised that the lateral tibiofemoral articulation is physiologically lax and as a consequence, the flexion gap in normal knees may not be rectangular.7-9 Because of technical difficulties, few quantitative data are available on the physiological laxity of the flexed, living knee. Such an analysis can only be performed if the flexed knee is imaged threedimensionally, both in a neutral position and under a varus-valgus stress. Recent developments in MRI have allowed the living knee to be examined in a variety of positions and flexion angles. Our aim was therefore to examine the varus-valgus laxity of the flexed knee using MRI, with reference to the tibiofemoral flexion gap.

Subjects and Methods

Imaging methods. Our subjects were 20 normal volunteers, ten men and ten women with a mean age of 27.2 years (18 to 53). They had no symptoms in the knee and radiographs were normal. The left knee was scanned in an open MRI unit (Airis; Hitachi, Tokyo, Japan) using a T1-weighted sequence (THR, 500 ms; TE, 20 ms; and the flip angle, 90°). Consecutive coronal scans of 3 mm in thickness were obtained across the distal femur and knee. Imaging was performed in the neutral position and under a passive varus-valgus stress at 90° of flexion (Fig. 1). Images under varus stress were obtained with the subject lying on his/her back in the unilateral cross-legged position (Fig. 1a). The varus stress was applied by the weight of the lower leg. Imaging under valgus stress was performed in the unilateral reversed-cross leg position (Fig. 1b) and that imaging in the neutral position performed in the left lateral position (Fig. 1c). During imaging, no special attention was paid to the rotational position of the tibiofemoral joint.

Methods of measurement. The slice which crossed the lateral and medial epicondyles of the femur and/or the longitudinal axis of the tibia was selected. Of the 60 image sequences obtained (20 knees in three positions), the epicondyles and the longitudinal axis of the tibia appeared in the same slice in 19 sequences. In the remaining 41 image sequences the epicondyles and the longitudinal axis of the tibia were not in the same slice and two different slices were used for the measurement.

The shape and width of the flexion gap were assessed, based upon four reference lines (A, B, C and D) and two reference points (E and F).
Line A was the epicondylar axis. This connected the lateral epicondylar prominence either to the medial sulcus (surgical epicondylar axis (SEA)) or to the medial prominence (clinical epicondylar axis (CEA)). The SEA was defined as line A if it could be seen but the CEA was used when the SEA could not be identified. Fourteen SEAs and 20 CEAs could be reproducibly determined and 14 SEAs and the six CEAs were used as line A. Line B was the posterior condylar axis (PCA) which connected the posterior margins of the lateral and medial femoral condyles. Line C was the tibial articular axis (TAA) which connected the proximal margins of the lateral and medial articular sur-

**Fig. 1a** Scanning positions under a) a passive varus stress, b) a passive valgus stress and c) in a neutral position.

**Fig. 2** Diagram and MR scan showing the reference lines and reference points which were used to assess the shape and width of the flexion gap. Detailed definitions are given in the text.
faces of the tibia. Line D was the tibial osteotomy axis (TOA) and was perpendicular to the longitudinal axis of the tibia, which was determined by connecting the midpoint of the width of the tibial diaphysis at two levels. Points E and F were the posterior tips of the lateral and medial femoral condyles.

The shape of the flexion gap in neutral and under a varus-valgus stress was assessed using an angle between line A and line D. This corresponded to the configuration of the flexion gap when an ideal bone resection in the proximal tibia and posterior femoral condyle was performed at TKA. The angle between line B and line C was also determined because this represented the physiological separation of the tibiofemoral articular surfaces. The width of the lateral and medial joint gaps was also measured as the distance between point E and point F and line C. The flexion angle was measured from the sagittal images of each knee.

The data were transferred to a personal computer (Apple Macintosh; Apple Computer Inc, Cupertino, California) and the angles and distances were measured using image analysis software (National Institute of Health image). The angles were expressed as a positive value when the femoral reference lines (lines A and B) were internally rotated relative to the reference lines for the tibia (line C and D).

Results

Representative images of the knees in neutral and under a varus-valgus stress are shown in Figure 3.

When no stress was applied, the lateral and medial femoral condyles were in contact with the tibial articular surface (width of the lateral and medial flexion gaps = 0 mm) with a mean flexion angle of $87.2 \pm 3.5^\circ$ SD (81.9 to 95.0) (Fig. 3a). When a varus stress was applied, the mean lateral flexion gap increased by $6.7 \pm 1.9$ mm (mean ± SD; 2.1 to 9.2) and the medial tibial and femoral joint surfaces were in contact with a mean flexion angle of $87.9 \pm 3.1^\circ$ (75.3 to 100.2) (Fig. 3b). Under a valgus stress, the mean medial flexion gap increased by only $2.1 \pm 1.1$ mm (0.2 to 4.2) and the lateral tibial and femoral joint surfaces were in contact with a mean flexion angle of $86.1 \pm 3.4^\circ$ (74.1 to 92.6) (Fig. 3c). The increase in the lateral flexion gap was significantly larger than that observed for the medial flexion gap paired $t$-test, $p < 0.0001$. The mean difference was $4.6 \pm 1.8$ mm (1.1 to 9.0) and implied that, when the flexion gap was distracted, the gap was trapezoidal and not rectangular.

Although there was a tendency for women to have a larger medial joint gap, the difference did not reach statistical significance; men $1.8 \pm 1.1$ mm (0.2 to 3.2); women $2.5 \pm 1.0$ mm (1.1 to 4.2); unpaired $t$-test, $p = 0.1487$. On the lateral side, there was no significant difference; men $6.5 \pm 2.3$ mm (2.1 to 9.2); women $6.9 \pm 1.5$ mm (4.5 to 9.2); unpaired $t$-test, $p = 0.6745$.

When the asymmetry of the flexion gap was expressed by the angle between lines A and D, the mean value was $11.0 \pm 2.5^\circ$ (6.2 to 15.0) under a varus stress and $0.1 \pm 2.4^\circ$ (-4.3 to +4.6) under a valgus stress (Table I). The mean asymmetry of the flexion gap in the knees which we examined was thus calculated to be $4.9^\circ$, based upon the angle in a neutral position of $3.1 \pm 1.7^\circ$ (1.3 to 7.5) and changes in the stressed positions of $7.9^\circ$ under a varus stress and $3.0^\circ$ under a valgus stress. When the asymmetry of the flexion gap was expressed by the angle between lines B and C, these values were $7.9 \pm 1.9^\circ$ (4.8 to 12.6) under a varus stress and $-2.8 \pm 0.9^\circ$ (-5.0 to -1.5) under a valgus stress. The mean
asymmetry of the flexion gap was thus calculated to be 5.1° based upon the angle in the neutral position (always 0°) (Table I).

**Discussion**

Our study is the first to analyse quantitatively the discrepancy of the joint gap in the medial and lateral tibiofemoral joint for normal knees. The results indicate that the flexion gap in a normal knee is not rectangular and demonstrates a discrepancy of 4.6 mm and a tilt of 5° in the femur and tibia. Although the relative lateral laxity in the normal knee in flexion has been widely recognised by many orthopaedic surgeons at arthroscopy, and reported by MRI, there has been a paucity of quantitative data.

A discrepancy of 4.6 mm is substantial in view of the detailed description on the symmetry of the flexion gap and related rotation of the femoral component in TKA. By general consensus, the femoral component is aligned to the SEAs and aims to make the flexion gap rectangular. This is essential for stability and kinematics during flexion. In the light of our findings, it is reasonable to ask if it is really necessary to make the flexion gap rectangular during TKA. Recent biomechanical studies have shown that flexion of the knee is associated with a significant medial-pivot internal rotation of the tibia. Thus, in rotation the medial condyle is immobile and the lateral condyle is mobile on the tibial articular surface. The different kinematics on the medial and lateral sides are partly due to the more congruent articular surfaces medially. However, the relative laxity on the lateral side is also likely to be important.

We did not use a special device to apply the varus-valgus stress, and therefore the amount of stress was not standardised and was affected by several factors including the weight of the leg and the mobility of the hip. Furthermore, it was not always possible to obtain the same scanning plane in the three positions (neutral, varus and valgus) which could misleadingly suggest a gap between the surfaces. However, the MR scans were consecutive 3 mm thick slices and the maximum error caused by measuring an adjacent slice was therefore calculated to be negligible (0.15 mm) when the radius of the femoral condyle was a sphere with a diameter of 30 mm. We, therefore, consider that the variation in slices had little or no impact on the main conclusion of our study. Another potential weakness was that the joint gaps were estimated by the application of a varus-valgus stress and not by a simultaneous, bilateral distraction force. Thus, the degree of asymmetry of the joint gap which we have shown may not be directly extrapolated to the joint gap at TKA.

In conclusion, our results indicate that the tibiofemoral flexion gap in the normal knee is not rectangular and that the lateral joint gap is significantly lax. The results fundamentally question the concept of a rectangular flexion gap at TKA and our understanding of tibiofemoral kinematics.

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### References