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The Knee

In vivo kinematics of medial unicompartmental osteoarthritic knees during activities of daily living

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ABSTRACT

Few studies exist describing unicompartmental osteoarthritic knee kinematics. Moreover, the role of the anterior cruciate ligament (ACL) in the determination of knee kinematics has not been fully described. The objective of the current study was to analyze the *in vivo* kinematics of knees with medial osteoarthritis (OA) and intact ACL during closed and open chained motion.

Eight patients scheduled for UKA diagnosed with primary medial OA underwent knee CT-scans and video-fluoroscopy. Fluoroscopic analysis included stair climbing, chair rising and leg extension. Three-dimensional bone positions were obtained from each image by iterative procedures using a CAD-model-based shape-matching technique. Patterns of axial rotation and anterior-posterior (AP) motion of the medial and lateral femoral condyle were obtained with specific software.

The femur reported an overall external rotation relative to the tibia from extension to flexion in all tasks. Average AP translation of the medial femoral condyle were smaller in open-chained tasks than in weight-bearing conditions. Average AP motion of the lateral femoral condyle reported an overall posterior translation with knee flexion.

The absent natural "screw-home" mechanism and the lack of medial condyle posterior translation was explained by bone-cartilage defects and meniscal degeneration. Relevant findings were the kinematic pattern differences between weight-bearing and open chained activities, suggesting that in biphasic muscle contraction and unloaded conditions, the function of the cruciate ligaments was not physiological. The kinematics of knees with medial OA and intact ACL differed from healthy knees.

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1. Introduction

The evaluation of *in vivo* knee kinematics is important in order to understand the effects of joint injury, diseases and in order to improve the outcome of surgical procedures.

Video-fluoroscopic analysis has been used for 20 years to determine knee motion from fluoroscopic image sequences [1,2], both for patients operated with total knee arthroplasty (TKA) [3,4] and more recently for motion measurements in normal or osteoarthritic joints.

Healthy knee kinematics has been assessed with video-fluoroscopic analyses to understand the deviations of the kinematics after surgical treatment [5]. Moro-oka et al. described healthy knee kinematics during the activities of squatting, stair climbing and kneeling and reported an overall femoral external rotation relative to the tibia with flexion. Anterior-posterior (AP) translation of the condylar contact regions showed three phases over the range of motion according to the performed activity: sharp femoral external rotation from 0° to 20° flexion (squatting) – the so-called "screw-home" mechanism – with posterior translation

of the medial and lateral contact points (CP). Relatively constant rotation and posterior translation of both condyles from 20° to 80° (stair climbing) and an increasing femoral external rotation from 80° to 150° flexion (kneeling) resulted predominantly from posterior lateral translation, essentially pivoting about the medial compartment. In this range of flexion, medial AP tibio-femoral translation was reduced, determining a medial pivot point kinematics [5].

Few studies have highlighted the kinematics of knees with unicompartmental osteoarthritis. Knees with medial osteoarthritis (OA) have shown somewhat similar kinematic patterns to those of the normal knee, such as femoral external rotation gradually increasing with flexion for squatting and kneeling, and gradually decreasing with extension for stair climbing [6]. Nevertheless, some differences have been described between medial osteoarthritic and healthy knees. The osteoarthritic joint starts knee flexion at reduced values of femoral external rotation, which is maintained during all the range of motion. Moreover, in knees with medial OA the natural screw-home movement has not been described and medial and lateral femoral condyle CP on the tibial plateau have not exhibited significant posterior translation, especially between 30° and 80° of knee flexion [6].

In the literature, the role of the anterior cruciate ligament (ACL) and its presence or absence in the determination of knee kinematics has not been clarified yet. For this reason, it's the authors' belief that function of the ACL, the articular surface

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geometry and the menisci should be investigated to better understand the overall knee kinematics.

The objective of the present study was to analyze the *in vivo* kinematics of knees with medial OA with intact ACL during closed and open chain motions. The kinematics of pathologic knees may influence the kinematics after unicompartmental knee arthroplasty (UKA). It is the author's belief that clarification of the differences in the kinematics between OA and normal knees is very important for enhancing implant design and positioning. It was hypothesized that the kinematic of knees with medial OA differs from healthy knees, showing similar patterns of axial rotation and reduced posterior translation of the femoral condyles, due to cartilage wear and menisci degeneration.

2. Material and methods

Eight consecutive patients scheduled for robotic UKA at the orthopaedic department of Modena University Hospital, Modena, Italy, between January 2013 and May 2014 were prospectively selected. All patients gave written informed consent prior to being included in the study, which was performed in accordance with the Ethical Standards of the 1964 Declaration of Helsinki, as revised in 2000. Patients with diagnosis of rheumatoid arthritis or post-traumatic knee arthritis were not included in the cohort. The mean age of the selected cohort was 70.4 (SD 7.9; range 60–85) years; four patients were males, four were females.

Primary medial unicompartmental knee osteoarthritis (Ahlbäck stage III-IV) was the diagnosis in all cases. Pre-operative clinical examination showed ACL integrity in all patients. This inclusion criterion was verified and confirmed intra-operatively during surgery. In all knees, cartilage destruction in the medial compartment on the femur and tibia was severe, with subchondral bone exposure and medial meniscus degeneration.

All patients underwent knee CT scan and video-fluoroscopy examination as standard pre-operative protocol. A General Electric 64 multislice CT with a collimation of 0.75 was used in all patients; knee CT scans were performed perpendicular to the long axis of the lower limb, with a slice thickness of 0.63 mm. From CT scan images, three-dimensional CAD models of the ostheoarthritic femur and tibia were eventually created using two open source softwares (ITK-Snap, Penn Image Computing and Science Laboratory, University of Pennsylvania, PN, USA and MeshLab, Computer Science Department of Pisa University, Pisa, Italy). Anatomic coordinate systems were embedded in each bone following conventions [5,7].

Fluoroscopy analysis was performed on the same day of CT scan acquisition during three activities of daily living: stair climbing, chair rising and leg extension. For stair climbing, three 21-cm-high steps were used; to assess stepping up, only the first step was used, and three up/down cycles were performed in a single repetition and the ascent phase was captured. For the rising, chair height was set specifically for each patient in order for him or her to begin with the knee flexed at about 80°. Even for this task, only the ascent phase was analyzed. For the extension against gravity task, patients were examined in a semi-supine position (i.e. sitting at 45°), with their knee hanging as flexed as possible over the end of the examination chair. Data collection and analysis procedures were as previously reported [8-10] and included the use of a standard flat panel detector (Opera Swing, GMM S.p.a, Italy) with 15 images per second. Three-dimensional bone positions and orientations were obtained from each fluoroscopic image by an iterative procedure using a CAD-model-based shape-matching technique [1] (Fig. 1). Condylar contact was assumed on the medial and lateral compartments as the two sets of points at minimum distance between the femoral condyles and the tibial plateau. The positions of these CP were expressed in the tibial
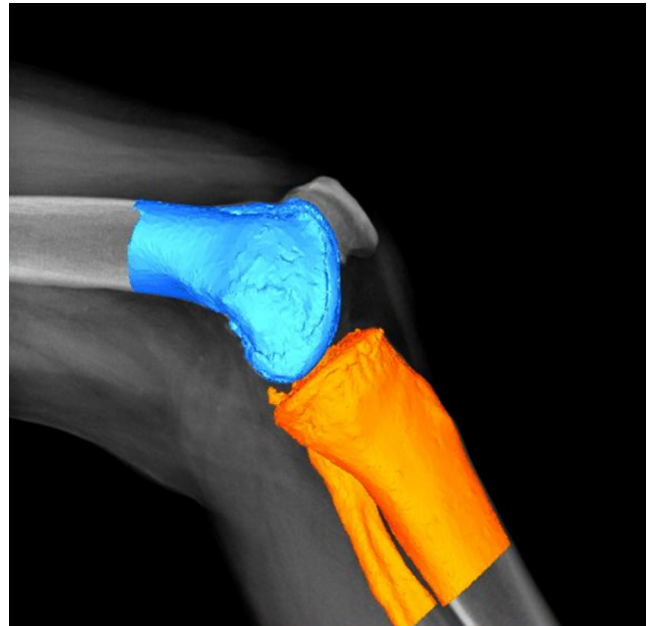

Fig. 1. 3D-to-2D CT model-to-flat panel image registration was used to determine the kinematics of medial OA knees during three activities of daily living.

plateau reference frame in terms of locations over the anterior-posterior length. Patterns of AP motion of the CP were therefore obtained independently for the medial and lateral condyles. Contact-line rotation, defined as rotation of the line connecting the medial and lateral CP with respect to the mediolateral axis on the tibial transverse plane, was calculated for each flexion angle, but here, it is reported over predefined flexion angles with 10° increments. Continuous data are here expressed as means and standard deviations (SD); categorical data are presented as absolute numbers.

3. Results

The femur reported an overall external rotation relative to the tibia from extension to flexion in all three motor tasks (Fig. 2). Based on the bone-embedded coordinate systems, femoral external rotation at minimal and maximal flexion (from 5° to 75° of knee flexion) resulted on average 14° (SD 4°) during chair rising (range –4° to +10°), 9° (SD 3°) during the stair climbing task (range –3° to +6°), and 6° (SD 1°) during leg extension (range –3° to +3°). Similar absolute values of femoral axial rotation were observed in chair rising and stair climbing from 10° to 70° of knee flexion.

Average AP translations of the medial femoral condyle CP were smaller in leg extension than in chair rising and stair climbing (Fig. 3). For chair rising, the average translation of the medial femoral condyle on the tibial plateau was 11 mm (SD 4; range 4–15 mm). For stair climbing, the average AP translation was 5 mm (SD 2; range 5–10 mm); in leg extension, the reported average AP translation was 5 mm (SD 2; range 2–7 mm).

Average AP translations of the lateral femoral condyle CP were smaller in leg extension than in chair rising and stair climbing (Fig. 4). For chair rising, the average translation of the lateral femoral condyle on the tibial plateau was 15 mm (SD 5; range –7 to 8 mm). For stair climbing, the average AP translation was 14 mm (SD 4; range –7 to 7 mm); in leg extension, the average AP translation was 4 mm (SD 1; range 1–4 mm).

In the stair climbing and chair rising tasks, the medial condyle CP showed a relatively small posterior translation from 10° to 50° of flexion, with a greater anterior translation from 50° to 75°. In leg extension, the medial femoral condyle CP showed a
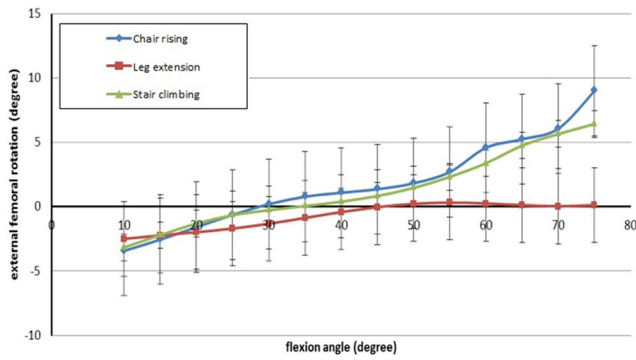
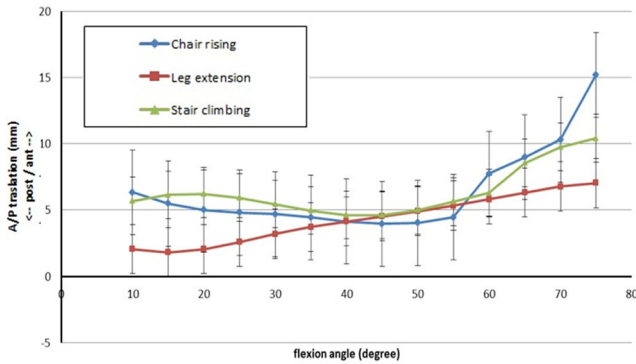**Fig. 2.** Femoral axial rotation in the three motor tasks at different knee flexion degrees.

Fig. 3. AP translation of the medial femoral condyle on the tibial plateau in the three motor tasks at different knee flexion degrees. Ascending curves are representative of femoral condyle anterior translation on the tibial plateau.

Fig. 4. AP translation of the lateral femoral condyle on the tibial plateau in the three motor tasks at different knee flexion degrees. Ascending curves are representative of femoral condyle anterior translation on the tibial plateau.
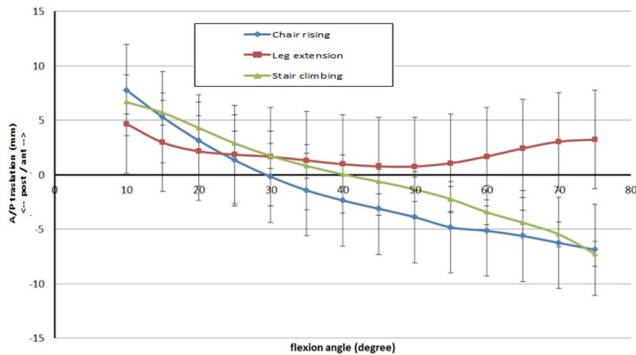
progressive anterior translation from 10° to 75°. In stair climbing and chair rising, the lateral femoral condyle CP showed a progressive posterior translation from 10° to 75° of knee flexion. In leg extension, the lateral condyle CP showed a relatively small posterior translation from 10° to 50°, with a small anterior translation from 50° to 75°.
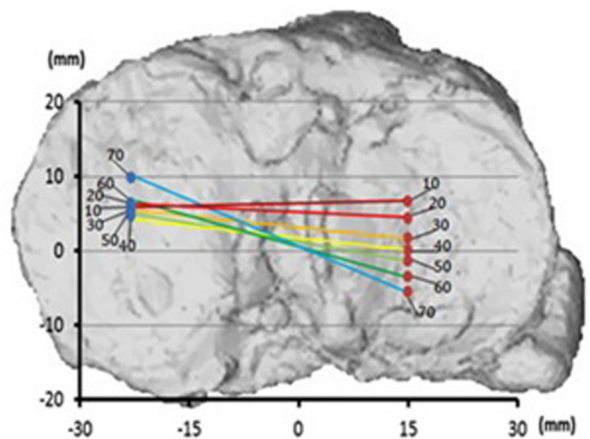
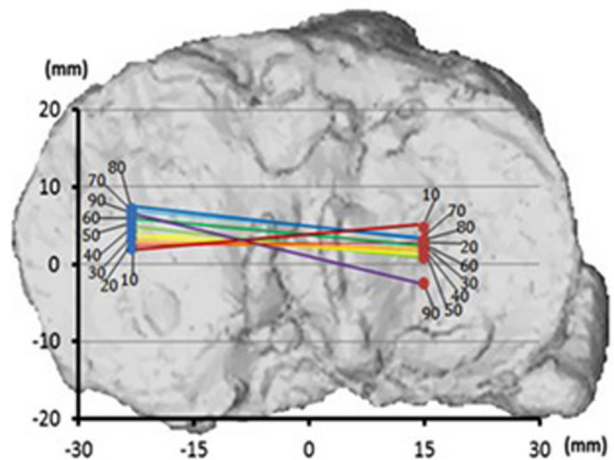In all three motor tasks, a medial pivot point was observed (Fig. 5).

4. Discussion

The most important finding of the present study is the demonstration that the kinematic pattern of knees with medial unicompartmental OA and intact ACL differs from the kinetic
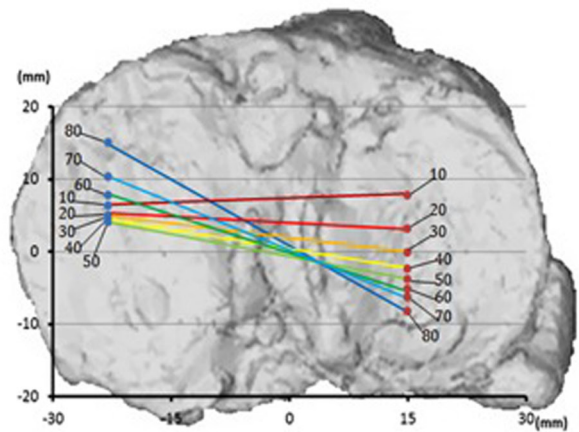
Chair rising/sitting contact points

Stair climbing/descending contact points

Leg extension/flexion contact points

Fig. 5. Average contact locations overimposed on a right tibial surface model of a representative knee with medial OA. Average contact locations are shown for 10° flexion increments for each motor task.

trend of the healthy knee [5]. In the present work, the dynamic 3D kinematic of OA knees was examined during three activities, including weight-bearing and open chained motor tasks.

Different values of knee axial rotation were observed in the three activities, with the greatest external rotation of the femur relative to the tibia reported during weight-bearing activities (stair climbing and chair rising) and reduced average values of femoral external rotation during open chained motor task (leg extension). The data describing the stair-climbing task were eventually compared with those by Moro-oka et al. [5] in healthy joints during the same motor task and analyzed with the same methodology. From 10° to 75° of knee flexion, an overall 9° femoral external rotation was reported both in healthy and OA knees (Fig. 2) [5]. However, at every degree of knee flexion, the OA knee axial rotation curve displayed a deviation of about 10° compared to the axial rotation of the healthy joint. This finding has already been noted by Matsui et al., who evaluated the femoro-tibial rotation using CT and reported that the femur tended to locate in a relative internal rotation position in knees with severe OA compared to normal joints [11], and by Hamai et al. in their video-fluoroscopic analysis of the kinematics of the osteoarthritic knee [6]. Moreover, in the present series the natural "screw-home" mechanism – which occurs between 0° to 20° of healthy knee flexion – was not observed, presumably because the patients could not reach full extension. This functional limitation is attributable to cartilage degeneration, osteophytes and menisci disease in the medial compartment of unicompartmental arthritic knees. The reduction of the sharp internal rotation of the femur relative to the tibia in the last degrees of extension in the osteoarthritic joint has already been described by Nagao et al., who investigated normal and OA knees with ultrasound and found that tibial external rotation at maximal extension and femoral rotation of the "screw-home" movement proportionately decreased with progression of medial compartment osteoarthritis [12].

The AP motion of the osteoarthritic knee has not been clearly described in the literature so far. The presented results showed that the medial femoral condyle CP described from 10° to approximately 50° of knee flexion reduced motion on the tibial plateau and an overall anterior translation from mid to full flexion in weight-bearing motor tasks. On the other hand, in open chained motor task the medial condyle reported a progressive anterior translation throughout the range of motion (Fig. 3). As described by Hamai at al., the lack of a posterior translation of the medial condyle may be caused by soft tissue contractures and osteophytes formation with cartilage-bone erosion in the medial compartment and may be related to the cartilage wear pattern on the tibial plateau [6,13]. Moreover, the anterior translation of the medial femoral condyle with knee flexion – and its backward movement with extension – can be assumed as responsible for cartilage and meniscus damage due to increased shear forces on the articular surfaces. In accordance with Moschella et al., the overall of the femoral condyle CP translation on the medial tibial plateau seems to be strictly dependent on ACL integrity. As reported by Moschella et al. in their study of tibial plateau wear patterns, cartilage erosion on OA knees with intact ACL occurred in the central to medial region of the medial plateau, despite of OA knees with ruptured ACL, which showed larger posterior wear [13] and tended to display more posterior contact during weight bearing activities as reported by Hamai et al. in their video-fluoroscopy analysis [6].

Regarding the translation of the lateral CP, an overall posterior motion of the femoral condyle was displayed. This contributes to create a medial pivot type of axial rotation pattern (Fig. 5), in which the femur externally rotates relative to the tibia as flexion progresses, as explained above. The AP translation of the lateral femoral condyle noted a progressive and remarkable posterior motion for weight-bearing activities and a small relative motion during leg extension/flexion task (Fig. 4). The described results are comparable to those presented by Moro-oka et al. and Lu in

the healthy knee [5,14]. The relative motion of the lateral condyle on the tibial plateau seems to be independent from osteoarthritic degeneration. Not even the ACL integrity seems to be a factor with major influence on the translation of the lateral femoral condyle. In fact, as described by Dennis et al., who compared healthy with ACL deficient knees, subjects with or without functional cruciate ligament reported similar posterior motion patterns [15].

Relevant findings of the present study were the kinematic pattern differences displayed between weight-bearing activities (chair rising and stair climbing) and open chained motor tasks, with smaller magnitude values for femoral axial rotation and medial and lateral AP translation reported by the leg extension motion. These findings are consistent with those of Lu et al. who compared the motion pattern of eight knees in conditions of load and unload [14]. The presented data display that in biphasic muscle contraction and unload conditions the function of the anterior cruciate ligament is not physiological. Nevertheless, it is yet to be acknowledged the influence of a loosened ACL and the degenerative changes in the bearing surfaces on the joint motion. However, the presented results appear to suggest different effects of load on the overall knee kinematics.

Several limitations of the present study need to be discussed. First, the current approach to analyzing joint contact ignores the degenerate menisci, which are invisible on radiographs but obviously affect joint contacts and load distribution. Moreover, the lowest CP are created starting from CT-derived models, which assume a uniform cartilage thickness. For osteoarthritic knees, models registration should be performed using CT-derived images for bone and MRI-derived pictures for cartilage surfaces. This approach would impose a bigger burden on preoperative subjects. Third, single-plane imaging has more uncertainties on the medio-lateral translations. Lastly, the current study included only eight cases and therefore can't be considered completely representative of knees with unicompartmental medial OA. Further study should be performed on a larger cohort of patients to confirm the presented findings.

5. Conclusion

Kinematics in knees with unicompartmental OA and intact ACL differs from healthy knee motion patterns. Pathological changes, such as cartilage wear, menisci degeneration and osteophytes influence knee kinematics. Load and unload conditions seem to have a role in the determination of the overall joint kinematics. These findings can be useful for enhancing UKA design.

6. Conflict of interest statement

All the authors certify that they do not have any conflict of interest relating to this paper.

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