Tibiofemoral movement 4: changes of axial tibial rotation caused by forced rotation at the weight-bearing knee studied by RSA

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We studied the knees of 11 volunteers using RSA during a step-up exercise requiring extension while weight-bearing from 50° to 0°. The findings on weight-bearing flexion with and without external rotation of the tibia based on MRI were confirmed.

*J Bone Joint Surg [Br] 2000;82-B:1201-3.
Received 29 October 1999; Accepted 7 January 2000*

On the basis of a study of the non-weight-bearing cadaver knee using MRI, Iwaki et al¹ predicted that the longitudinal rotation of the tibia which accompanies flexion/extension in the unloaded knee would be abolished were it to be flexed while an external rotation torque was applied to the tibia. We have tested this hypothesis on the living weight-bearing knee using roentgen stereophotogrammetric analysis (RSA).

Subjects and Methods

We studied 11 volunteers, eight men and three women, with a median age of 24 years (17 to 41) and no history of injury or symptoms in the knee which was investigated. On the opposite side they had an old tear of the anterior cruciate ligament and tantalum markers had been inserted into the distal femur and proximal tibia of the normal knee bilaterally at the time of arthroscopy.

Two ceiling-mounted x-ray tubes were used to obtain simultaneous exposures. Film-exchangers were mounted on a stand, which allowed vertical and transverse adjustment and up to 90° of angulation. Initially, the knee was radiographed for RSA in extension with the subject supine, the 'reference' position. All examinations of knee kinematics were related to this position since we had earlier found it difficult to align the knee correctly on standing and because

its use facilitated comparison with previous studies.² The kinematic studies were also preceded by a calibration procedure.

The subjects ascended an 8 cm step, extending the weight-bearing knee from 50° to 65° to full extension. After five to seven trials when the patients had obtained a constant speed, the knee movements were recorded by nine pairs of simultaneous exposures over three to five seconds. Eleven knees were studied with the foot in neutral rotation. In four a further examination was done with the foot placed on the step in maximum external rotation. Since external rotation of the foot induced a consistent pattern of movement, the remaining seven subjects were not examined to limit exposure to radiation. The reproducibility of the movements recorded by this method has been determined in patients with total knee prostheses.³ Between two step-ups at an interval of 15 minutes, the standard deviations of rotation and translation, respectively, have varied from 1.6° to 2.3° and from 1.2 to 2.2 mm, when interpolated at 5° intervals of flexion. These values are at least ten times higher than the error of measurement. Thus, despite a number of preceding trials, subjects cannot reproduce an exact path of movement from one examination to another.

Relative tibial rotation about the longitudinal axis was measured using the tantalum markers in the distal femur as a fixed reference segment. The anterior-to-posterior translations of the medial and lateral femoral condyles were measured using the tibial markers as the fixed reference. To obtain reproducible sites from which to measure translations, two points were plotted on radiographs at the centres of the posterior circular surfaces of the medial and lateral femoral condyles using circular templates. The distances of these points from the joint line were recorded and used to find the corresponding points on the AP view. The medial-to-lateral positions of the points were measured by identifying the more dense cortical bone on the medial and lateral sides of the femoral condyles. These points correspond to the centres of the flexion facets described by Iwaki et al¹ who reported a precision of 1.5 mm. In our study the maximum observed error of crossing lines from focus 1 and 2 was 1.0 mm.

The two-dimensional co-ordinates of these plotted points were used to calculate their three-dimensional co-ordinates. Their locations were then related to the positions of the

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0301-620X/00/810715 \$2.00

Fig. 1

Mean ($\pm 1SD$) relative tibial rotations around the longitudinal axis. The number of observations for each series is at the bottom. The motion progressed from flexion to extension, i.e., from right to left on the graph.

tantalum markers in the distal femur. This information was used to find the three-dimensional co-ordinates of corresponding points at all the subsequent examinations of each knee.

Statistical analysis. Repeated-measures ANOVA was used to compare the two series of observations with the foot in a neutral position and in external rotation. The statistical comparisons were done between 15° and 50° of flexion when observations from all knees were available.

Results

Tibial rotation (Fig. 1). At 50° flexion with the foot in neutral rotation the tibia was found to be internally rotated by a mean of 4.9° (9.9 IR to 1.6 ER) relative to its reference position. As the knee extended, internal rotation (IR) increased slightly to 35°. Thereafter, the tibia rotated externally (ER) so that at 0° it was in <0.6° ER (median 2°) relative to the unloaded reference position. In six knees in which observations were made at 5° hyperextension, tibial ER increased to 1.5° (median 2.4; range 3.7 ER to 1.7 IR). In a solitary case observed with greater than 5° of hyperextension, ER increased to 7°.

In the four patients who were studied with the foot placed on the step in maximum ER, the tibia was found to be between 15.6° and 2.7° ER (mean/median 9.0/8.8° ER) at 50° of flexion. At full extension the mean/median values had changed to 6.8/6.0° ER (13.0° to 1.5°). Thus, placing the foot in full ER resulted in increased tibial ER both at

Fig. 2

Diagram of the tibial plateau to show the positions of the medial and lateral FCCs in relation to the reference position ('X', see text). Positions in neutral rotation: solid; in external rotation: dotted. Distances between the data points and the reference positions are in millimetres. The diagram itself is not scaled. A full description of diagrams of this type is in Iwaki et al.¹

50° and at 0°. The tibial IR which occurred as the neutrally-rotated knee was flexed to 50° was abolished as was the ER which had occurred as the neutrally-rotated knee was extended.

Anterior-to-posterior translations of the medial femoral condyle (Fig. 2). At 50° with the foot in neutral, the medial condyle lay 3 mm anterior to the reference position. The condyle then translated posteriorly during extension so that at 0° the femoral flexion facet centre (FFC) was 2.5 mm posterior to the reference position.

In the four cases studied in ER, the pattern of motion was similar, save that the medial condylar FFC maintained a more posterior position by 3 mm throughout the arc of motion.

Anterior-to-posterior translations of the lateral femoral condyle (Fig. 2). In neutral rotation, in contrast to the observation on the medial side, the lateral condyle translated anteriorly during extension. At 50° the condyle lay 4.1 mm posterior to the reference position, increasing to 5 mm at 40°. Thereafter there was a mean anterior displacement, which increased close to full extension. At full extension, the weight-bearing lateral femoral condyle lay 1.6 mm posterior to the reference position.

External rotation of the tibia changed the pattern of lateral condylar motion. At 50° the lateral condyle lay 3.7 mm anterior to the reference position as compared with posterior to it in neutral rotation. As the knee extended, posterior displacement was observed up to 25°. Thereafter no, or only minor, anterior-to-posterior motion was seen. At 0° the condyle lay 0.4 mm anterior to its reference position.

Conclusions

In the living weight-bearing knee we have confirmed the predictions made by Iwaki et al.¹ in the cadaver. In the

absence of tibial torque the tibia rotated internally relative to the femur with flexion and then rotated externally with extension. These rotations were suppressed, and to a slight extent reversed, if the knee was flexed and extended while the tibia was rotated externally.

Our findings are similar but not identical to those of Hill et al⁴ who examined the living knee flexing during a squat, as against, in our case, extending during a step-climb. We found less tibiofemoral rotation (10° v 15°) in neutral rotation and it occurred around a slightly more lateral axis. In both studies the medial femoral condyle moved forwards about 4 mm during flexion in neutral rotation but in our study the lateral femoral condyle moved back less. In external tibial rotation, little or no longitudinal rotation accompanied flexion in either study. Hill et al⁴ found, however, that both femoral condyles moved slightly back while we found both to move about 5 mm forwards. We cannot say whether these differences are due to variation

between the knees, the methods or the activities studied.

Financial support was obtained from IngaBritt and Arne Lundberg Research Foundation, Doctor Félix Neubergh foundation and Swedish Medical Research Foundation

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A list of consulted publications concerning the normal knee will be found on the *Journal of Bone and Joint Surgery* web site (www.jbjs.org.uk) for this issue until 2002.