The application of roentgenstereophotogrammetry for evaluation of knee-joint kinematics in vitro

16. THE APPLICATION OF ROENTGENSTEREOPHOTOGRAMMETRY FOR EVALUATION OF KNEE-JOINT KINEMATICS IN VITRO

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1. INTRODUCTION

Accurate quantitative knowledge about the motion freedom in human knee-joints, and how it is influenced by joint restraints (articular surfaces, ligaments and capsular structures) is necessary to develop criteria for diagnosis and treatment of joint diseases and traumatic conditions, for artificial joint designs, and to provide a data base for modelling in patient evaluation techniques (i.e. gait analysis). A two-dimensional (e.g. 1,2) or quasi-three-dimensional (e.g. 3) approach to knee kinematics may be adequate in first-order approximations. However, it was the objective of this experimental study to obtain accurate data on all aspects of 3-D knee motion in vitro. The methods used are based on Roentgenstereophotogrammetry. The experimental technique and the results to be obtained are illustrated here, using a single knee specimen, although more than one have been investigated.

2. METHODS

In the experimental procedure a Roentgenstereophotogrammetric measuring system developed by Selvik (4) is used. The technique as applied to knee-joint kinematics was discussed previously (5). Double roentgenexposures are made of the joint in subsequent positions. Small tantalum markers are inserted in the bones. A reference plate with markers defining the laboratory coordinate system is exposed simultaneously. Using a coordinate measuring table, the positions of the bone and reference markers on the double roentgenexposures are determined, and the 3-D position of each bone marker in the laboratory coordinate system is reconstructed by a computer program (using the spatial positions of the roentgen foci as determined previously in a similar fashion). The 3-D positions of three or more markers in each bone determine its position in space, hence rigid body displacements in joint-motion steps can be determined and described by kinematic parameters (i.e. Euler rotation angles, translation vectors, and screw axes). Because a highly accurate coordinate

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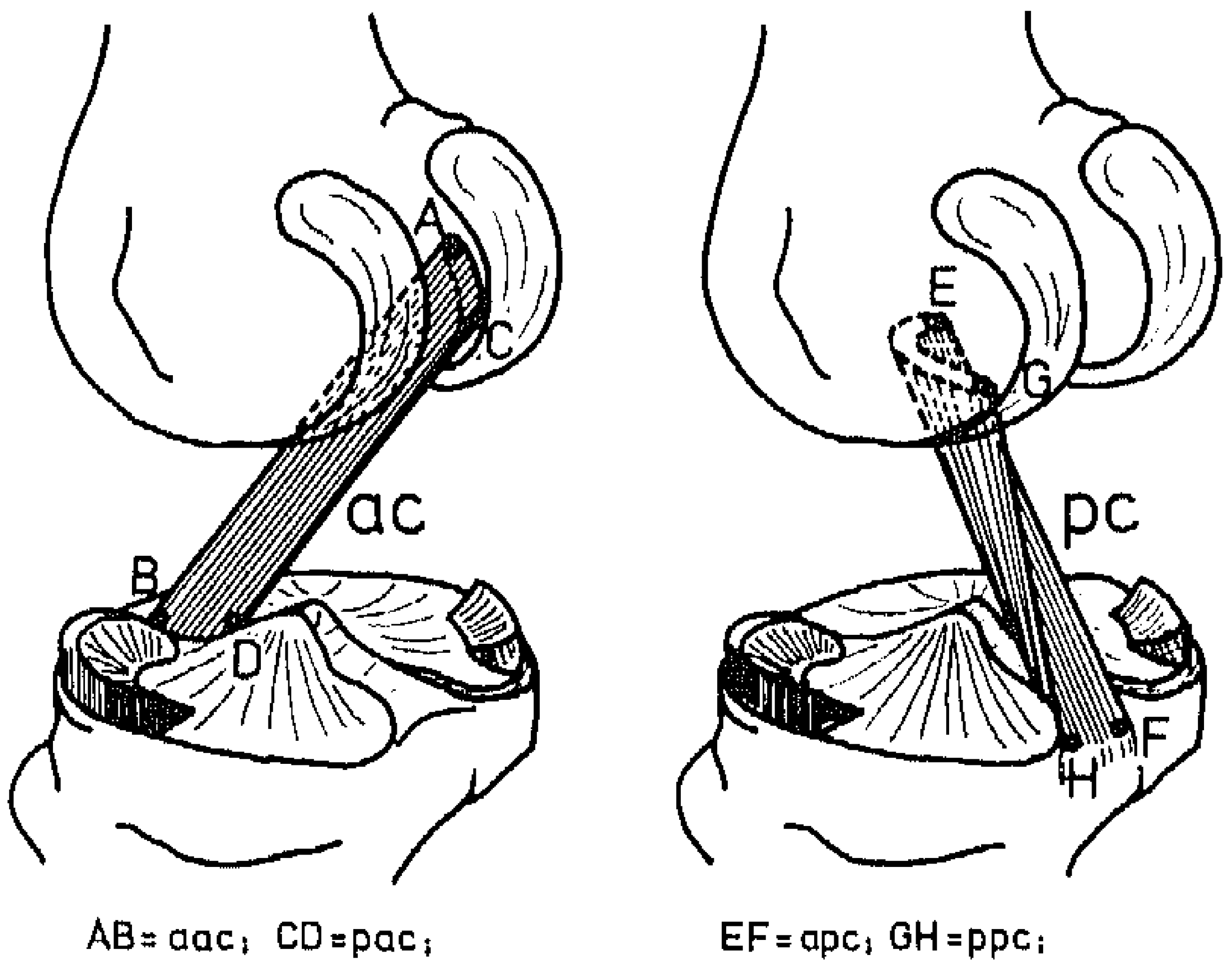
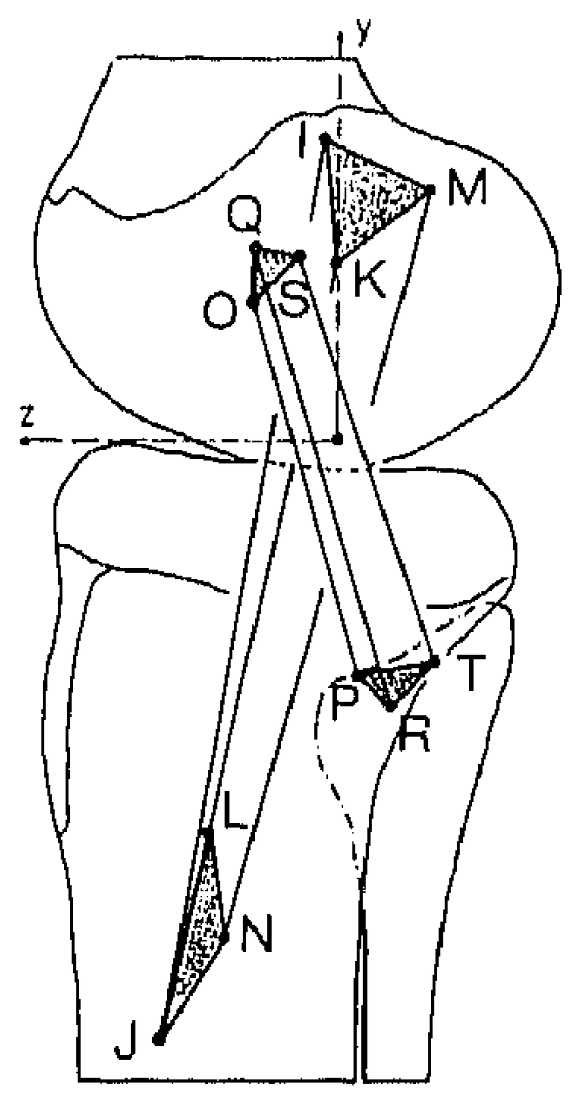
measuring table is used, because the system of bone and reference markers is overdetermined, and because a very precise manufacturing procedure for reference plate and test cages has been applied, the spatial position of a marker can be established with an accuracy of 10 μm and rigid body rotations and translations with an accuracy of better than 0.1° and 200 μm respectively.

The specimen described here is a right knee of a 16 yr old male. The knee was moved from hyperextension to about 120° flexion, in steps of 15° approximately. After every flexion step three double exposures were made, of the knee in an arbitrarily chosen mid-position with respect to the endo-exo-rotation angle (neutral position), the knee gently forced in position one, and in position two. Due to the rather arbitrary manipulation of the joint, the positions one and two cannot be interpreted accurately in terms of "anatomical" rotations; however, it was evident that in extension these positions represented the limits of the ad - abduction motion, while after about 30° flexion they represented the limits of exo-endorotation motion. Limits as used here have to be understood within the concept of primary laxity, with no significant loading applied.

The specimens were cut approximately 15 cm from the joint on each side, the soft tissues were left intact to prevent drying out. In addition, they were kept wet with Ringers solution. The patella was left free, thus presenting no restraints to the joint motion. After the experiments, the joint was dissected and tantalum markers were placed in the insertion regions of the anterior and posterior cruciate ligaments (AC and PC, two in each region; Fig.1), and the medial and lateral collateral ligaments (MC and LC, three in each region; Fig.2). Once more double exposures were made of the bones, including these ligament insertion markers.

The roentgenexposures were measured, and the relative rigid body motion described in translation vectors and Euler rotation angles, tibia with respect to femur, expressed in body-fixed coordinate axes. In addition, screw axes were determined for each motion step. Using the positions of the ligament insertion markers with respect to the body-fixed axes as determined from the last double exposure, the length patterns of parts of the cruciate and collateral ligaments during knee motion were calculated as well (in fact: changes in length between lig.ins.markers, see Fig.1 and 2).





FIGURES 1 and 2. The ligament insertion markers, defining ligament fiber bundles in the cruciate (Fig.1, left) and collateral (Fig.2, right) ligaments. (Collateral ligaments, lateral: OP=ALC, QR=SLC, ST=PLC; medial: IJ=SMC, KL=IMC, MN=PMC)

3. RESULTS

3.1 Motion parameters

Exo-Endorotation and ad-abduction angles as function of flexion angle are shown in Fig.3. In the higher flexion-angle regions, a considerable freedom of exo-endorotation motion exists. Evidently, the pathway of the neutral position is rather arbitrary within the wide boundaries of this motion region. The knee displays a forced increase in abduction-angle, coupled with the flexion angle (Fig.3, lower graph). The ad-abduction freedom of motion is small, and can be interpreted as "play". In comparing these graphs with results from other specimen it was found that their shape is rather typical, although the absolute values of the rotations slightly differ.

Screw axes for the subsequent flexion-angle steps (neutral pathway, femur with respect to the tibia) are shown in Fig.4. Projections of the subsequent axes in frontal plane, and their intersections with lateral, mid-sagittal and medial planes are shown. This graph indicates the flaws in 2-D approaches to knee-kinematics, using the "instant center of rotation" concept. The intersection points with the mid-sagittal plane display a pathway in a distal-posterior direction with increasing flexion, which is consistent in other than the neutral pathway and in other specimens as well. The lateral and medial intersections, however, vary more randomly. Generally speaking, the axes are more oblique in the first flexion steps. The oblique course of the axes indicate that more slipping between articular surfaces occurs in

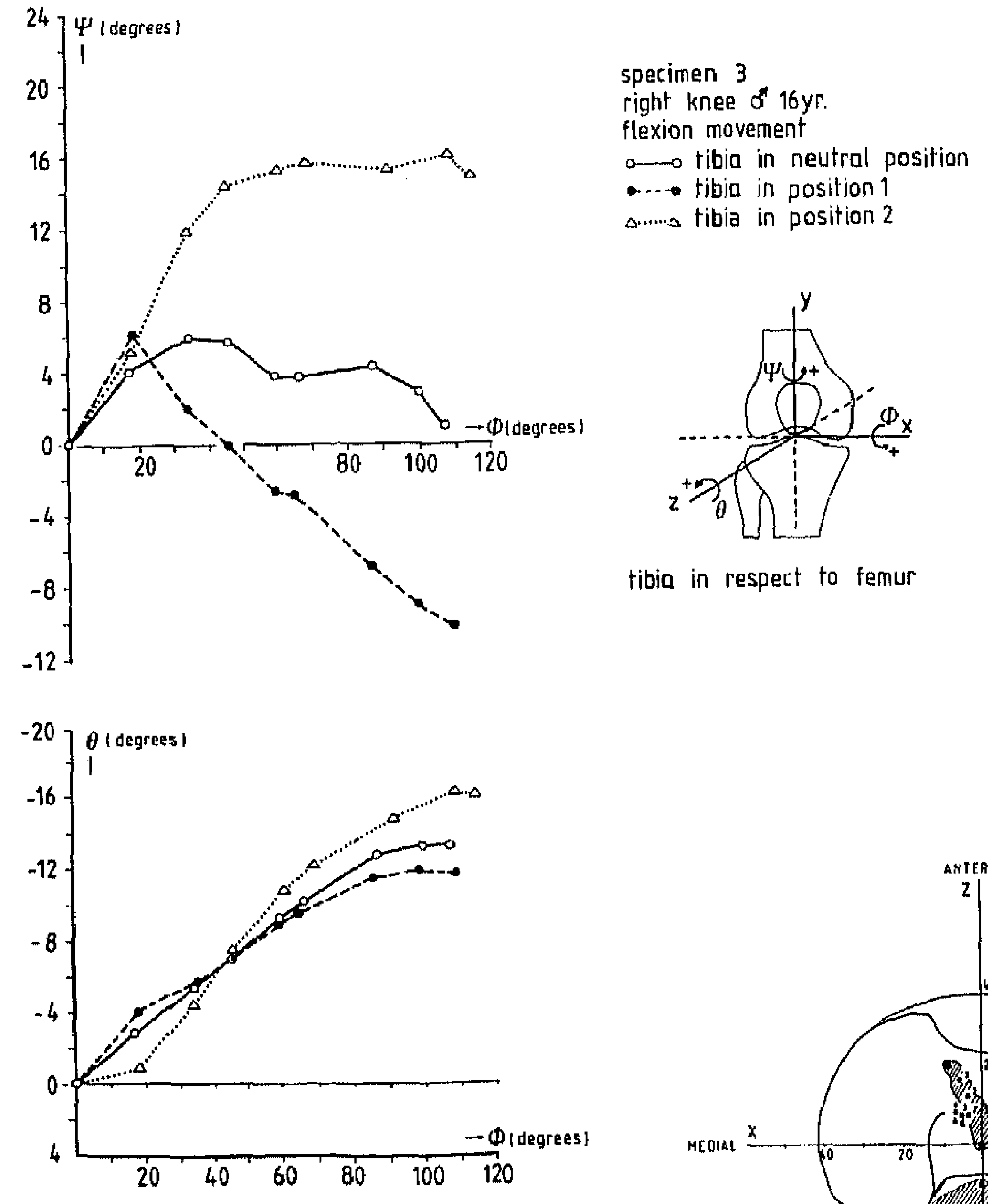


FIGURE 3. The exo-endo-rotation (top) and ad-abduction (bottom) angles as functions of the flexion angle, for the three pathways indicated (positive values are endo-rotation and adduction respectively).

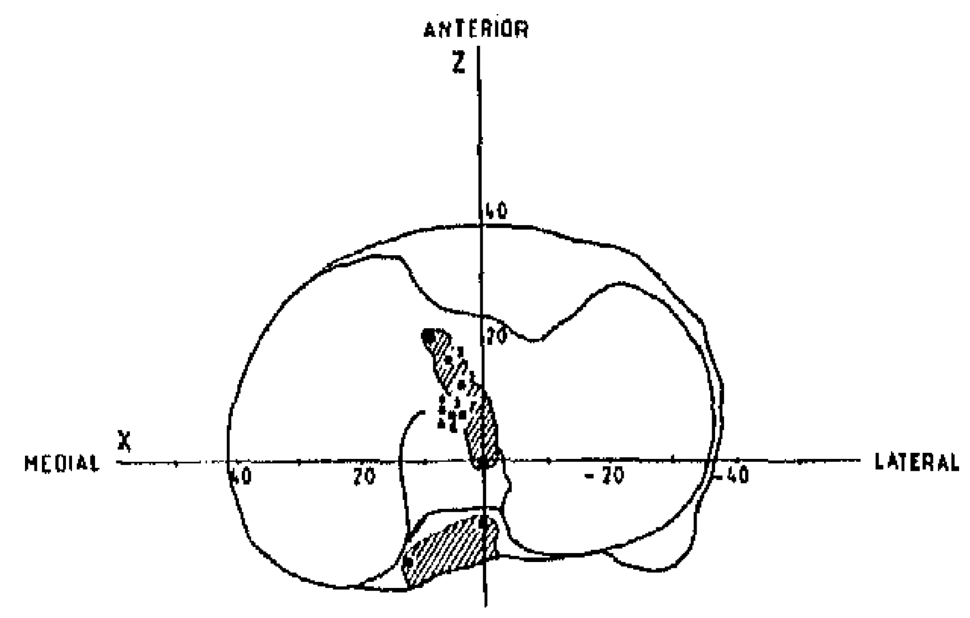


FIGURE 5. Intersections with the horizontal plane of screw axes for exo-endorotation motion in 8 flexion positions.

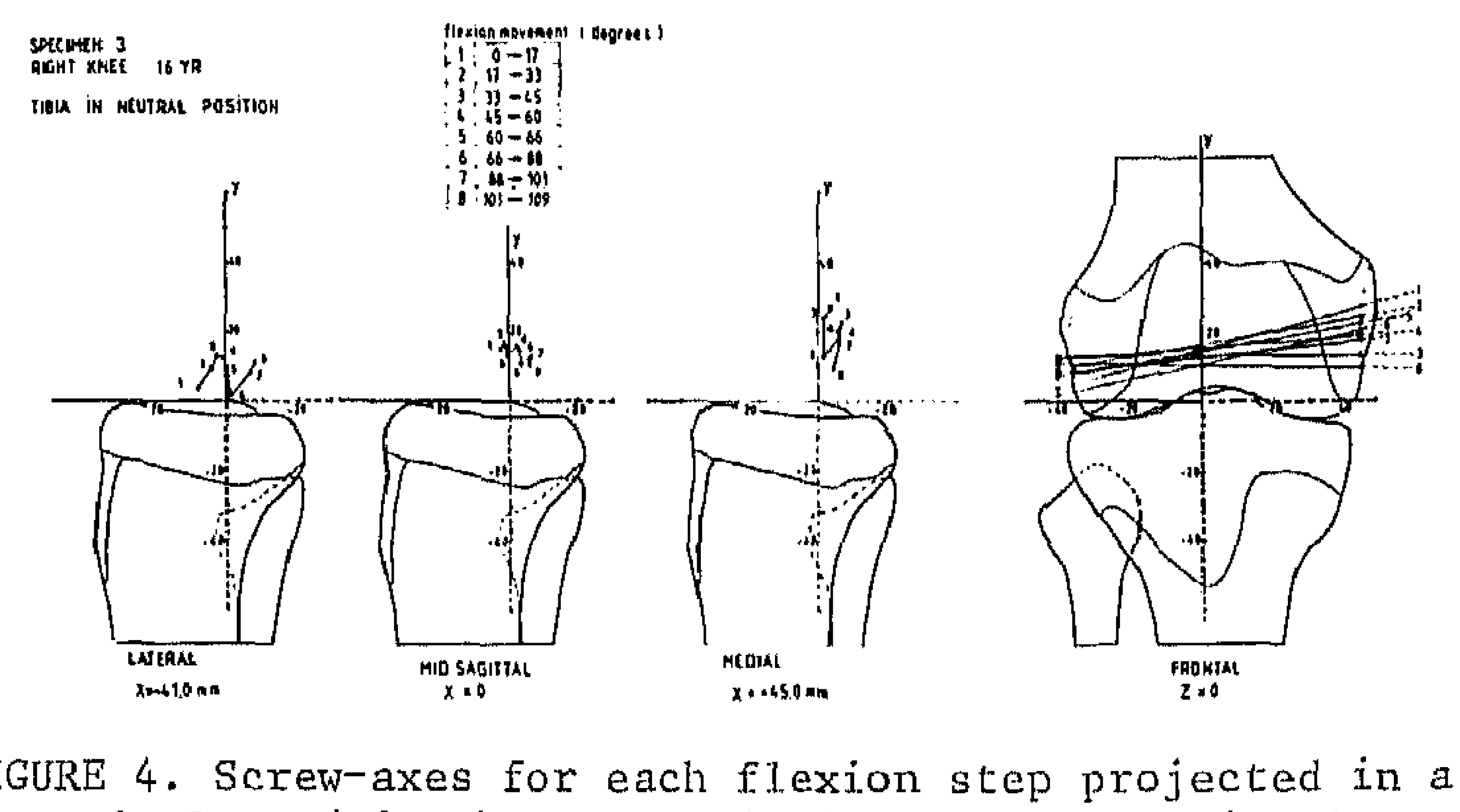


FIGURE 4. Screw-axes for each flexion step projected in a frontal plane (right), and their intersections with 3 sagittal planes.

the medial compartment, as compared to the lateral side

Fig.5 shows intersectional points with the horizontal plane of screw axes for a motion from position one (appr. the exorotation limit) to position two (appr. the endorotation limit) in 8 flexion positions. These points are located rather closely together, in the eminentiae intercondylares, close to the tibial insertion area of the anterior cruciate ligament. This finding was again consistent in other specimen as well.

3.2 Ligament length patterns

Relative length changes in the anterior and posterior fibers of the anterior cruciate (AAC and PAC), and of the posterior cruciate (APC and PPC) are shown in Fig.6, as functions of the flexion angle, again for the three different pathways (Compare Fig.1). Apparently, the exo-endorotation freedom of motion hardly influences the length patterns. It is evident from these graphs, that not all fiber bundles of a ligament are stretched simultaneously, but the strain progresses through the ligaments (from posterior to anterior), which can be regarded for this reason as true 3-D structures. Relative length patterns of the lateral collateral ligament bundles as functions of the flexion angle are shown in Fig.7, of the medial one in Fig.8 (Compare Fig.2). Although absolute length values differ to some extent, the general shape of all ligament curves is consistent for other specimen as well.

The geometrical behavior of the four ligaments can be illustrated by the changing configurations of their projections on frontal and sagittal planes, in different flexion steps (Figs.9 and 10, neutral pathway).

4. DISCUSSION

As far as the authors are aware, this is probably the most accurate (and elaborate) investigation of 3-D kinematics in vitro as yet. Nevertheless, there are still a number of incertainties in the results presented here. First of all, no loading was measured, nor prescribed. Hence, the limits of the primary laxity freedom of motion are rather arbitrary. Fig.3 specifically, should therefor be interpreted with care; the "true" endo-exorotation freedom of motion is certainly not represented completely and accurately. The interpretation of the "neutral pathway" should be regarded with care as well, especially where screw axes are concerned (Fig.4 and 5); due to the multiple degrees of freedom of the joint, this pathway is not unique. Furthermore, the ligament length patterns are in fact changes in distances between points

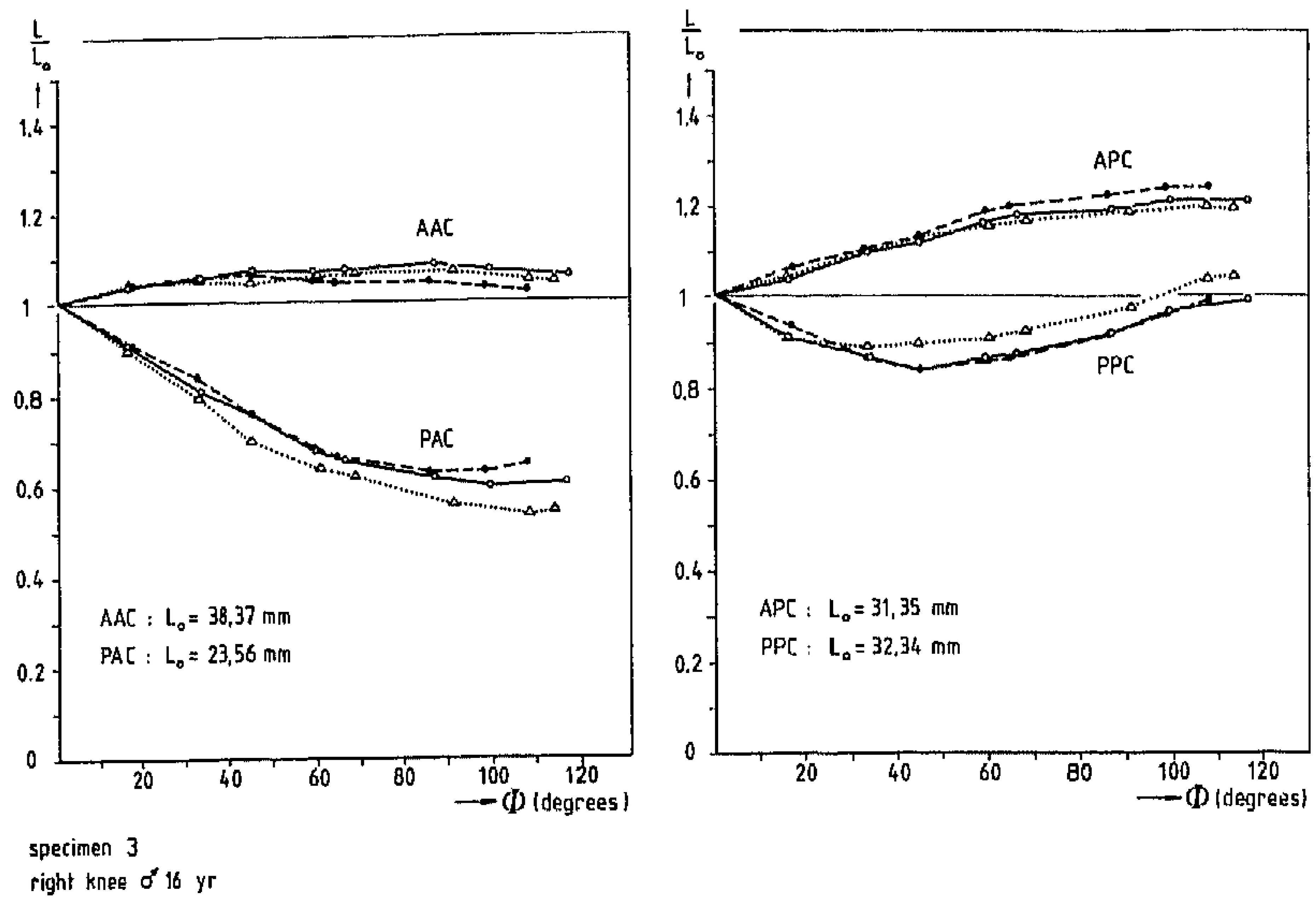


FIGURE 6. Relative length changes of anterior and posterior fibers of the anterior (left) and posterior (right) cruciate ligaments, as functions of flexion, for the three different pathways (line-code keys as in Fig.3).

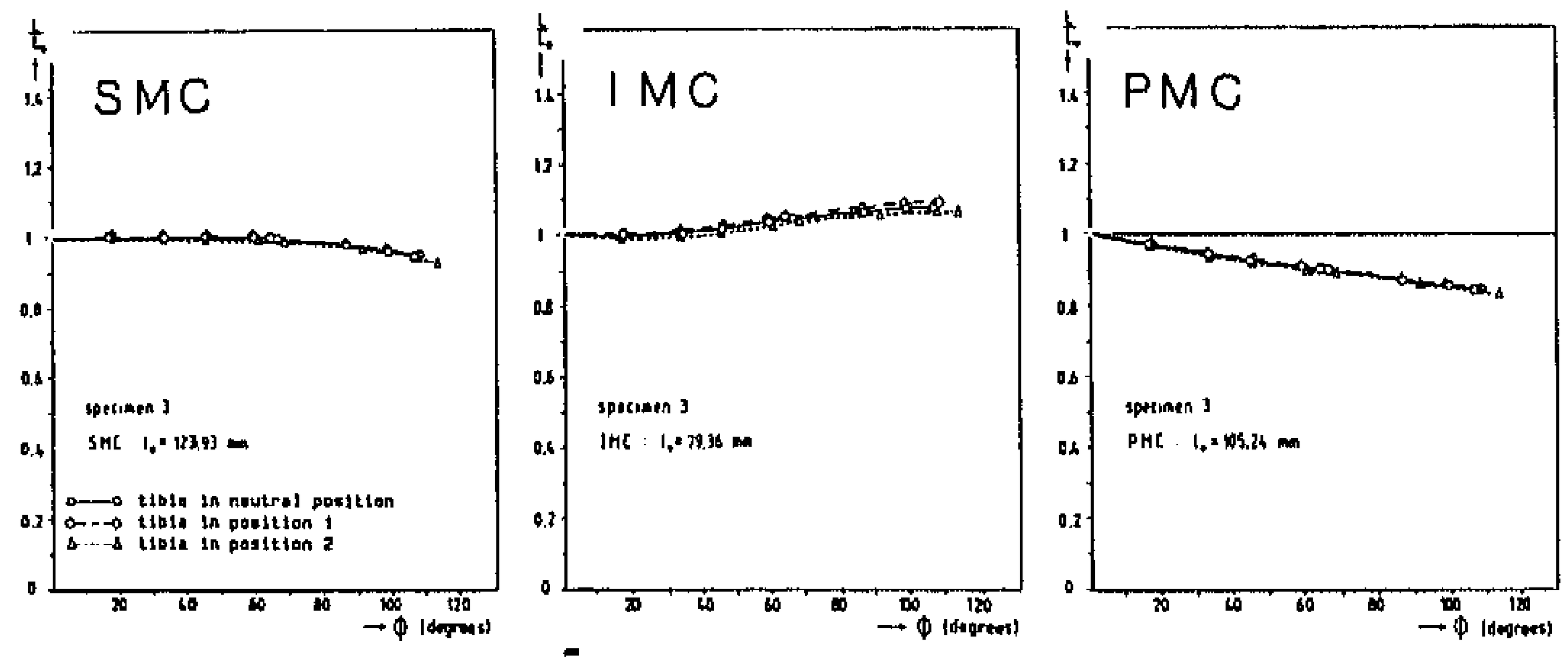


FIGURE 7. Relative length changes of parts of the medial collateral ligament as functions of flexion, for the three different pathways (compare Fig.2).

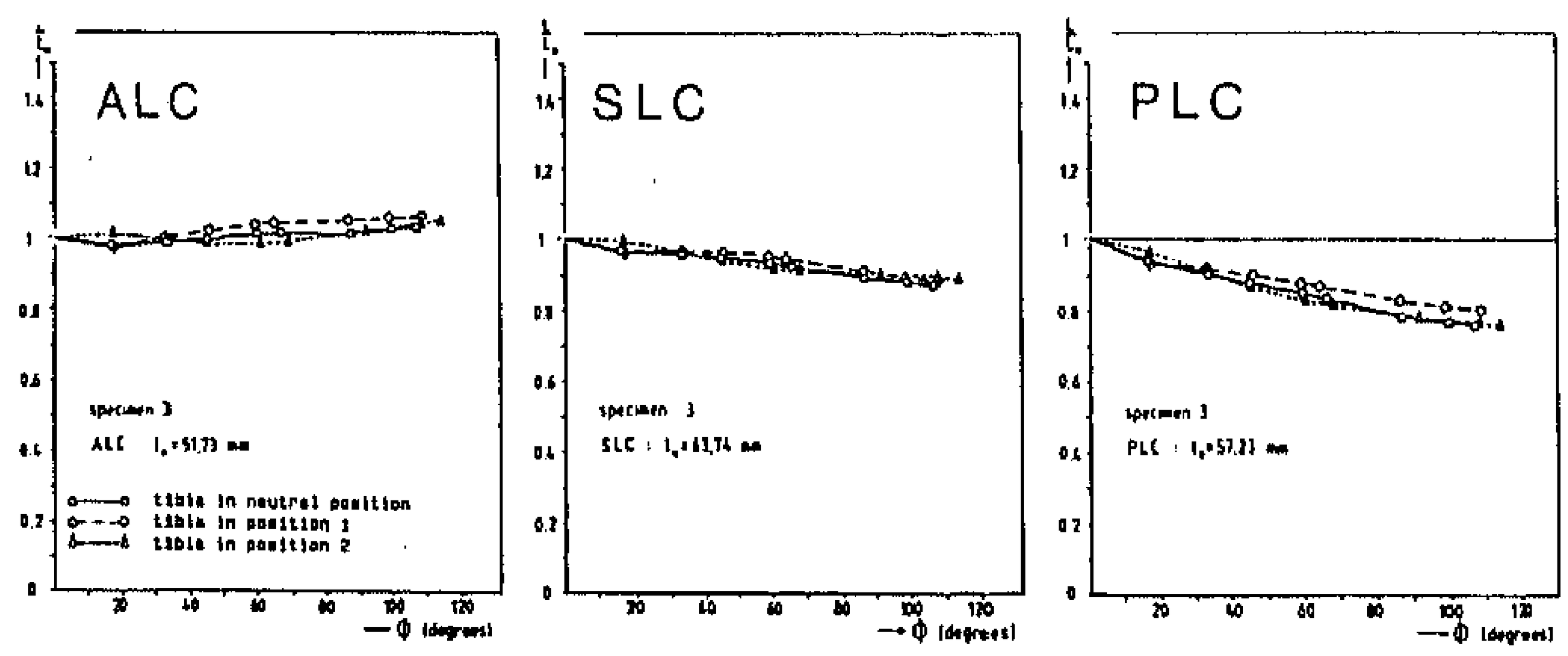


FIGURE 8. Relative length changes of parts of the lateral collateral ligament as functions of flexion, for the three different pathways (compare Fig.2).

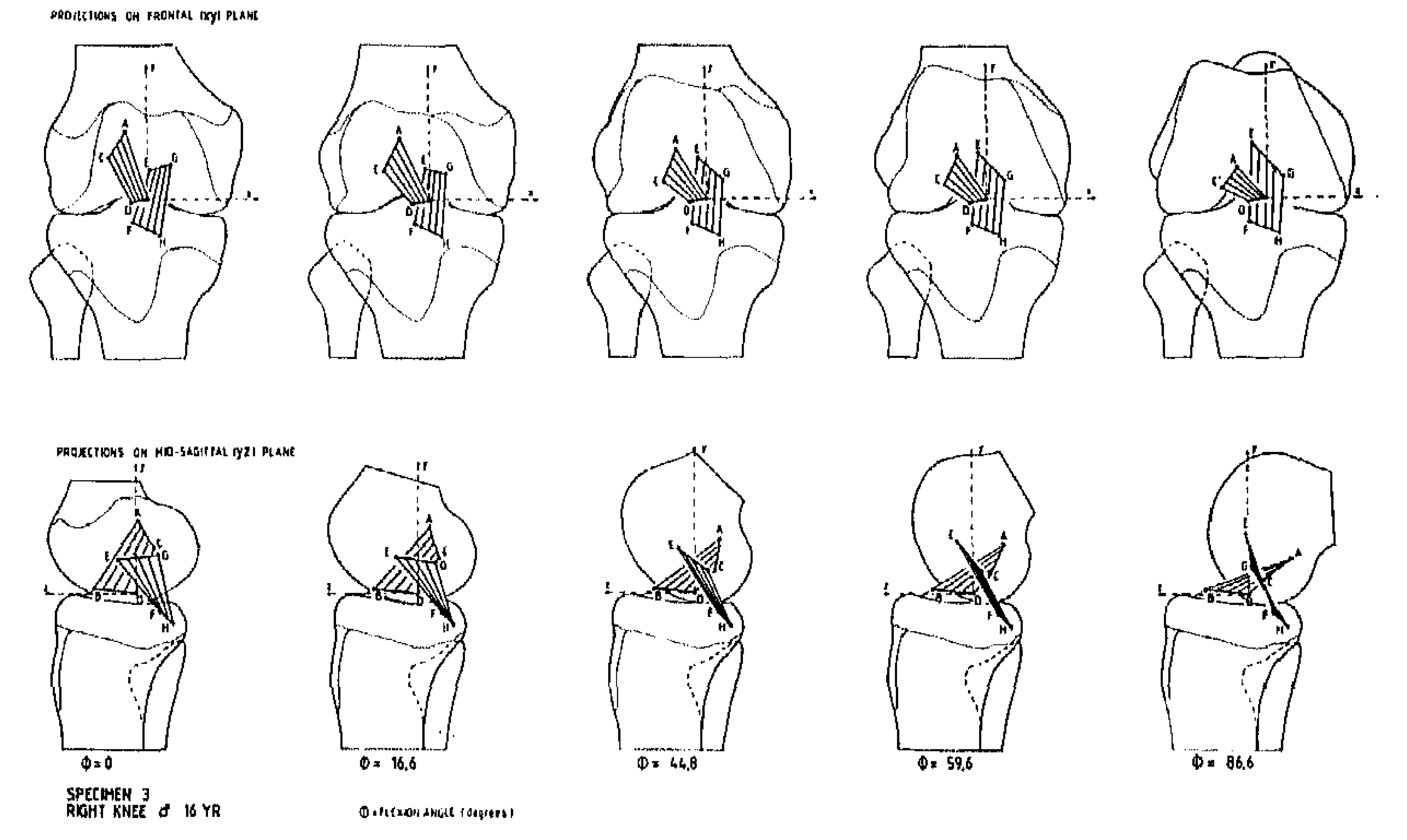


FIGURE 9. Cruciate ligament dimensional behavior as illustrated with projections on frontal (top) and sagittal (bottom) planes, for 5 flexion angles.

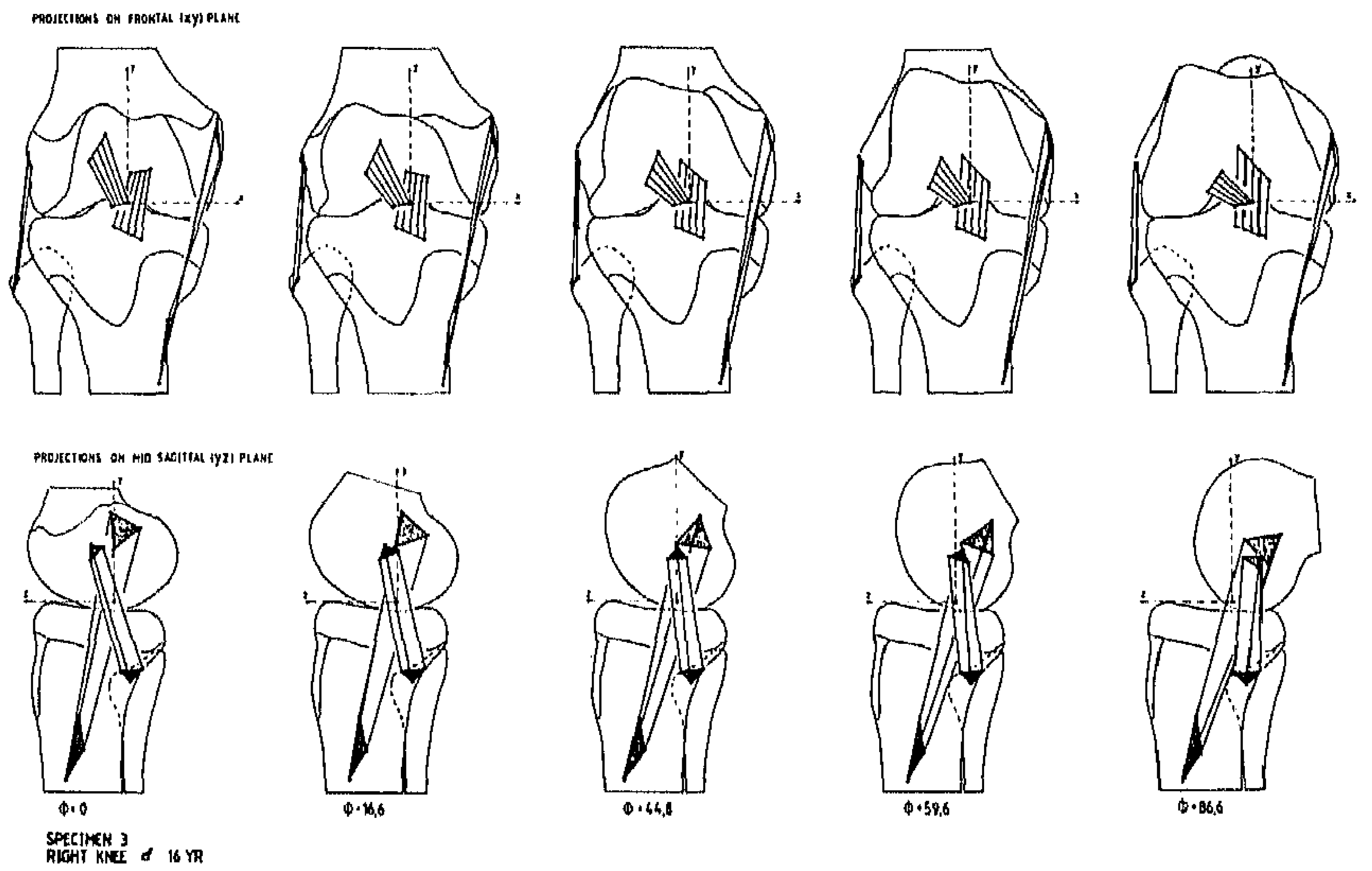


FIGURE 10. Collateral ligament dimensional behavior as illustrated with projections on frontal (top) and sagittal (bottom) planes, for 5 flexion angles.

in space; there is no guarantee that a ligament bundle between these points runs straight (which indeed cannot always be the case, as witnessed by the behavior of the medial collateral ligament in Fig.10, frontal view). In addition, the length patterns cannot be translated directly into strain patterns.

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