Knee Kinematics in Lateral Knee Osteoarthritis studied with Radiostereometry

Jonas Weidow M.D.; Johan Kärrholm M.D. Ph D. Professor in Orthopedics; Tuuli Saari M.D. Ph. D.; and Andy McPherson B.Sc.

From the Department of Orthopaedics, Sahlgrenska Hospital, Göteborg University, Göteborg, Sweden.

Correspondence to: Jonas Weidow, MD, Department of Orthopaedics, Sahlgrenska University Hospital, SE-413 45 Göteborg, Sweden.
Phone: +46-31-3424298
Fax: +46-31-825539
Email: jonas@weidow.se.

Abstract

Knowledge of knee kinematics in patients with lateral osteoarthritis (OA) may facilitate the understanding of its pathogenesis and is of value for improved treatment. Based on findings of decreased anterior-posterior femoral condylar translation in knees with medial knee OA, we considered whether changes in lateral OA could be related to the wear pattern on the tibial plateau.

Sequential radiostereometric recordings were used to study the kinematics during active weight-bearing extension in 5 knees with lateral OA and 11 controls. At 45° of flexion the medial femoral flexion facet center had displaced anteriorly as an effect of internal tibial rotation in both groups, but this motion was more pronounced in cases with lateral OA. The lateral femoral facet center had displaced posteriorly at 45° and moved anteriorly during extension, in both groups. The medial femoral condylar flexion facet center translated proximally during extension in both groups. On the lateral side, there was also a proximal displacement with extension, but from a more distal position in the OA group. The OA knees showed increasing valgus angulation with extension, whereas normal knees rotated slightly into varus. The kinematics of knees with lateral OA could be related to the wear pattern on the tibial plateau, but not in the way we had expected.

Level of evidence: II
Introduction

The place on the tibial plateau for maximum wear in the knee osteoarthritis (OA) is probably caused by biomechanical factors including kinematics. In a previous radiographic evaluation we observed that patients with lateral knee OA had a broader pelvis and lesser offset than those with medial OA. In a gait analysis, patients with lateral OA showed higher outward rotation of the femur (relative to the pelvis) than patients with medial OA and control subjects. This might be explained by a smaller functional offset as suggested by the radiographic observation. In the gait analysis quoted above it was found that patients with lateral OA had statistically significantly more internal tibial rotation than those with medial OA.

Recordings of joint motions using skin markers are associated with more error than those recorded radiographically with skeletal markers. Dynamic radiostereometry was developed 20 years ago to overcome problems with such errors. Until recently these studies focused on the knee kinematics after anterior cruciate ligament rupture and total joint arthroplasty, in addition to studies of the normal kinematics of the knee. In 2005, Saari et al reported that patients with medial OA of the knee had decreased or absent internal tibial rotation (i.e., less posterior displacement of the lateral femoral condyle), a kinematic abnormality also observed in knees after anterior cruciate ligament rupture. These findings generated the hypothesis that when the knee is subjected to a degenerative disease with medial OA as end stage, it could be that the kinematics of the knee deteriorates according to a specific pattern. Previous gait analyses of knees with medial and lateral OA suggest that the any such progressive changes of the knee kinematics in lateral OA might be different. One of the first steps to further evaluate such a hypothesis is to determine the detailed kinematics of knee with lateral OA during activity. Recordings were made based on markers fixed to the skeleton. We used dynamic radiostereometric analysis to ensure the highest possible accuracy of recording.

Previous observations of anterior and central wear in medial OA and central and posterior tibial wear in lateral OA suggest that in the latter case the lateral femoral condyle relative to a fixed tibia occupies a more posterior position, which may be either a cause or an effect of the disease. We therefore presumed that the lateral femoral condyle would maintain a more posterior position in knees with lateral OA when compared to normal knees. The translation of the femoral condyles during knee motion becomes the inverse of the magnitude and direction of the relative knee rotations. Based on previous gait analysis we expected that the internal tibial rotation relative to a fixed femur during extension should be unaffected or slightly increased. As an effect of lateral compartmental wear in the OA group a more pronounced valgus position and a more distal position of the lateral flexion facet center could be expected during extension and weight-bearing.

Materials And Methods

Patients with lateral OA on the waiting list for total knee prosthesis surgery were asked to participate. During a period of 18 months, 5 patients (4 women and 1 man; 70 year, 62-74, Ahlbäck median Grade = 3; range 3-4) of 10 available were accepted. The other 5 were denied or were judged to be too handicapped to be able to perform a step up in a reproducible way and without any assistance. The intact knee in eleven patients (eight men and three women) with a unilateral traumatic anterior cruciate ligament rupture acted as controls. The average age of the control group was 6 years (range, 6–4). All patients signed an informed consent. The local ethical committee approved our study. We measured the anterior/posterior and proximal/distal translations of the femoral flexion facet centers with the tibia...
fixed. We also computed tibial rotations in terms of flexion - extension, internal - external rotation and varus- valgus angulation. Because of a thorough previous documentation of various conditions of the knee, the anterior – posterior translations of a midpoint on the tibial plateau during active knee motion with a fixed femur are reported as comparable with these previous observations.4, 12, 15-20

Our set-up for dynamic radiography during active extension of the knee has been described previously 4, 17-20. Briefly, 2 to 4 weeks before the examination, we inserted spherical tantalum markers (0.8 mm) using local anesthesia. Four to 8 markers were placed in the proximal tibia and the distal femur, respectively. In the control subjects, we inserted markers bilaterally during arthroscopy of the injured knee.

To obtain a standardized starting position, a pair of stereoradiographs was exposed supine at 0° extension with the knee inside a biplanar cage. At this exposure, the tibia and femur were aligned with the longitudinal axis of the cage and the posterior cortices of the femoral condyles were positioned to project over each other. This meant that the transverse axis of the cage, which defined the reference coordinate system, was parallel with the posterior condylar plane.

During the recording of the knee kinematics at active extension, the patients mounted a 16 cm high platform after practicing several times. The goal was to obtain a standardized speed during a period of 3 to 4 seconds. The exposures were done with two X-ray tubes designed for simultaneous and continuous exposures. They were placed at a 90° angle in relation to each other. We used a speed rate of 2 to 4 frames per second. The patients and control subjects started the active extension at median 57° flexion and ended at 2° hyperextension. Seven to 13 (median 10) exposures were available for analysis. Observations from all subjects were available between 15° and 45°. The median value of the “mean errors of rigid body fitting” (marker stability indicator) and condition numbers (marker scatter indicator) were 0.14 and 0.09 mm (range, 0.05–0.26 mm; 0.05–0.22 mm) and 83 and 82 (range, 29–136; 39–166) for the femoral and tibial markers, respectively.

We used film-exchangers designed for conventional roentgen films. The films were scanned in a flat-bed scanner (Scanmaker 9800, Microtek®, Carson, CA, USA). The digitized images were measured using dedicated software (UmRSA Biomedical®, Umeå, Sweden).2, 3 We recorded the relative tibial rotations using the femoral markers as a fixed reference. We measured translations of the flexion facet centers of the medial and lateral femoral condyles (Fig 1)9 and of a point located between the two tips of the tibial eminence using the point transfer technique.4, 17 This technique is used to assure that translations are measured at about the same location in all knees and to obtain equal influence on the translatory motions of concomitant knee rotations between the different knees studied. The point of interest is identified on one pair of stereoradiographs in each knee and is mathematically transferred to all subsequent examinations. The first step in this transferal is to determine the three-dimensional coordinates of the fictive point. Its location in relation to the bone markers within the same bone is determined. This information is used to relocate exactly the same point at all subsequent examinations of interest. Repeated plotting of the tibial intercondylar eminence and the flexion facet centers have revealed a maximum error in any direction of 1-1.5 mm. This error means that translations not could be measured at exactly the same anatomical position in all patients, partly because of the error of the plotting procedure itself and partly
because of normal variations of the anatomy of the knee.

To reduce the amount of data, we focused on 7 parameters. We recorded femoral translations with the tibia fixed. These translations were measured at the flexion facet centers $8^8$, $10^8$, $17^8$ of the two condyles (Fig 1). Anterior (+)/posterior(−) and proximal (+)/distal (−) translations were accounted for. Relative tibial rotations with a fixed femur were recorded as flexion (+)/extension (−), internal (+)/external (−) rotation, and varus (+)/valgus (−) angulation. Recordings of tibial translations were restricted to anterior (+)/posterior (−) motions of a midpoint between the two tips of the tibial intercondylar eminence, related to a fixed femur. To evaluate the relative tibial position at the reference (starting) position corresponding to the stereoradiographic examination at 0°, we used the lateral view according to Nilsson et al.$^6$ The quotient $a/a+b \times 100$ (Fig 2) did not differ between the study group and control subjects (lateral OA median, 23; range, 0–42; control subjects median, 22; range, 10–25; $p = 0.8$).

In a previous study in the same laboratory,$^{20}$ the repeatability between two series in the same patient was found to be 1.6° to 2.3° and 1.2 to 2.2 mm. These values are one standard deviation of the error scatter based on the presumption that there is no systematic deviation between two series. During these examinations the patients repeated the knee extension a second time and after an interval of 15–20 minutes, when a new series of radiographs were exposed. The difference between these two series is up to ten times higher than the accuracy of radiostereometry,$^3$ which means that despite a number of trials the patient was not able to exactly reproduce the same knee motion between two occasions.

The observed motions were interpolated at 5° intervals in flexion-extension. Observations were collected at 10° to 50°. We used Mann-Whitney U-test for comparison at 15° and 45° of flexion. Wilcoxon signed rank test was used for comparison within each group of the two groups. We considered $p$ values equal to or less than 0.05 significant.

---

**Fig 1.** Positions of the flexion facet centers 8, 10 are illustrated. These positions were identified on the reference stereoradiographs. Before the final evaluation of translation data, the identical positions on the subsequent (dynamic examinations) were mathematically computed by use of their known positions in relation to the tantalum markers in the distal femur (point transfer function in UmRSA).

**Figure 2.** The relative anterior/posterior position of the tibia was measured on the lateral view of the reference position. The reconstructed central femoral line divided the tibia into one anterior (distance $a$) and one posterior (distance $b$) part. The quotient $a/a+b \times 100$ was computed.
Results

Our hypothesis concerning the anterior-posterior translations of the flexion facet centers could not be verified. The other findings were more or less expected.

In both groups the medial flexion facet center had displaced anteriorly at 45° of flexion. This translation was more pronounced in the OA group (mean/median = 7.2/7.8 mm) compared to the controls (2.6/2.3 mm, p=0.027, Table 1, Fig 3). At 15° the OA group had a greater mean and median anterior displacement (p = 0.05).

<table>
<thead>
<tr>
<th>Table 1. Kinematic recordings at 15 and 45 degrees of knee flexion. Values are median (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tibial rotations, degrees</td>
</tr>
<tr>
<td>internal(+)/external(-)</td>
</tr>
<tr>
<td>varus(+)/valgus(-)</td>
</tr>
<tr>
<td>Tibial translations, mm</td>
</tr>
<tr>
<td>anterior(+)/posterior(-)</td>
</tr>
<tr>
<td>Femoral translations, mm</td>
</tr>
<tr>
<td>– medial condyle</td>
</tr>
<tr>
<td>proximal(+)/distal(-)</td>
</tr>
<tr>
<td>anterior(+)/posterior(-)</td>
</tr>
<tr>
<td>– lateral condyle</td>
</tr>
<tr>
<td>proximal(+)/distal(-)</td>
</tr>
<tr>
<td>anterior(+)/posterior(-)</td>
</tr>
</tbody>
</table>

<sup>a</sup> Mann-Whitney test.

Fig 3. Anteroposterior translations of the medial flexion facet center are illustrated. In lateral osteoarthritis the medial condyle had a more anterior position. Numbers of observations are placed at the bottom. Mean and standard error of the mean (SE) are shown.

Fig 4. Anteroposterior translations of the lateral flexion facet center are illustrated. These motions were small without any substantial difference between the two groups. Numbers of observations are according to Figure 2. Mean and standard error of the mean (SE) are shown.
At 45° the lateral flexion center had translated posteriorly (mean/median: -0.9/-3.4 mm) in both the OA and the control groups (-4.5/-2.7 mm) without any difference (p = 0.7). Extension to 15° was associated with minimum changes of the anterior – posterior position in both groups (OA vs. controls: p = 0.6, Figs 4). At 45° the medial flexion facet center had displaced 3 to 4 mm distally in both groups. With extension of the knee it moved proximally and to about the same amount in the study and control groups.

In the OA group and at 45°, the lateral flexion facet center had displaced 3-4 mm more distally than in the control subjects (p = 0.05, Fig 5). With increasing extension, the lateral flexion center translated proximally in both groups (lateral OA, 1.2 mm; control subjects, 0.6 mm) resulting in a median difference of 3.2 mm at 15° of flexion (p = 0.001).

At 45° of flexion, the tibia rotated inwards regardless of whether the knee had lateral OA. Both groups showed a tendency to valgus angulation during active extension. At 45° there was no difference (Fig 6). With increasing extension, knees with lateral OA rotated into slightly more valgus, whereas the normal knees showed slight varus angulation, resulting in a
median valgus tilt of -2.1º in the OA group and a neutral position (0º) in the control group (p = 0.001, Table 1).

With the femur fixed, the center of the tibial plateau displaced slightly more than 1 cm posteriorly at 45º (OA vs. controls: p=0.3). This displacement decreased to slightly less than 2 mm at 15º (OA group: p = 0.04, controls: p=0.006, Wilcoxon signed rank test) without any difference between the two groups (p=0.7)

**Discussion**

Presence of lateral OA did change the pattern of anterior-posterior condylar translations, but not in the way that we had expected. Instead, the medial flexion facet center displaced more anteriorly than normal. On the lateral side, the anterior – posterior position did not change.

Several studies using both magnetic resonance imaging and radiostereometry have shown that in the natural knee placed in a neutral position the femoral condyles move in a very reproducible way (for review see Freeman and Pinskerova)\(^8\). Interestingly, consistent changes occur when the knee suffers from degenerative disease, but these changes differ markedly between lateral and medial OA. In lateral OA the anterior – posterior motions of the medial condyle tended to be greater than normal, whereas in medial OA Saari et al\(^7\) found them to be smaller and normal (Fig 7). These authors observed about 1 mm of anterior displacement of the medial facet center at 50º and 20º flexion. In our study, control subjects moved this center 2-3 mm posteriorly from 45º to 15º.

In lateral OA, the medial flexion facet center was situated 4 to 5 mm further anteriorly at 45º and displaced 5-6 mm posteriorly up to 15º.

In knees with lateral OA the anterior – posterior movement of the lateral flexion facet center was small (0.8–1.5 mm), as previously observed in knees with medial knee OA (1.1 mm)\(^7\). In these knees, the lateral facet center was more anteriorly located when the extension was initiated (0.5 mm anterior to its reference location compared with 4 mm and 1 mm posteriorly in control subjects and lateral OA).

Our study has several limitations. Few cases were available, partly because idiopathic lateral OA has a considerably smaller prevalence than medial OA. Thus, the numbers of observations were small. Even if these numbers were sufficient to demonstrate significant differences when compared to controls, expansion of the study group could be of interest to obtain more firm conclusions. The arc of motion studied corresponds to that most used during many daily activities. Further observations at deeper flexion however, could be interesting since in lateral OA the position for maximum wear is often found far posteriorly on the femoral condyle. Studies of knee kinematics in those patients at more pronounced flexion during weight is difficult because many of

---

**Fig 7.** Reconstruction of the tibial plateau and the projections of the flexion facet centers between the reference position (x) and 45º (dot or square) are shown. The tibial plateau was reconstructed from CT data of a normal knee. In addition to data from control subjects and knees with lateral osteoarthritis (OA) the corresponding mean translations in 14 knees with medial OA (from Saari et al117) are illustrated. As an effect of internal tibial rotation at 45º the medial femoral condylar center displaced anteriorly and the lateral one posteriorly (mean values) in control subjects and knees with lateral OA. In medial OA, the mean AP translations were small and in the opposite directions (posteriorly in medial compartment and anteriorly in the lateral one).
them are unable to perform such a motion in a reproducible way because of pain and instability.

One possible source of error in any study of the kinematics is that the previous injury or degenerative disease itself has changed the relative position between the tibia and femur at the chosen starting or reference position. We measured the relative tibiofibular positions on the lateral view of our chosen starting position at 0° (Fig 1), but found no such difference between the OA and the control group. Small systematic changes such as minor internal or external rotations cannot be properly evaluated on radiographs. Thus, it could be that the lateral condyle in the supine reference or starting position was positioned slightly more posteriorly in the OA group than in the natural knee. Recently our group showed that tantalum markers inserted into cadaveric bone could be localized on one CT image volume with good precision and thereafter used to reconstruct the outlines of the bone on a series of radiostereometric recordings. In the future this technique may be used to facilitate the interpretation of radiostereometric recordings in vivo. It also has the potential to provide additional information about the relative positions of the bones primarily based on RSA recordings.4

Our controls were younger than the patients in the study group. In addition they had had a tear of the anterior cruciate ligament on their opposite side and may from a theoretical point of view, represent a part of the general population, that is more susceptible to this type of injury. These circumstances should be considered at the interpretation of our data, even if their potential influence is unclear.

Multiple factors influence changes of motion parameters in patients with medial and lateral OA and the reasons for their appearance are only partially known. Contrary to our findings in lateral OA, Saari et al.7 found that patients with medial OA had no or almost no internal-external tibial rotation close to extension corresponding to the loss of screw-home rotation. In lateral OA the tibia rotated externally with extension. Even if this rotation was of similar magnitude as in normal knees the anterior – posterior translations of the femoral condyles were not the same, with more anterior translations medially and an insignificant tendency to smaller translations laterally. This observation is equivalent to a lateral displacement of the instant center of rotation. The reasons for these changes are not known. One reason might be that patients with lateral knee OA tend to walk with increased external rotation of their femur as an effect of changes of their hip and pelvic anatomy.23, 24 Matsuda et al.15 measured the angle between the transepicondylar axis and the posterior condylar tangent on MRI images in normal and OA knees with varus and valgus deformity. In the first two groups this angle was slightly more than 6°, whereas in cases with valgus deformity it reached 11.5° consistent with pronounced deformity or hypoplasia of the lateral femoral condyle. This abnormality can be expected to above all result in increasing relative abduction with flexion, but may also be one reason for changes of the condylar translations.

Our observations of the relative tibial rotations during loaded extension are partly supported in a previously performed gait analysis.24 The authors observed that cases with medial knee OA had 9° more external rotation, and cases with lateral knee OA had 6° more internal rotation than control subjects. The differences between the previous study and our study could be explained by a number of factors, such as the resolution of the methods used, different patient selection, and different examined knee motions (knee extension versus normal gait).

A number of studies have shown the kinematics
of the knee are altered after a total knee arthroplasty. These changes may be an effect of absent cruciate ligaments and the joint area design of the individual implant. According to some studies, there is a variation between different designs of knee replacements depending on the designs of the joint area, but so far there is no total knee arthroplasty found to articulate as the natural knees. If the surgical procedure during insertion of a total knee arthroplasty and the implant itself are important reasons for altered knee kinematics, changes might also be caused by the degenerative joint disease before the implantation, but this hypothesis needs additional study.

The kinematics of the natural knee during different types of activities reflects the anatomy of the knee and the surrounding structures, such as the ligaments, the joint capsule, and tendons and muscles acting over the knee. The forces acting over the joint will also be influenced by the anatomy of more proximal and distal parts of the body and probably in a complex way. One could speculate subjects, who will subsequently develop OA to some extent move their lower leg and especially the knee in a certain way, which may make them more vulnerable to a degenerative disease. The observation of changes in knee kinematics similar to those observed in medial OA following a tear of the anterior cruciate ligament may support this theory. If so, predicting and perhaps preventing degenerative knee disease would be possible.

We found presence of lateral OA is associated with specific changes of the pattern of knee motion. Studies of knees at various stages of the disease process and repeated recordings over long periods of time are necessary to evaluate if and to what extent the observed changes are an effect of the degenerative disease or if they have also contributed to their development. We think knowledge about the kinematics of knees with medial and lateral OA is also of value in the interpretation of knee kinematics after knee replacement.

References


