Roentgen stereophotogrammetry

Review of orthopedic applications

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Roentgen stereophotogrammetry is based on radiographic examinations of calibration cages and object markers implanted in the skeleton. Accurate measurements of radiographs and computer-assisted calculations can provide a three-dimensional motion analysis. Since its introduction 15 years ago, roentgen stereophotogrammetry has found an increasing number of orthopedic applications, which are reviewed here: growth, prosthetic fixation, joint kinematics and stability, fracture stability, and the healing course of spinal fusion and pelvic and tibial osteotomies.

Measurements on conventional radiographs can have an accuracy of 1–5 mm and 1–6° depending on the technique employed, the anatomic region investigated, and the number of examiners[1–5]. Roentgen stereophotogrammetry of metallic markers implanted in the skeleton permits analysis of very small movements, important in many fields of orthopedics. This review provides an introduction to Selvik's[6] roentgen stereophotogrammetric analysis (RSA) and a short survey of its applications in orthopedics.

Roentgen stereophotogrammetry

Roentgen stereophotogrammetry is a technique to obtain accurate three-dimensional measurements from radiographs[7,8]. The geometric characteristics of an object is determined enabling calculations of movements between repeated examinations.

History

Determination of positions in space by radiography was tried shortly after the discovery of this technique. In 1898, Davidsson[9] used silk threads to reconstruct x-rays between the two roentgen foci and the images of the object points on the films. Other investigators (for review, see Köhnle[10]) focused on stereoscopic viewing or measurements on virtual images[11]. The development of roentgen stereophotogrammetry proceeded slowly; as late as 1967, Köhnle[10] felt that the evolution of this technique was but in its infancy.

Analytic photogrammetry was further developed by Hallert[8,12], whose methods were used by Hollender[13] to show that no systematic deviation of roentgen rays occurs. He also demonstrated that measurements with the aid of radiography could yield an accuracy of 10–50 microns. Because there are no sufficiently distinct anatomic landmarks in the skeleton, small metallic implants are necessary to obtain this accuracy.

Björk[14,15] used metallic implants of vitallium and later tantalum to improve reorientation in roentgen cephalometry and to increase the precision of growth measurements of the craniofacial skeleton in children. Roentgen stereophotogrammetry using metal indicators was introduced in orthopedics by Lysell[16], who implanted steel balls into cadaver cervical-spine specimens to record vertebral motions. Later, additional systems were introduced to investigate migration of knee and hip prostheses[17–22] and movements of the spine[23–25] and the tarsal bones[26].

Based on the previous studies of implant technique[15], analytic photogrammetry[8,12], and mathematical principles of rigid-body motion[27,28], Göran Selvik[6] constructed a roentgen stereophotogrammetric system, which he later named *roentgen stereophotogrammetric analysis* (RSA). The basic principles were presented in 1974. Since then, the method has been subjected to numerous updatings[7,29–31].

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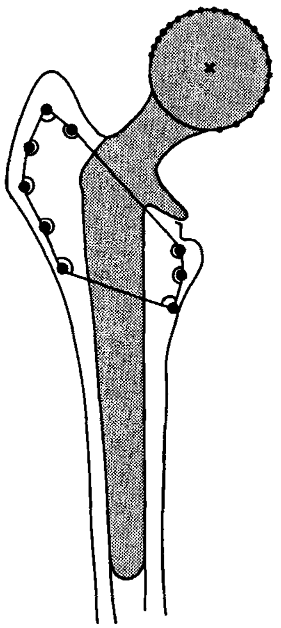


Figure 1. Schematic drawing of optimal configuration of tantalum balls in the proximal femur. Instability of one or more of the markers will change the distances between the markers, the angles of the segment, and the mean error of rigid-body fitting. Exclusion of 1–2 markers due to instability can be done with a minimal loss of accuracy. Prosthetic movements between two examinations are here represented by displacements of the center of the femoral head using the bone markers as the fixed reference segment.

RSA has been extensively used not only in orthopedic research and practice, but also to investigate problems in pediatrics[32], odontology and plastic surgery[33–35], oncology[36], rheumatology[37], anesthesiology[38], neurosurgery[39], and hand surgery[40].

Roentgen stereophotogrammetric analysis

An RSA investigation can be separated into four parts: 1) implantation of tantalum markers, 2) the radiographic examination, 3) measurements on radiographs, and 4) mathematic calculations.

Implantation of markers

Spherical tantalum balls with a diameter of 0.8 mm (or less commonly 0.5 or 1.0 mm) are used to obtain distinct points of measurement. Initially, the implants were pin-shaped, but their use is now restricted to investigations of the facial skeleton.

Tantalum has a high atomic number facilitating identification on radiographs. It has been used in sutures[41], wires[41], foil[42], clips[43], or for diagnostic purposes as powder[44,45] for some 50 years, is biocompatible[32,46,47], and is resistant to corrosion[41]. The insertion of tantalum markers is well established for clinical use[33,34]. Since 1972, more than 20,000 balls have been implanted in more than 2,000 patients. One case of chronic urticaria caused by tantalum staples has been reported[48], but no adverse reactions after implantation of tantalum balls have occurred.

The tantalum balls are introduced into the tip of a stainless-steel cannula. The position of the ball is secured with a small piece of bone wax. A tapered point and a spring-loaded piston[49] can be used, especially when the bone is thin, as in the facial skeleton. In orthopedic investigations, cannulas with beveled tips, introduced into the bone in combination with hand-operated pistons, have proved to provide satisfactory stability of the implants.

For a complete kinematic analysis, at least three noncollinear markers must be implanted. To increase the accuracy and to be able to exclude occasionally loose tantalum balls, five or more well-separated markers can be used (Figure 1).

In bone undergoing rapid metabolism, an initial instability of the markers can occur[50]. Therefore, it is advisable not to initiate the roentgen examinations until 10–14 days after the implantation when children are studied. Investigations of femoral neck fractures[51] 1–2 hours after implantation of markers and several months later have indicated that an initial and long-lasting stability can be achieved in adults.

After predrilling, tantalum balls have also been inserted in the polyethylene component of joint prostheses[52–54] and in prostheses made of chrome-cobolt[55] or titanium-aluminium-vanadium alloy (Figure 2). Radiographic visualization of tantalum markers implanted in metallic prostheses is often difficult, and usually implies a more or less pronounced loss of accuracy. The center of the femoral head[52,56,57], the circular stainless-steel wire in the polyethylene acetabular component[5], or the two ends of a semicircular wire[56] can also be used to measure migration, wear, or inducible displacements.

Radiographic examination

Two roentgen tubes are used for simultaneous exposures of a glass or Plexiglas® calibration cage supplied with tantalum markers. The positions of the cage markers are determined by a calibration procedure[6,7]. The

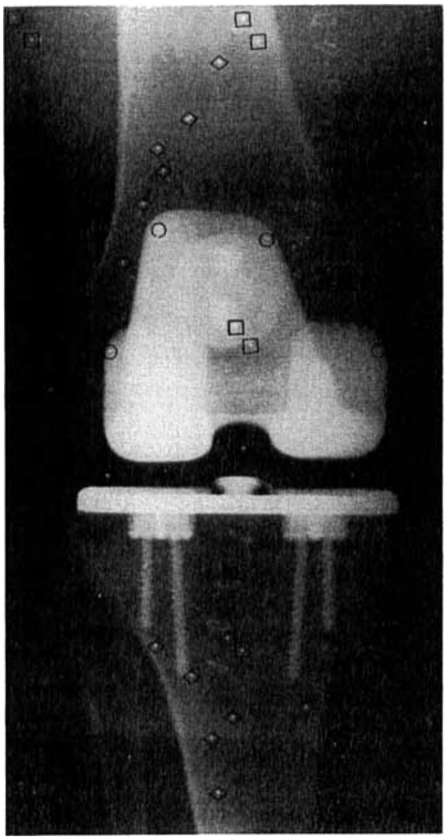


Figure 2. RSA radiograph (Focus 1) of a Ti-Al-V (Tivanium®) knee prosthesis. High kilovoltages enable visualization of femoral component markers (circles). Tantalum balls in the tibial polyethylene plate (triangle), bone markers (rhombus), fiducial marks, and control points (square).

system may be uniplanar or biplanar corresponding to the positions of the roentgen foci and films. This also implies that two or four of the walls are supplied with tantalum markers. Tantalum balls in the wall(s) closest and parallel (not a prerequisite) to the roentgen films are called *fiducial marks* and identify the laboratory coordinate system. The markers in the wall(s) nearest to the roentgen tubes (control points) are used to calculate the positions of the roentgen foci (Figures 3 and 4).

If the patient cannot be examined inside the cage

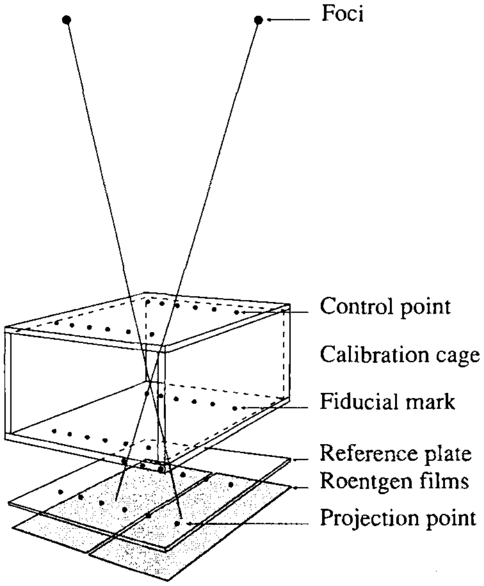


Figure 3. Calibration cage with the two roentgen films in the same plane. This type of cage is often used in hip and spine examinations together with reference plates. The angle between the x-ray tubes is about 40°.

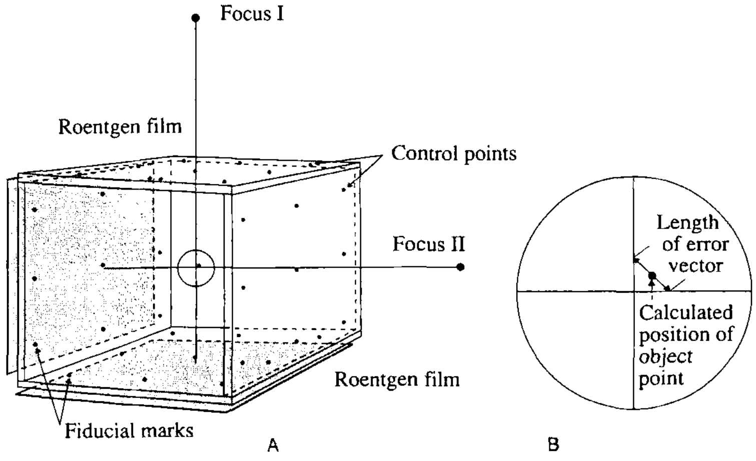
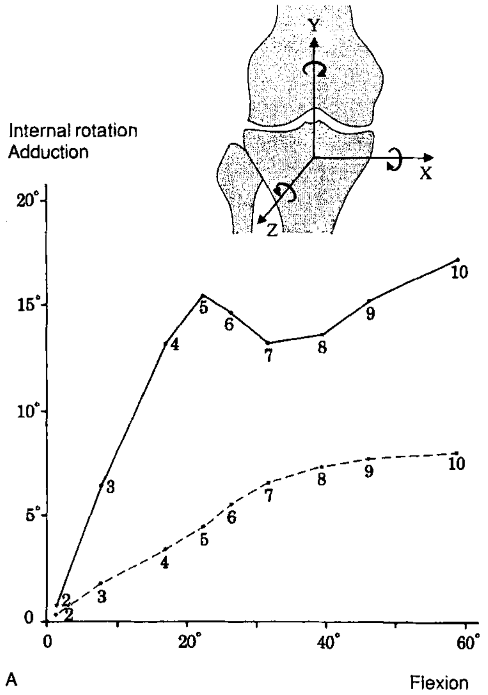


Figure 4 A. Calibration cage with film planes perpendicular to each other. This set-up is often employed in examinations of the distal extremities (e.g., knee, ankle).

Figure 4 B. Illustration of the smallest distance between two computed rays through an object point. The midpoint of the error vector represents the calculated position of the marker.



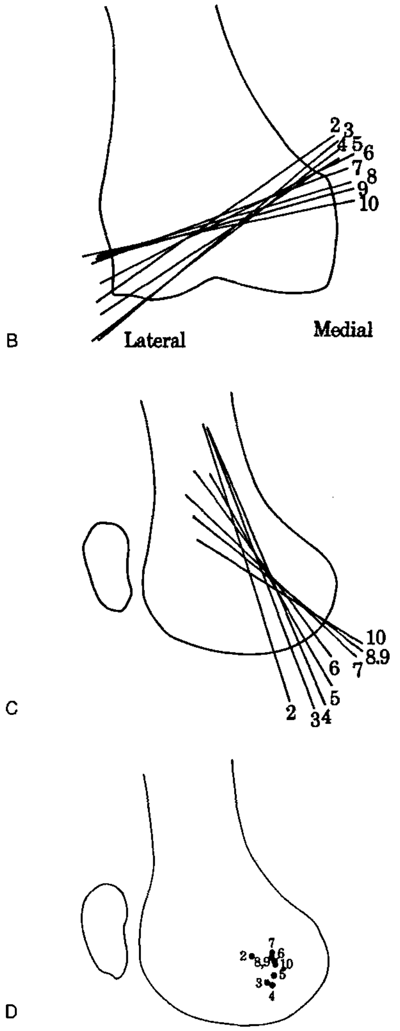


Figure 5. RSA investigation of a normal knee during active flexion (film-exchanger technique, two double exposures). Recordings of tibial rotations. Each number corresponds to proceeding double exposures (observations). Number 1 is relaxed, extended knee (reference position). The contours of the distal femur (5B-D) were reconstructed in this patient according to the technique presented in Figure 6.

A. Tibial rotations in relation to a body-fixed coordinate axis.

B. The projection of the screw axes in the frontal plane.

C. The projection of the screw axes in the sagittal plane.

D. The intersection of the screw axes through a sagittal plane through the center of the distal femur.

(e.g., hip and spine examinations), one or two reference plates supplied with tantalum markers can be used[56–58] (Figure 3). The cage and the reference plate(s) are radiographed, and thereafter the patient and the plate(s). A fixed position of the roentgen tubes and the plates has to be assured throughout the examination. As an alternative a modified calibration cage may be placed beneath the examination table when uniplanar technique is employed.

The part of the body under examination should at least at one (usually the initial one) of the examinations be aligned with the laboratory coordinate system, i.e., the cage. As a result, all the movements will be recorded in relation to axes with a standardized orientation in relation to anatomic landmarks[58,59]. This is especially important when large movements are recorded. At the subsequent examinations the position of the object can be chosen according to the intentions of the investigation, provided that optimal visualization of the markers is possible.

There is no consensus concerning the orientation of the laboratory coordinate system in relation to the anatomy of the body. A standardized position facilitates interpretation of data. The following orientation has been recommended[60]: the transverse axis should be directed to the left, the longitudinal axis upwards, and the sagittal axis anteriorly. If the extremities are examined, the transverse axis should extend medially (Figure 5).

The radiation doses at RSA examinations have proved to be low compared with corresponding conventional radiographic examinations[35,53,58,61].

Measurements on radiographs

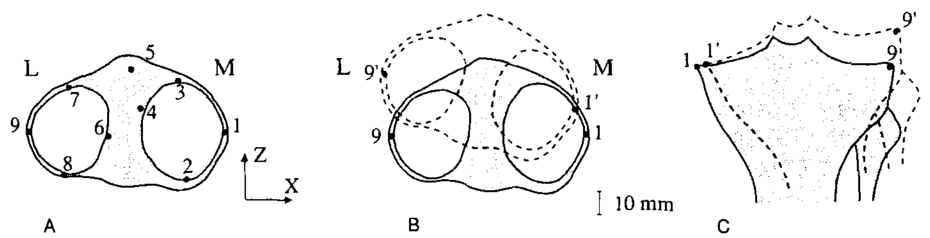


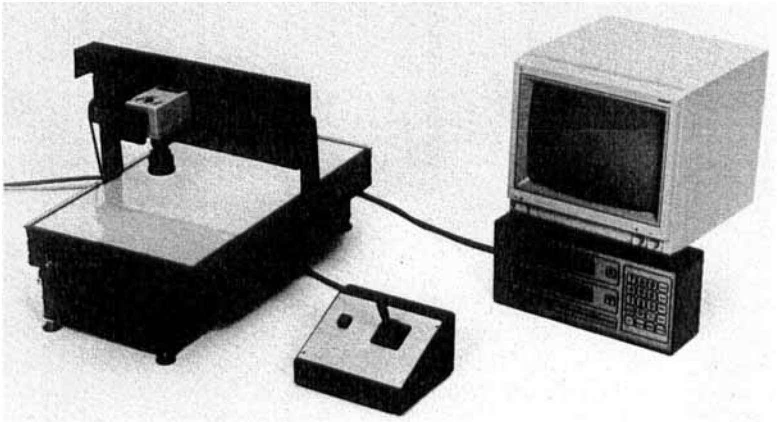
Figure 6. Reconstruction of the projection of the tibial plateau in the horizontal and frontal planes in a patient who actively could dislocate his knee because of a rupture of the anterior cruciate ligament. Three double exposures were performed (extended knee, 20°flexion, active dislocation), and the three-dimensional movements of the distal femur and proximal tibia were calculated (segment motion, KINLAB).

A. Nine points have been plotted on the x-rays (Foci 1 and 2) of the extended position of the knee. After determination of the three-dimensional positions of these points, they have been used to delineate the contours of the tibial plateau.

B. The nine points have been transformed into the other two positions of the knee by using four tantalum balls representing the proximal tibia (point transfer, KINLAB). The tibia has been mathematically realigned to the coordinate system corresponding to its position during knee extension. The femoral tantalum markers have been subjected to the same rotations (ROTATE). After these procedures the displacements of points 1 and 9 in the horizontal plane have been chosen to represent the tibial subluxation (point motion, KINLAB). Full line = position before dislocation, dashed line = position after displacement. A slight distortion of the contours of the tibial plateau in the dislocated position due to small tibial rotations (extension and abduction) between the flexed and the dislocated positions has not been accounted for.

C. The projection of the proximal tibia in the frontal plane. For details and symbols, see Figure 6 B.

Figure 7. Measuring table (Hasselblad) suitable for roentgen films with a size of 30x40 cm or smaller. This instrument has an accuracy of 10 µm. A television camera facilitates optimal setting exactness. The camera, connected to two perpendicular linear gauges, is moved with the aid of servomotors and a joystick.



The images of the markers (cage and patient markers) are numbered according to a standardized pattern. Optionally, one or more fictive points corresponding to anatomic landmarks can be plotted on one pair of radiographs (Figure 6). The two-dimensional position of each point is measured and stored in a computer. The measuring table of a cartographer (Wild A8 or Wild A7z, Heerbrugg, Switzerland), with a precision of 5–25 microns, has been used. A television camera is attached to the plotting carriage, and the measuring points are enlarged up to 15 times. Smaller and more convenient measuring tables have recently been developed (Figure 7).

Mathematic calculations

The mathematical computations were initially performed on a large-size computer (Sperry Univac 1100/80). The software has recently been adopted to personal computers (PC-AT, 1 Mb random access memory and coprocessor).

Six computer programs (XRAY, KINERR, KINLAB, GROWTH, ROTATE, and MEDVOL) embrace all possible evaluation procedures. XRAY calculates the three-dimensional positions of markers from measured film coordinates. In KINERR, erroneous identification of tantalum markers can be detected and corrected. This program also discovers and deletes loose tantalum balls. KINLAB (KINEMA) includes the procedures necessary to evaluate three-dimensional motions of a rigid body or a point. GROWTH ena-

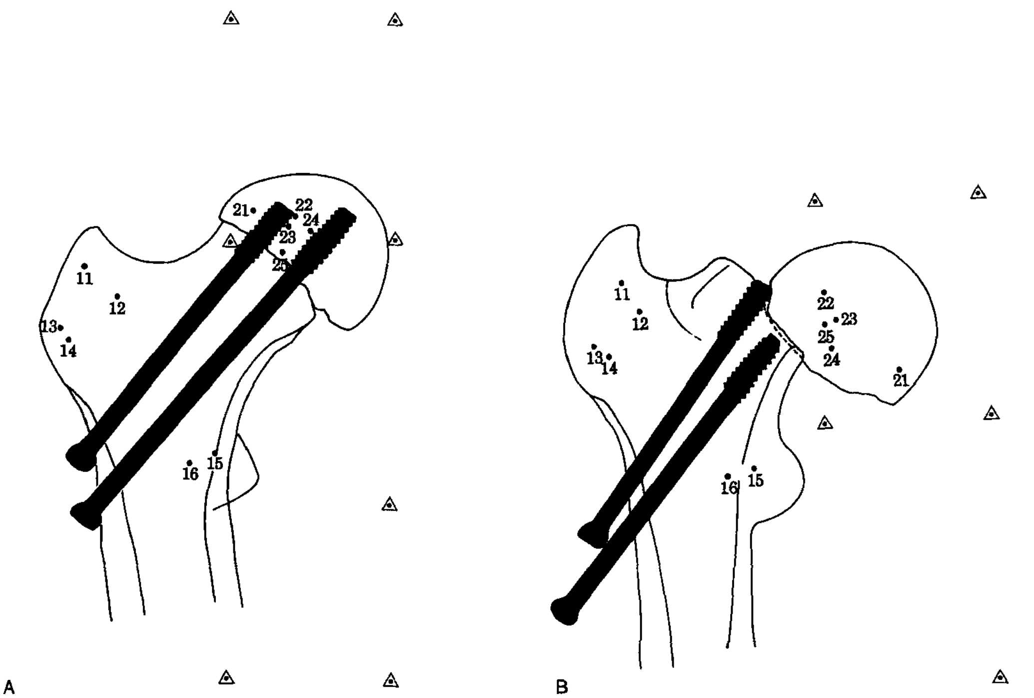


Figure 8. Drawings of RSA radiographs (Focus 1) of a displaced femoral neck fracture. Closed reduction and fixation with titanium screws have been performed. Each marker has a specific identification number. Triangles are measured projection points.

A. Postoperative examination.

B. Redisplacement 1 month later. Pronounced rotatory displacement making correct identification of tantalum balls in the femoral head difficult. Evaluation in KINERR revealed acceptable stability of markers 2–5 (mean error of rigid-body fitting 0.25 mm). The rotatory displacement was most pronounced when measured about the transverse axis (78.3°).

bles recordings of changes in length between two points. ROTATE performs reorientation of an object by adjusting axis directions. Finally, the volume enclosed in a polyhedron can be calculated (MED-VOL)[36,62,63], but has so far not been used in orthopedics. Plotting routines enable graphic illustrations of the results.

XRAY and KINERR. The predetermined coordinates of the cage markers are stored in XRAY. During the evaluation of a pair of radiographs, the film coordinates of the images of the fiducial marks are transformed into the laboratory coordinate system using a projective or similarity transformation depending on the radiographic set-up at the examination (for details including mathematical formulas, see Selvik[6]).

At the next step, the intersection of a ray from the focus through a control point with the plane of the fiducial marks can be reconstructed, because the control point and its image are given in the same coordinate system. Four rays not on a line have to be calculated employing a central projective transformation. Provided parallelism between the films and the plane of fiducial marks, a similarity transformation requiring only two control points can be used; but to achieve an overdetermination, routinely at least four rays from each focus are computed. The best fit to the crossing of the reconstructed rays corresponds to the position of the foci.

If a reference plate has been employed, the calibration examination determines the positions of the roentgen foci. The projection points (Figure 3) are transformed into the cage system and serve as fiducial marks at the subsequent examination of the patient.

The computed projections of the object points are used to calculate the intersection of two roentgen rays, one from each focus through an object point and the three-dimensional coordinates of this point.

Reliable identification of corresponding images of tantalum markers on the two radiographs can be performed in different ways. If the uniplanar technique is used and a line joining the two foci is parallel to the film plane, the coupling between markers on Foci 1 and 2 can be reconstructed with parallel lines.

In the mathematical calculation, the two rays do not exactly intersect because of measurement errors. The midpoint of the shortest error vector is primarily used to represent the three-dimensional position of an object point (Figure 4). If the patient has moved between the exposures corresponding to synchronous movements of all the object points, the shortest deviation from the average error vector can be used.

The ultimate test of the identification and stability of the markers is to determine the deformation of a rigid body, identified with at least three noncollinear tantalum markers between two examinations. The actual movement of a rigid body is calculated by the numerical determination of the rotation matrix M and translation vector $\bar{d}$ by minimizing the sum

$$ME = e_{rb} = \sqrt{\frac{\sum_{v=1}^{n}\left(\bar{r}_{2,v} - M\bar{r}_{1,v} - \bar{d}\right)^2}{n}}$$

over the n markers common for t_1 and t_2. Finally, $\bar{r}_{1,v}$ and $\bar{r}_{2,v}$ are the measured positions before and after the segment has been moved. If no deformation of the rigid body has occurred between the examinations, this sum is zero. A residual indicates a more or less pronounced distortion. The square root of this residual divided by the number of indicators is called the mean error of rigid-body fitting[6] (Figure 1).

By testing different identification numbers that might have been confused during the marking and excluding of any unstable marker, the most optimal rigid-body configuration is identified (Figure 8).

To calculate the center of the femoral head or a circular wire in acetabular prostheses, 20 points corresponding to the edge of the ellipsoid images are digitized on each pair of radiographs (Figure 1). The coordinates of the center of the sphere or circle and their diameters are computed.

KINLAB. Movements can be represented by the rotations about and the translations along three coordinate axes or a single axis called the screw axis (Figure 5). In KINLAB the absolute motions of each bone segment and the mean error of rigid-body fitting are calculated. The configuration of each segment is read out explicitly and by a single number indicating the quality of the segment.

At each calculation the reference segment is positioned according to an examination (usually the first one), with a desired orientation of the patient in relation to the cage. The absolute and relative movements between two examinations are computed using an optionally chosen, fixed reference segment. The relative movements of one or several rigid bodies (segment motion), single tantalum balls, or fictive points can be calculated (point motion). Before computation of fictive point motion, the plotted point has to be transformed between the examinations (point transfer)[51,58,64]. Segment motions are calculated in the following order: rotations about transverse (x), longitudinal (y) and sagittal (z) axes (Figure 5).

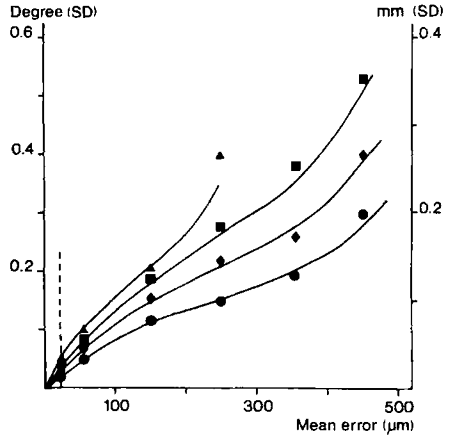


Figure 9. The influence on the accuracy of RSA for increasing ME and number of markers in a cadaver specimen with widely spaced tantalum markers in the proximal tibia according to Ryd[53]. The dashed line indicates the ME obtained under optimal conditions and represents the technical errors exclusively. Three markers (triangle), four markers (square), five markers (rhombus), and six markers (circle). Left ordinate, single-axis rotation; right ordinate, translation (MTPM). Reprint by courtesy of the author.

Translations can be recorded as movements of the center of gravity of a bone segment or of a single tantalum marker. However, most movements of the skeleton are a combination of rotations and translations. Therefore, it is recommended that translations are measured at standardized positions to obtain comparable data between all the patients in an investigation. This can be accomplished by plotting a point on the films corresponding to an anatomic landmark (e.g., the tibial intercondylar eminence[58], the center of the femoral head[51]). When the three-dimensional position of this point has been determined in XRAY, its corresponding position at subsequent examinations can be calculated using the tantalum markers within the same bone segment. By this procedure the contours of an anatomic configuration can be approximately delineated to visualize the movements of anatomic landmarks (Figure 5, 6).

GROWTH. Longitudinal growth in children can be recorded as changes of distances between tantalum markers placed on each side of the growth plate[7,32,65,66].

ROTATE. By inverting the rotation matrix corresponding to the absolute rotations calculated in KINLAB, an object can be reorientated according to a previously recorded position of one of the bone segments.

Table 1. Calculation of the accuracy (SD) from 16 stereophotogrammetric examinations of a bone specimen (proximal tibia with a cemented prosthesis) according to Ryd[53]. Number of markers pertain to the bone-rigid bodies.

	No. of markers	X-axis	Y-axis	Z-axis	
Segment motion					
Rotation (°)	6	0.035	0.032	0.025	(df 8)
Translation (µm)	6	18	10	11	
Point motion (µm)	6	24	18	25	(df 32)

Table 2. Calculation of the accuracy (SD) of in vivo investigations of knee (biplanar technique according to Ryd[53]) and hip prostheses (uniplanar technique according to Mjöberg[52]). The SD of segment rotation employing uniplanar technique were evaluated by 52 double examinations of acetabular prostheses (unpublished).

	X-axis	Y-axis	Z-axis	
Biplanar technique				
Segment motion				
Rotation (°)	0.10	0.07	0.09	(df 13)
Translation (µm)	32	26	48	(df 13)
Point motion (µm)	47	54	62	(df 52)
Uniplanar technique				
Segment motion				
Rotation (°)	0.46	0.57	0.20	(df 52)
Translation (µm)	100	60	230	(df 30)
Point motion (µm)	130	60	250	(df 23)

Accuracy

Roentgen stereophotogrammetric analysis can be performed with an accuracy of 10–250 µm and 0.03–0.6° (SD). This accuracy depends on such factors as the type and quality of the calibration equipment, image quality, film flatness, the precision of the measuring instrument, and the number (Figure 9) and configuration of the tantalum markers. Repeated examinations of test objects [53,66] (Table 1) or patients [52,53,56] (Table 2) have been performed to determine the accuracy of RSA. Poor film quality and inadequate configuration or instability of tantalum markers have proved to be the most important limiting factors to achieve high accuracy measurements, especially in the studies of fixation of joint prostheses, whereas other factors, such as the reproducibility of the induced movements, are limiting studies of joint stability and kinematics[64,67,68].

Clinical investigations

In orthopedics, RSA has been applied to studies of skeletal growth, prosthetic fixation, joint stability, joint kinematics, fracture stability, vertebral motions and healing course after fusions of the spine and osteotomies of the tibia and pelvis.

Growth

Bylander et al.[69] recorded the longitudinal growth after fracture of the distal femoral and proximal tibial physes and found a high frequency of growth disturbances. Kärrholm et al.[61,70,71] identified five types of growth patterns after ankle fractures in children and concluded that these fractures usually resulted in a temporary or permanent growth disturbance. Both Bylander et al.[69] and Kärrholm et al.[61,70,71] concluded that the Salter and Harris[72] classification was of limited value for predicting the posttraumatic growth after injury to the knee and ankle regions. The effects of operative procedures to retard growth due to unequal bone length or to stimulate growth after physeal fractures were recorded[73–75]. Bylander et al.[73,74] demonstrated that Blount physeodesis[76] resulted in retardation of growth at a basal level depending on skeletal maturity at the time of operation. Slow continued growth of the physis and epiphysis caused widening and transverse movements of the staples, whereas increasing and asymmetric growth was found to be an early sign of implant loosening. Hägglund et al.[77] measured longitudinal growth in the distal fibula in children with slipped capital femoral epiphyses and compared the results with a previously presented normal material[66]. Later, the growth of the proximal femoral physis and the trochanter in some of these children with slipped capital femoral epiphyses was presented[78].

Prosthetic fixation

Baldursson et al.[56,57] introduced RSA evaluation of joint prostheses in orthopedics, and measured the migration and wear of the acetabular component in patients with rheumatoid arthritis operated on with Charnley prostheses. Mogensen[79] recorded migration of surface replacement of the hip in 11 cases; more than half of the components had migrated significantly.

In a comparative study using 99mTc-MDP scintimetry, contrast and radionuclide arthrography, and RSA in patients with symptomatic hip arthroplasties, Mjöberg et al.[80] concluded that migration was the most sensitive parameter for revealing prosthetic loosening. Migration of cemented prostheses was more frequently recorded on the acetabular side, and could in most patients be detected during the initial 4 postoperative months. The use of low-viscosity bone cement did not prevent this postoperative migration, whereas a modified cement with reduced specific heat production did [52]. Later studies of cemented revisions of hip prostheses[81] and uncemented primary hip prostheses [54,55,82] disclosed a migration in all or most of the patients. In contrast to primary cemented prostheses[52], significant migration did not occur in some patients until 6 to 12 months after the operation[54,81], suggesting failure because of too small a contact area between the implant and the bone.

Ryd [53,83,84] studied the stability and migration of the tibial component of different types of knee prostheses and found tendencies to increased movements in uncemented prostheses. Primary migration and inducible displacement were found in almost every patient, and were regarded as a normal phenomenon after these operations[84]

Jónsson[85] investigated the fixation of cemented cup arthroplasties in 12 rheumatoid shoulders and found eleven stable prostheses during the initial postoperative year. More favorable loading conditions than in cup arthroplasties of the hip and the use of a thin cement layer reducing the risk of heat necrosis were thought to be of importance.

Joint stability

Movements within the pelvic ring in normal subjects and patients with clinical symptoms from the sacroiliac joints have been evaluated during different types of provocations[86-88]. These studies displayed average innominate rotations of about 2–3° on both the symptomatic and the asymptomatic side. It was concluded that analysis of mobility under physiologic conditions cannot identify disorders of the sacroiliac joint[88], thus refusing the claims of some chiropractors and practitioner of "alternative medicine."

The mechanical stability of the talocrural joint has been studied after rupture of the anterior talofibular ligament[89] and in patients with chronic lateral ankle instability [68]. Symptoms of instability were not always associated with increased talar movement during the adduction and anterior drawer tests, indicating an alternative etiology in some of the patients.

Roentgen stereophotogrammetric recordings of the anterior-posterior[64] and rotatory stability [67] of the knee after a tear of the anterior cruciate cruciate ligament revealed a more complex instability than was previously known. Absence of the ligament implied a more external rotatory position of the tibia in the supine and the relaxed position at 20–30° of flexion [64].

Joint kinematics

The three-dimensional movements of the wrist were investigated in vivo by de Lange et al.[90], who concluded that the carpal bones do not act as a rigid group, and especially not during radioulnar deviation.

In a kinematic study of the ankle and the subtalar joints, Lundberg [91,92] delineated the screw axes of these joints; he observed that plantar flexion and pro-supination induced rotations of the ankle and the subtalar joints, whereas dorsiflexion mainly occurred in the ankle joint. Posterolateral fibular displacement occurred when the talus was moved from plantar to dorsiflexion [59,93].

Knee joint kinematics have been studied in vitro[94–96] and in vivo [58,97]. With the aid of film exchangers, abnormal tibiofemoral motion was recorded during active flexion and extension in patients with a unilateral tear of the anterior cruciate ligament. It was suggested that these changed tibiofemoral movements were of etiologic importance in the development of secondary arthrosis. Nilson et al.[98] measured the in vivo kinematics of cruciate-sacrificing tricompartmental knee arthroplasties, and recorded a more pronounced posterolateral and valgus position of the prosthetic knees as compared with normal subjects. It was suggested that the configuration of the artificial joint area and the absence of the cruciate ligaments were responsible for these abnormal movements.

During flexion of four cadaver knees in a motion rig, van Kampen[99] recorded simultaneous patellar flexion, medial or medio-lateral tilting and rotations about the sagittal axis resulting in medial displacement of the apex. The center of the patella was laterally displaced at maximum flexion. Internal or external tibial rotation changed the patellar movements, whereas alteration of the total quadriceps load from 112N to 28N had minimum effects. Lateral release on these specimens did not significantly change the recorded movements, but subsequent elevation of the tibial tubercle did. Due to lack of or unpredictable biomechanical effects of these two operations, their ability to reduce the patellofemoral joint pressure was questioned.

Fracture stability

In randomized studies, Ahl et al.[100–101] found that early weight bearing did not jeopardize the stability of malleolar fractures treated with open reduction and internal fixation using wires, pins, and staples. At follow-up 18 months after fracture, supination injuries proved to be more stable than pronation ankle fractures[102].

Ragnarsson et al.[51] recorded the spontaneous compression of femoral neck fractures between operation and mobilization of the patients, and found an average movement of 3.7 mm in displaced fractures, corresponding to about one third of the total fracture movements during the initial postoperative month.

Vertebral movements

RSA has been used to study vertebral movements in patients with spondylolisthesis[103] and loss of correction after Harrington fusion of structural scoliosis[104]. In posterolateral fusions[105], vertebral motions did not decrease until 5–6 months after successful operations, suggesting that solid fusion is not necessary for pain relief[105–107].

Osteotomies

Tjörnstrand et al.[108] measured the obtained correction after high tibial osteotomy for gonarthrosis and recorded up to 3–4° loss of correction during the postoperative period. Comparison with conventional radiographic techniques revealed a sufficient accuracy of the latter when angular deviations were measured in the frontal plane. Hansson et al[109] recorded changes of the acetabular position after innominate osteotomy for hip dysplasia. Rotations of 32° and mainly craniodorsal translations of the acetabulum were found.

Conclusions

Roentgen stereophotogrammetry has proved to be an accurate and safe method to objectify skeletal kinematics. Whenever applicable, it is the method of choice to study fixation of orthopedic implants. Recent developments of computer programs have reduced problems associated with incorrect marking of the radiographs. Marker instability, suboptimal configuration of tantalum markers, and to some extent, insufficient radiographic technique remain the most important sources of error. Therefore, bone markers should be inserted with meticulous care assuring their implantation into locations of the cancellous bone with optimal quality. If the anatomic part of interest is of sufficient size, a minimum of five markers is recommended to reduce the effects of accidental loosening of one or two of the tantalum implants.

In orthopedic research, RSA will probably maintain its position as a superior method for high-accuracy measurements of skeletal movements. In selected cases, it may be of value to study clinical problems and provide guidelines for treatment. In the future, development of advanced graphic presentation of data and optical reading of standardized roentgen stereophotogrammetric radiographs may further improve its availability.

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