

Roentgen stereophotogrammetric methods for the evaluation of the three dimensional kinematic behaviour and cruciate ligament length patterns of the human knee joint

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TECHNICAL NOTE

ROENTGEN STEREOPHOTOGAMMETRIC METHODS FOR THE EVALUATION OF THE THREE DIMENSIONAL KINEMATIC BEHAVIOUR AND CRUCIATE LIGAMENT LENGTH PATTERNS OF THE HUMAN KNEE JOINT*

Abstract - Using high-accuracy roentgen stereophotogrammetry, some aspects of the three dimensional kinematics of two amputated knee joints have been studied. Instant axes of rotation, as well as cruciate ligament length patterns, were evaluated as function of the flexion-extension angle. As demonstrated by the results, this method of investigation proved to be most effective, in its accuracy as well as in its flexibility aspects.

INTRODUCTION

Much interest has been focused, in recent orthopaedic and biomechanics literature, on the kinematic behaviour of the human knee joint. As has been demonstrated repeatedly, its motion is quite complicated and can hardly be compared with a single hinge. Although roughly speaking a flexion-extension movement, the motion does not take place in one plane and hence should be considered as truly three dimensional.

Accurate general knowledge of the kinematical behaviour of the joint and the influence of the joint structures on kinematics and stability is of crucial importance for designs of artificial knee joints, diagnostic methods with respect to the joint function and a variety of orthopaedic interventions, such as menisectomies, corrective osteotomies, ligament repair and replacements.

Many experimental measurements have recently been reported; either two dimensional, using the Rouleaux constructions on conventional roentgenograms (e.g. Frankel and Burstein, 1970; Walker *et al.*, 1972; Harding and Goodfellow, 1977), or three-dimensional, using the same method with cinematography (e.g. Wang *et al.*, 1973; Blacharski *et al.*, 1975). Usually these methods were accurate enough to serve their specific purposes, to find first order approximations, to develop clinical evaluation methods, and to study the influences of drastic anatomical destructions.

Many basic questions with respect to the knee joint function remain unanswered. Some authors, for instance, apparently assume that the knee joint motion is unique; in other words, that the motion can be described by one degree of freedom. This means that, for instance, all rotational movement of the tibia with respect to the femur would be uniquely coupled with the flexion-extension movement. Although this might be true for the so-called extension rotation, or 'screw-home' mechanism, it is not for the remainder of the excursion, as orthopaedic clinicians know from their observations. Also much confusion exists about the influences of the knee structures, such as cruciate and collateral ligaments, articular surfaces and menisci. Blacharski *et al.* (1975), for instance, conclude from their experiments that the cruciate ligaments do not influence the kinematical behaviour of the knee joint, while others (e.g. Huson, 1974) emphasize their important function. To analyze these, and similar, fundamental problems with respect to knee kinematics and stability, so that general conclusions can be

derived, an accurate and flexible measuring method is needed. It is the object of this paper to present such a method and to show results of two pilot studies.

The method is based on roentgen stereophotogrammetry, a principle previously used for a number of applications (e.g. Brown and Burstein, 1976). The space coordinates of a point inside the system to be investigated, called an 'object point', is calculated from its projections from two roentgen tubes. A reference cage with reference markers is exposed together with the object. A measuring system consisting of hardware and computer software, was developed by Selvik (1974). This system was previously used for a variety of experimental and clinical investigations (e.g. Olin *et al.*, 1976; Olsson *et al.*, 1976; Hansson *et al.*, 1977; Rune *et al.*, 1975; Aronson *et al.*, 1977; Claesson *et al.*, 1977; Huiskes *et al.*, 1978). Positions of roentgen foci do not have to be measured; the positions of the projected points on the roentgen exposures can be measured by nonspecialists on a coordinate measuring table; coordinates are, together with point identification numbers, fed to the computer and positions of foci and object points are calculated. For reasons of accurate identification, object points are usually tantalum balls of 0.5, 0.8 or 1.0 mm dia., implanted into the bone with a specially developed insertion instrument (Aronson *et al.*, 1974). By implanting three or more markers into a bone and measuring their space coordinates, the rigid body position of the bone in space is determined. Rigid body displacements between bone parts can be measured and described with translation vector and rotation matrix or screw axes. By overdeterminating the system through application of more object and reference markers as theoretically necessary, the accuracy can be optimized using mathematical optimization methods. All arithmetic operations are carried out by computer. Depending on the film size and reference cage size used, the accuracy in determining the three dimensional coordinates of an object point can be approximately 0.01-0.05 mm.

The mathematical background for the calculations of space coordinates, the rigid body kinematics and optimization methods has been published previously (Selvik, 1974).

MATERIALS AND METHODS

Two amputated knee joints of males aged 60 and 79 yr, respectively, were used to measure the three dimensional kinematical parameters and the length patterns of the cruciate ligaments. The knee joints were judged stable by manual testing and no musculo-skeletal disorder was known to be present. The joints were prepared in such a way that patella, capsule and ligaments remained intact. Femoral and

* Received 17 November 1978.

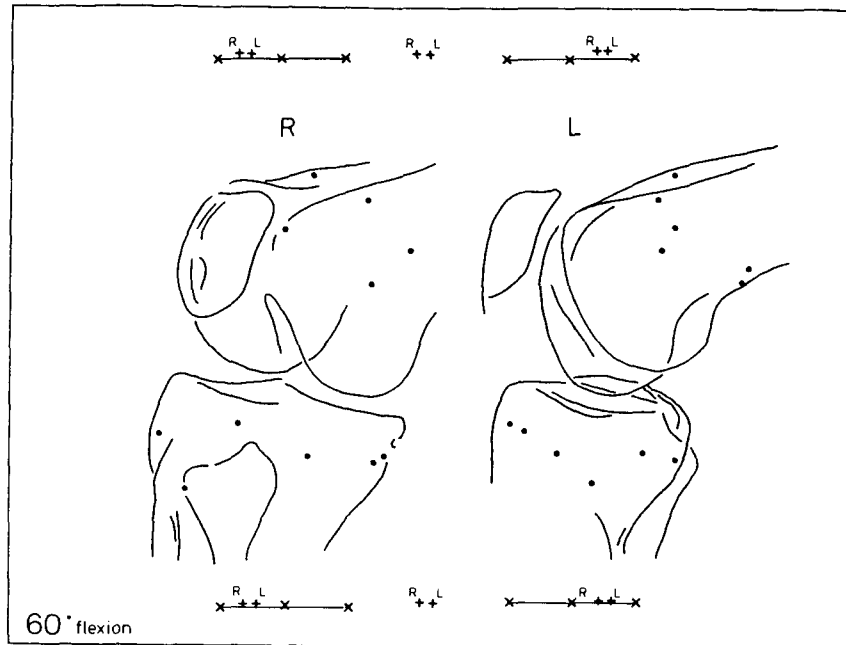


Fig. 1. Tracings of a stereo roentgenogram showing the six object markers in both femur and tibia. The images of the 6+6 reference cage markers used for calibrating the stereo set-up are also shown, R = image from the right focus; L = image from the left focus. The calibration markers are situated in two planes, those marked + are situated near the film and those marked x are glued on a glass plate 135 mm closer to the roentgen foci. The calibration markers are tantalum balls, 0.5 mm in diameter.

tibial bone pieces were approximately 15 cm in length. The joints had been stored in the deep freezer. Six tantalum balls, each with a diameter of 0.8 mm, were implanted in the tibia and the femur. The tibia was fixed and roentgen exposures from two tubes, using the previously described technique, were taken with the femur hyperextended and flexed in various angles from about 10 to 120° (Fig. 1). After the exposures the intact knee specimen was removed, the knee joint cavity was opened and all connecting structures, except the cruciate ligaments, between the femur and the tibia were cut. The most anterior and posterior fibres of both cruciate ligaments were exposed (van Dijk, 1978) and their bony attachment points were marked with tantalum balls (Fig. 2). Following this, double exposures were made of the separated femur and tibia (Fig. 3).

All roentgenograms were measured and the three dimensional position of all markers were calculated. Using the

computer program for rigid body motion (Selvik, 1974), the rotation matrices, translation vectors and screw axes, describing the relative motion between tibia and femur for all sequential flexion angle steps, were calculated for the first series of roentgenograms. The roentgenograms with the attachment markers were used to calculate the positions of these markers with respect to their femoral or tibial bone pieces. By transformation to their sequential positions during the flexion movement, using the kinematic parameters previously described, the changing distance between each pair of attachment markers could be calculated.

In order to be able to interpret the results, an approximately mid-sagittal and a perpendicular frontal plane were mathematically defined. The flexion-extension angle is defined as relative rotation between the two bone parts in the mid-sagittal plane.

Computer graphs of the results were automatically drawn,

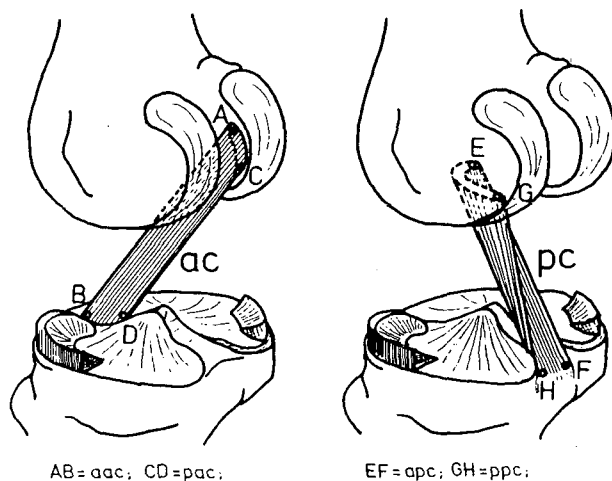


Fig. 2. The eight points (A-H) marking anterior and posterior fibers of the cruciate ligaments. aac: anterior fiber of anterior cruciate ligament; pac: posterior fiber; apc: anterior fiber of posterior cruciate ligament; ppc: posterior fiber (modified after Kapandji, 1970).

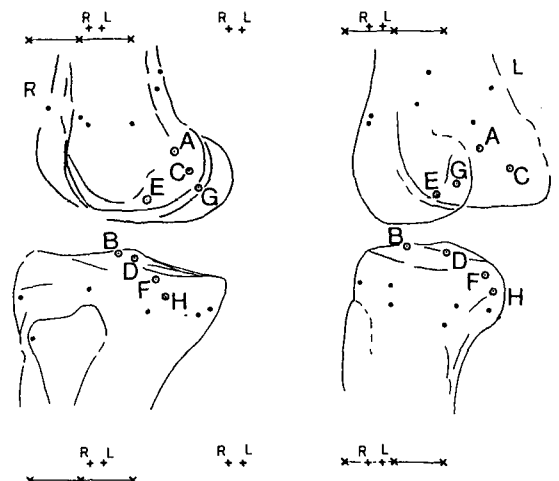


Fig. 3. Tracing of a stereo roentgenogram showing, beside the calibration markers and the femoral and tibial object markers, the eight markers defining the cruciate ligament attachments (A-H). The notations for those markers are the same as in Fig. 2.

showing: distances between pairs of attachment markers as function of flexion angle; orthogonal projections of the attachment points and the instant axis of rotation on the mid-sagittal and frontal plane, for different flexion angles; and intersections of the successive axes of rotation with the mid-sagittal plane, relative to the femur and relative to the tibia.

RESULTS

Specimen 1

Using the hyperextended position as a reference, the flexion angles were determined to be 0°, 13°, 21°, 41°, 63° and 120° for the six positions of the intact knee. During the flexion from 0° to 13°, an external rotation of 4° of the femur occurred, otherwise the rotations took place almost purely about a transverse axis.

The cruciate ligament attachment markers were transformed from their separate recordings to their positions in the intact knee, using the kinematic parameters as evaluated, and the line segment lengths were computed, using the three-dimensional Pythagorean theorem. The lengths of the ante-

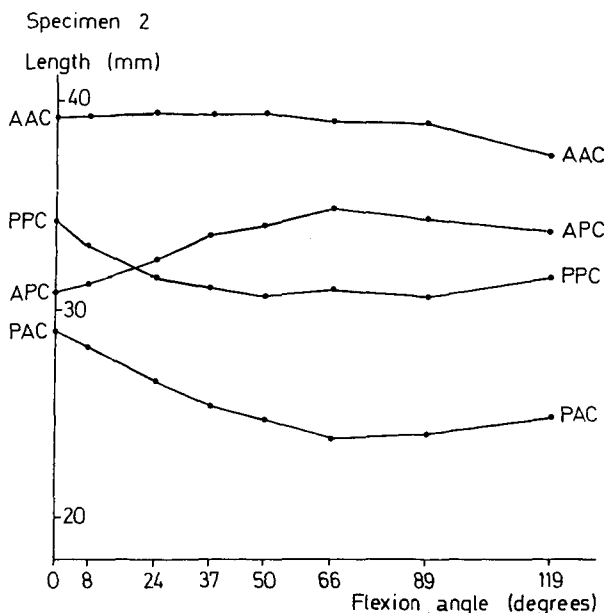
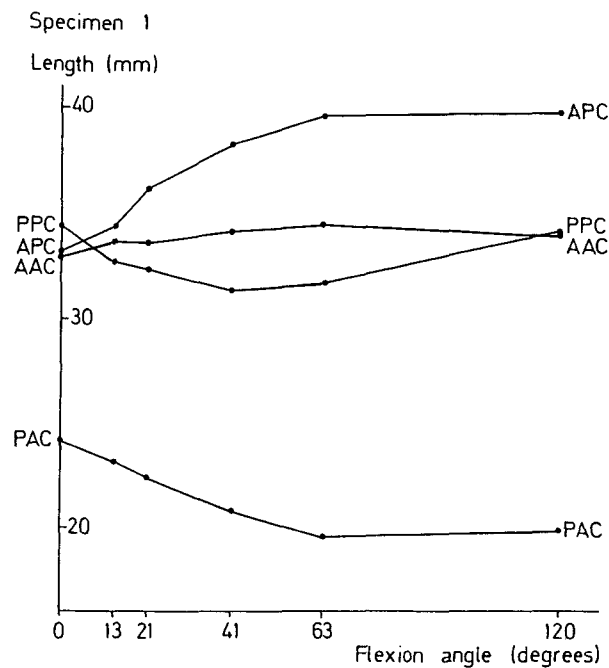


Fig. 4. The lengths of the fiber bundles of the cruciate ligaments as function of the flexion angle in the knee joint, as calculated from measurements of specimens 1 and 2.

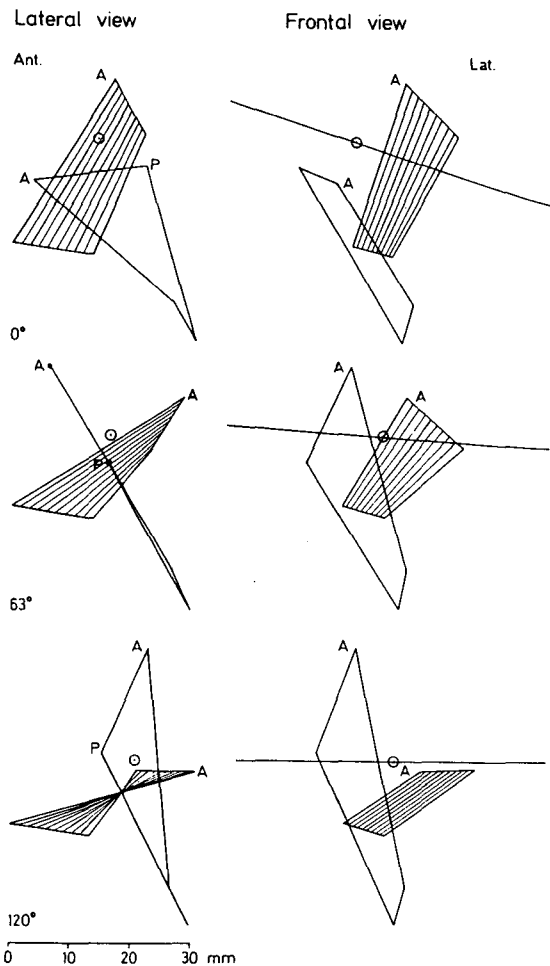


Fig. 5. The orthogonal lateral and frontal projections of the markers defining the anterior (striped) and posterior cruciate ligaments in a left knee (specimen 1). A = anterior part, P = posterior part; note the twisting of the anterior cruciate fibers as seen in the lateral view. The intersection of the axis of rotation with a sagittal plane through the center of the femoral object indicators is marked with a dot in a circle.

rior and posterior segments during the six recordings are given in Fig. 4(a). In Fig. 5, the ligaments, as characterized by four markers, for three of the investigated angles (0°, 63° and 120° of flexion) and the screw axes for the motion from 0° to 13°, 41° to 63°, and 63° to 120°, respectively, are drawn as projections on the two planes.

Specimen 2

The flexion angles at eight exposures, starting with the hyperextended position, were found to be 0°, 8°, 24°, 37°, 50°, 66°, 89° and 119°. During the flexion from 0° to 8°, an external rotation of 4° of the femur occurred. The intersections of the axes of rotation for the successive movements, i.e. 0°-8°, 8°-24°, etc. are shown in Fig. 6. It should be remarked that the subsequent flexion angles measured were positioned going from hyperextension (0°) to full flexion (119°), except for the angles 50° and 89°, which were positioned while going back from full flexion to hyperextension. The irregularities found in the path of the rotational axis (Fig. 6) for these angles hence probably reflect the non-uniqueness of the motion. The non-uniqueness will be evaluated in further tests. The lengths of the anterior and posterior line segments of the cruciate ligaments as function of flexion angle are shown in Fig. 4(b).

Accuracy of the method

By re-evaluating the six roentgenograms from the kinematic investigation of specimen 1, the accuracy of the rotation angles between the femur and the tibia between two exam-

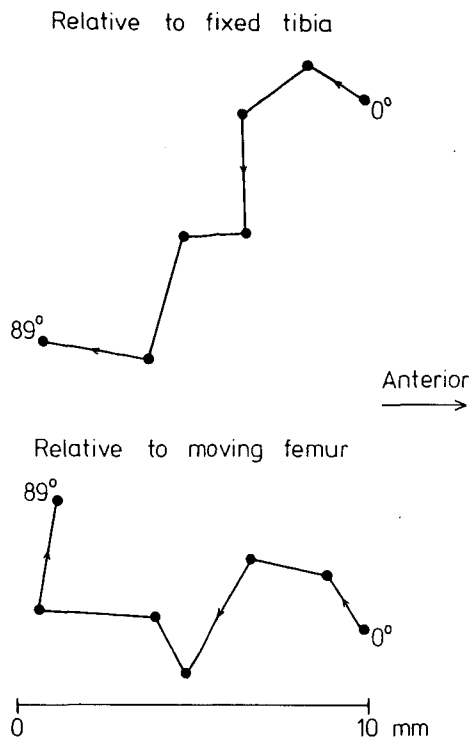


Fig. 6. The absolute positions in space of the intersections with a mid-sagittal plane of the axes of rotation for the successive movements in the right knee joint of specimen 2, from 0° - 8° up to 89° - 119° (top). The corresponding intersections in relation to the femur, drawn in the position of the femur at hyperextension (0° , bottom). Note the irregularities for the 37° - 50° and 66° - 89° rotation axes (see text).

inations were determined to be 0.06° , 0.09° and 0.15° about the sagittal, longitudinal and transverse axes, respectively. It can be noted that the corresponding translations were determined with a standard deviation of about 0.05 mm. In a corresponding test, the precision in locating the three-dimensional positions of the ligament attachment points during transformations of the reference segment was estimated to be about 0.1 mm. From the precision tests, the radial error in determining the intersection of the screw axis with the sagittal plane was estimated to be 0.2 mm (S.D.). When two separate evaluations of the radiograph with the ligament attachment points were performed, the lengths of the line segments could be determined from two completely different sets of evaluations and transformations (each of 6 + 1 roentgenograms). Thus, comparing the computed lengths of the line segments, the precision in determining a length was found to be 0.09 mm. Not all reference markers could be detected on all stereo roentgenograms. On average, 4 markers in the femur could be used; by using 6 markers, the precision will be even better.

DISCUSSION

One should be aware that the examples presented here are only meant to demonstrate the possibilities, the accuracy and the flexibility of the roentgen stereophotogrammetric measurement method, if used to analyze joint kinematics. The method is as noninvasive as possible and the system itself hardly has to be disturbed. Several tests and pilot studies (e.g. Aronson, 1976) have shown that no objections exist against the use of the tantalum balls *in vivo*, which opens the possibilities for application of the same method for *in vivo* analyses. Of course, only the joint kinematics can be studied in this case, and the method used here to mark the ligament attachments then becomes impossible.

The results, with respect to the joint kinematics and the

circumstances in which they were evaluated, can be rightly criticized. For that matter, the same criticism is, in our opinion, justified with respect to other experimental results published until now. It appears quite unrealistic to assume the knee joint to have only one degree of freedom. Indeed, while prescribing the flexion angle steps during the experiment, it was found that by applying only very small forces other than to change the flexion angle, the positions of the bone parts changed relative to each other. Rotations about a longitudinal axis are performed especially easily. The motion of the joint is certainly not unique and the results presented here refer to a somewhat arbitrarily chosen mid position, with respect to exo- and endorotation. In our opinion, while carrying out the experiments, the three-dimensional load system on the joint parts should be very accurately prescribed or measured. An apparatus for such accurate three-dimensional load measurements is now being developed. With such an experimental setting, very accurate stability measurements can be performed and mathematical models (Crowninshield *et al.*, 1976; Wismans *et al.*, 1977; Lew and Lewis, 1978) can be verified.

With respect to the ligament length patterns, it should be noted that only the changes in distance between points are evaluated. Nothing is known about the real stretching of the fibers. The choice of location for the attachment markers proved to be of crucial importance for the results and this can make comparison with other results difficult.

In spite of the above mentioned error sources in the experimental procedures, the agreement between the results of both specimens is reasonable. With respect to the ligament length patterns, the results agree globally with those of Girgis *et al.* (1975), Trent *et al.* (1976) and Wang *et al.* (1973). The partly conflicting results, as compared with Crowninshield *et al.* (1976), may to some extent be explained by comparing the attachment point coordinates in frontal and lateral projections.

The changing positions and directions of the instant axes of rotation proved to be less irregular as compared with other authors, which may be due to the high metric accuracy of the roentgen stereophotogrammetric method.

CONCLUSIONS

The roentgen stereophotogrammetric measurement system, as developed by Selvik (1974), offers excellent options for three-dimensional measurements of joint kinematics and anatomical data. The method proved to be both accurate and flexible, while use for *in vivo* objects is possible. With respect to accurate evaluation of joint kinematics, one should be aware that the loading system also has to be accurately measured, in order to give the results actual value.

Department of Orthopaedic Surgery,
Biomechanics Laboratory,
University of Nijmegen,
Nijmegen,
The Netherlands

R. VAN DIJK
R. HUISKES

Department of Anatomy,
University of Lund,
Lund,
Sweden

G. SELVIK

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