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“The Rotation Ratios Method”

A method to describe altered spatial orientation in sequential radiographs from one pelvis.

Thesis for the degree of doctor medicinae

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Norwegian University of Science and Technology

Faculty of Medicine

Department of Neuroscience

Section of Orthopaedics and Rheumatology

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A method to describe altered spatial orientation in sequential radiographs from one pelvis.

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Norsk tittel:

The Rotation Ratios Method
En metode for beskrivelse av endret romlig bekkeninnstilling ved sekvensielle røntgenopptak av samme bekken

Sammendraget:
Sekvensielle røntgenopptak av ett og samme bekken blir rutinemessig brukt bl.a. innen ortopedisk kirurgi. Ofte sammenliknes korresponderende røntgenmål for å vurdere sykdomsutvikling eller vurdere effekten av en behandling.
Tre-dimensjonale objekt blir transformert til to-dimensjonale bilder ved røntgenopptak. Både den romlige innstillingen av objektet og fokusering av røntgenrøret i forhold til objektet påvirker avbildingen. Endringer i disse innstillingene kan derfor påvirke aktuelle røntgenmål og representere en feilkilde når korresponderende røntgenmål sammenliknes.
I en serie av fire arbeid presenteres utviklingen av en målemetode som beskriver endringer i bekkeninnstilling om to akser, basert på standard frontale (AP) bekkenopptak.

To parametre som beskriver endring i bekkeninnstilling eller endring i røntgen-fokusering ble validert ved bruk av definerte røntgenopptak av et bekkenfantom.

Et dataprogram for simulering av røntgenopptak av rigide objekt ble utviklet og validert. Dette programmet representerer et virtuelt røntgenlaboratorium der objekt-orientering, røntgenfokusering, mm. kan endres.

Dette dataprogrammet ble brukt til simulering av 4653 røntgenbilder av 141 utvalgte bekken, representerende en normalpopulasjon. Simulerte røntgenmål fra disse bildene ble brukt i utviklingen av et formelapparat for klinisk bruk. Korreksjonsfaktorer for kjønn og bekkenstørrelse ble innarbeidet.

Metoden, som er en algoritme inkluderende både manuelle og matematiske prosedyrer ble validert. Først ble de manuelle delene validert enkeltvis før en samlet validering ble gjort der en sammenliknet 1020 beregnede bekkenrotasjoner mot korresponderende reelle.

Metoden synes å ha god nok nøyaktighet for klinisk bruk.

Navn kandidat: **Olav A. Foss**
Institutt: **Institutt for Nevromedisin**
Veileder(e): **Prof. Svein Sofus Anda og Prof. Pål Benum**
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Contents

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I wish to express my sincere gratitude to my supervisors Professor **Pål Benum** and Professor **Svein Anda**. Both my supervisors were vital in the investigation, Benum mostly in the first years and Anda in the later.

Benum and Anda are both to thank for their everlasting support and positive criticism.

Jomar Klaksvik is the head of biomechanical laboratory at NKSOI. Without Jomar, the work presented in this thesis would newer have been started and far less completed. Jomar and I have puzzled and struggled in a journey with seemingly endless number of new obstacles. His everlasting patience and his clear and inventive mind are true gifts and it has been a pleasure to work together with him.

Kristin Haugan is the coordinator and involved in most activities carried out at NKSOI. Her constantly positive criticism and support were in many occasions helpful in clearing clouded thoughts.

Per Olav Østbyhaug and **Geir Bjerkan** are two orthopaedic colleagues who helped me in clarifying how the work could be presented and constantly reminded me of my background as an orthopaedic surgeon and thereby to keep my feet on the ground.

My dear parents **Ragnhild Foss** and **Olav P. Foss** always have encouraged me in exploring the world and generously provided the necessities to do so including the chemicals needed to make my own black powder or filling another balloon with hydrogen gas.

Kjære Mor og Far, tusen tusen takk !

At last I will thank my beloved wife **Eidi** and our two daughters **Idd Andrea** and **Lea Lin** who all make my life meaningful.

My personal background for developing: "The Rotation Ratios Method".

Pål Benum introduced me into biomechanical research as he always encourages his staff members to explore the world of science. At this time he was the head of our Orthopaedic Department and had been deeply involved in the development of a customized hip prosthesis. Originally my research was related to analyzing polyethylene wear in acetabular components in hip prostheses since there is a correlation between polyethylene wear rate and survival of such prostheses. Sequential standard pelvic radiographs are routinely used where corresponding radiographic measurements are compared. Computer based analysis with automatic edge detecting techniques are presently the "state of art" when standard pelvic radiographs are employed in polyethylene wear measurements. Computer based methods are claimed to be far more accurate than former methods, based on manually edge detecting by replacing the human eye and hand with a computer when defining and marking the edges of the projections of the prosthetic femoral heads and the acetabular components. Both the manual and computer based methods are influenced by sources of error including variations in the picture formation.

The pelvic orientation influences the picture formation when standard pelvic AP radiograph are obtained. A difference in orientation consequently influences the projections of the prosthetic components and therefore must be a source of error in polyethylene wear measures. While performing polyethylene wear analyzes, I found several patients with seemingly larger wear at the e.g. 3 years follow up than at 5

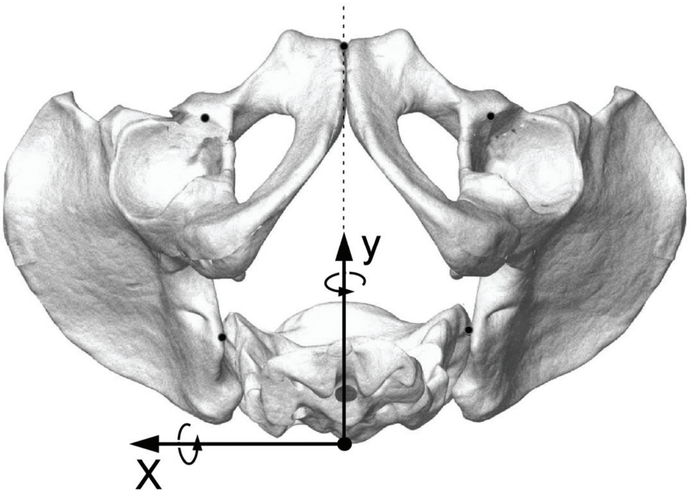
years follow up. These observations had to be results of some kind of measurement error. I then realized the importance of describing the accuracy of the methods employed in wear measurements.
As a consequence, a detour in my planned research activities took place leading from strict biomechanical research into an area involving orthopaedic radiology in order to describe effects caused by variations in pelvic orientation as a source of error.

I first meet **Svein Anda** in 1992 when I stood before a crossroad with one direction pointing to the field of radiology and the other into the field of surgery. Even though Anda most kindly offered me a way into radiology I ended into surgery. After some years employed in general surgery, I became a staff member of Benum in the orthopaedic department where Anda was presenting the radiographs.
No wonder that my research activities became a mixture of elements from both orthopaedic surgery and radiology, supervised by one professor in orthopaedic surgery and one professor in radiology.
On several occasions I found my self lost in the field of radiology. Of the most importance, Anda guided me through these mazes.

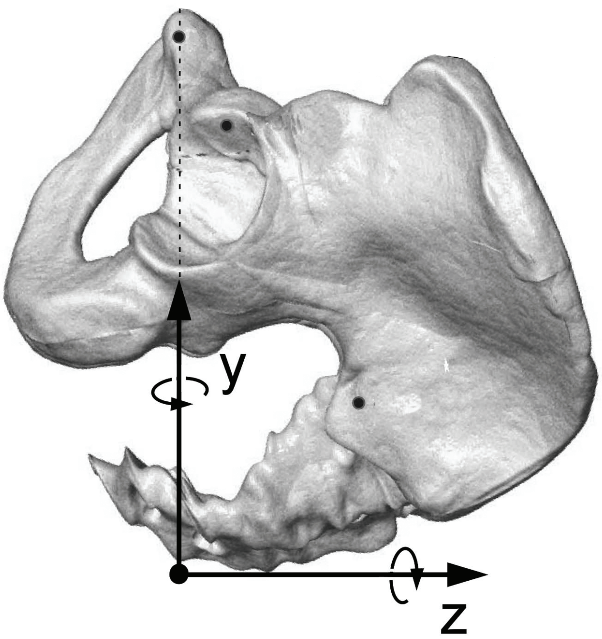
Definitions and abbreviations:

Orthogonal coordinate system:	a system to relate each point through two numbers when two-dimensional systems are used or by three numbers when three-dimensional systems are used. Two or three axes are directed perpendicular to each other where each number (coordinate) defines the points in respect to the corresponding axis. Three-dimensional coordinate system was used in the present work. Pelvic movements were related to a vertical, a transversal and an antroposterior axis.
Rotations:	moving an object in a circular motion. Two dimensional objects rotate around a point whereas three-dimensional objects rotate around a line, an axis.
Translocations:	moving every point of an object in constant distance in a defined direction. Such movement can be interpreted as adding a constant vector to every point in the object.

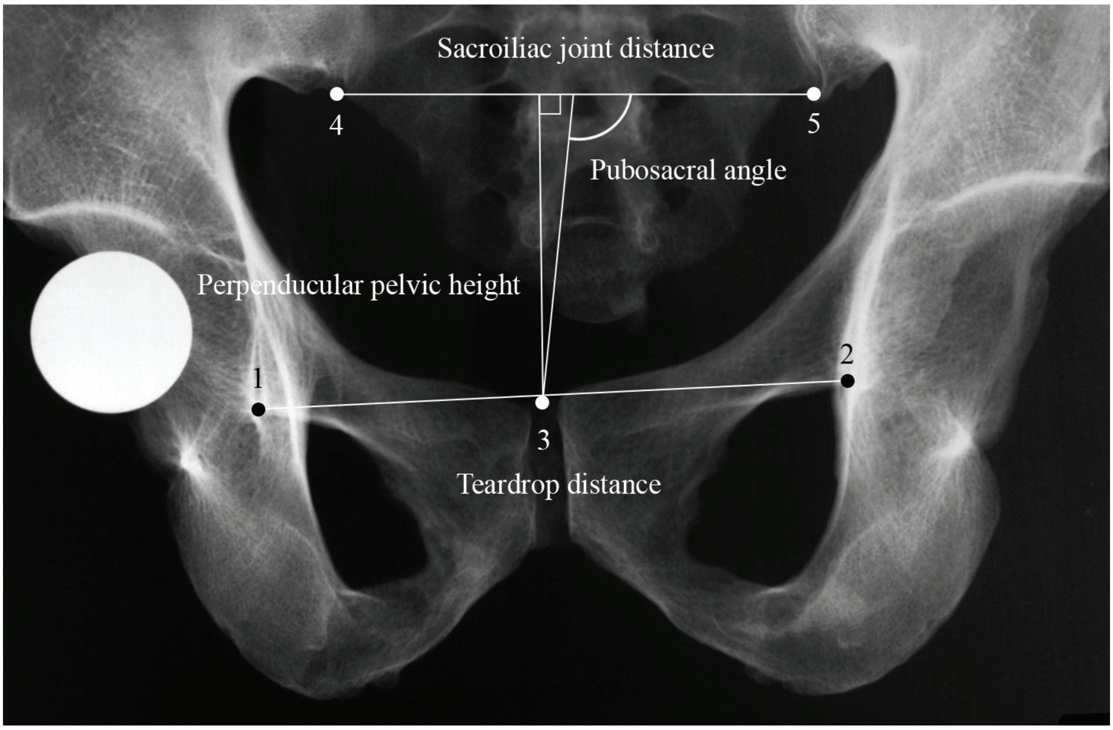
Pelvic transversal rotations: rotations around the transversal X axis. This may also be defined as variations in pelvic tilt.



Pelvic vertical rotations: rotations around the vertical Z axis.



Pelvic vertical translocations:	pelvic translocation along a vertical axis.
Pelvic transversal translocations:	pelvic translocation along a transversal axis.
Central Röntgen ray:	the theoretical Röntgen beam that exits from the exact centre of the focal spot in a radiographic tube.
Distortion:	a misrepresentation of the size or the shape of the object being radiographically examined.
Focus-Film Distance (FFD):	the distance from the focal spot in a radiographic tube to the radiographic film plane.
Object-Film Distance (OFD):	the distance from an object (or a part of an object) to the film plane.
The pelvic teardrop shadow:	a projection on antroposterior pelvic radiographs of defined structures located in the anteroinferior portion of the pelvic acetabular fossa at the acetabular notch.



Teardrop distance (Ted):	the interconnecting line between the middle of the most caudal part of the two pelvic teardrops.
Sacroiliac joint distance (Sid):	the interconnecting line between the radiographic projections of the middle of the most caudal part of the two sacroiliac joints.
Perpendicular pelvic height (Pph):	the perpendicular interconnecting line from the middle, most cranial portion of the projection of

	the pelvic symphysis to the Sacroiliac joint distance.
Pelvic height (Pht):	the interconnecting line from the middle, most cranial portion of the projection of the pelvic symphysis to the midpoint of the Sacroiliac joint distance.
Pubosacrale angle (Psa):	The angle formed by the Pelvic height and the Sacroiliac joint distance.
Partial sacroiliac joint distance (Psd):	The perpendicular pelvic height divides the sacroiliac joint distance into two parts. Psd is defined as the ratio between the right part of the sacroiliac joint distance and the total sacroiliac joint distance.
Rotation Ratios (RR):	two ratios, Vertical Rotation Ratio and Transversal Rotation Ratio, based on the former defined interconnecting lines; Ted, Sid, Pph and Psd.
Vertical Rotation Ratio (VRR):	the ratio between the right part and the total length of the sacroiliac joint distance, Psd/Sid.

Transversal Rotation Ratio (TRR):	the ratio between the perpendicular pelvic height and the pelvic teardrop distance, Pph/Ted.
Algorithm:	a set of rules for solving a problem in a finite number of steps.
Rigid point object:	an idealization of a solid body of finite size. Possible deformation is neglected leaving the distance between any two given points constant unaffected of external forces exerted on it.
Rotation Ratios Method (RRM):	a method to describe pelvic rotations when two standard pelvic AP radiographs obtained from the same pelvis are compared. The method is an algorithm including differences of the two RR between the two radiographs compared in a set of formulas categorized by gender with teardrop distance included as a continuous variable.

List of papers:

1. Foss OA, Klaksvik J, Benum P, Anda S. **Pelvic rotations, a pelvic phantom study.** Acta Radiologica. 2007;48:650-657.

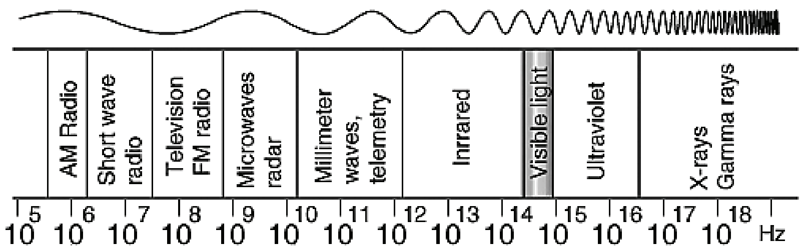
2. Klaksvik J, Foss OA, Benum P, Anda S. **Computer simulation of pelvic rotations and virtual radiographs.** Submitted "Journal of Biomechanics."

3. Foss OA, Klaksvik J, Benum P, Anda S. **The Rotation Ratios Method, A method to describe altered pelvic orientation in sequential radiographs.** Acta Radiologica. 2007;48:1011-1019

4. Foss OA, Klaksvik J, Benum P, Anda S. **The Rotational Ratios Method, validation.** Acta Radiologica. 2007;48:658-664.

General introduction

Short introduction to the nature of the Röntgen rays



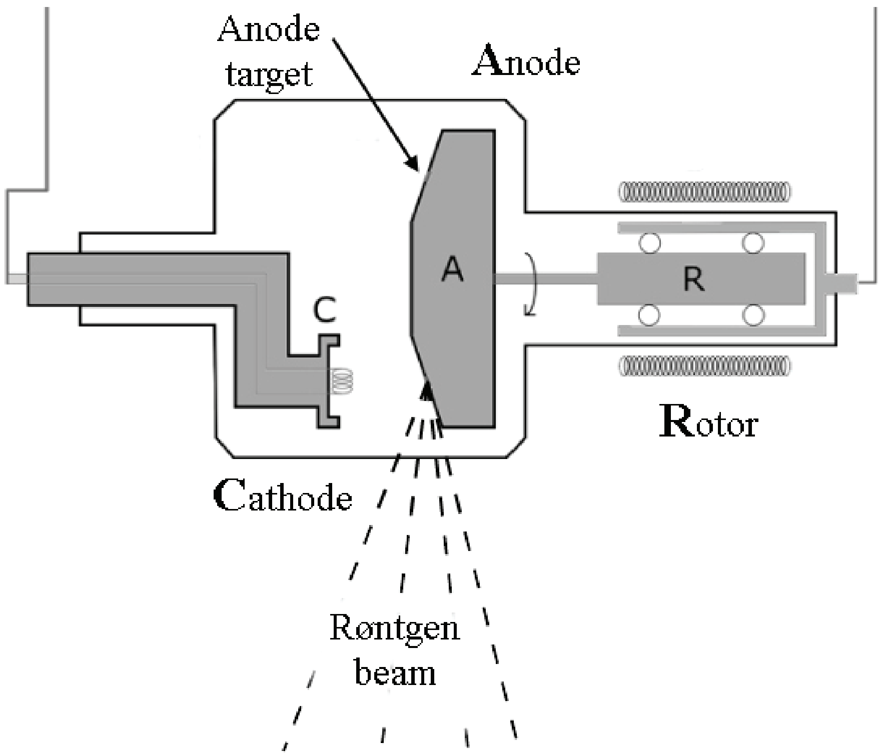
Röntgen-rays are part of the electromagnetic spectrum(39). All electromagnetic radiations are waves travelling in space with both electric and magnetic components. They are classified by their frequency and the electromagnetic spectrum includes radio waves, microwaves infra red radiation, visible light, Röntgen and gamma waves. Photons carried energy can be calculated by Planck´s equation: $E = hf$, where E is energy, h is the Planck´s constant and f is frequency. The Röntgen ray photons contain more than1000 times the energy of the photons of visible light.

There are a variety of astronomical sources which emit electromagnetic radiation in the Röntgen-ray spectrum(58) but these are for obvious reasons beyond the scope of this thesis.

Wilhelm Conrad Röntgen

Wilhelm Conrad Röntgen observed in the late after noon on November 8 in1895 an unusual phenomenon while he was working in his laboratory at the University of Würzburg(4). He and his physicists' colleagues had for some time investigated effects of high tension electrical discharges in evacuated glass tubes and late in 1895 they started investigating the properties of cathode rays outside such tubes. While performing a test, Röntgen observed a shimmering light from a bench some distance away from the tube he was working with. The unexpected shimmering came from a platinocyanide screen placed on this bench and the next hours he repeated the experiment many times. In the following weeks he described nearly all properties of the new rays causing the phenomena. The ability of various materials to stop the rays was explored and while he placed a peace of lead between the tube and the platinocyanide screen, he suddenly saw a flickering image of his own skeleton on the screen. Röntgen published his first results on December 28; “Über eine neue Art von Strahlen“ including a radiograph of his wife Anna Berthas hand. Röntgen published a total of three papers on x-rays between 1895 and 1897 and he received the first Nobel Prize of physics in 1901 for this work(3). Röntgen named the rays x, after the mathematical term for an unknown. Later, the x-rays were named after him and both terms; x-rays and Röntgen rays are used today.

A short description of commonly used radiographic tubes



A rotating anode radiographic tube.

The production of Röntgen rays in medicine is made inside a radiographic tube (24). The tube consists of a cathode and an anode both enclosed by a vacuum glass container. Electrons are driven by high voltage from the negative charged cathode to the positive anode. Hitting the anode the electrons interacts with the atoms on the anode producing Röntgen photons. The cathode is composed of a small coil regularly made of tungsten situated in a focusing cup. Tungsten is selected due to the high melting point. A short pulse of high voltage electricity is directed to the coil and this flow of electricity produces electrons. The focusing cup narrows the electron beam as the electrons are driven towards the anode. When the electrons hit the anode only approximately 1% of the electron energy is transformed into Röntgen-rays and the remaining 99% produces heat. High temperature will damaged the anode and one mean to reduce this problem is to increase the area on witch the heat is distributed by rotating the anode during the exposure and thereby increasing the target area up to 300 times. The heat produced is than distributed to this elongated target area. Optimal heat distribution permits higher efficiency and extends the duration life of the tube. The target area on the anode disk is usually composed of tungsten selected for its high atomic number, high melting point and good heat-conducting ability. From this area, named actual focal spot the Röntgen rays are emitted. The actual focal spot has a relative large area. The Röntgen beam emitted from the tube is focused by a "line-focus principle" based on geometry of the electron beam and the anode surface. This area is regularly named "the effective focal spot" and has a rectangular shape e.g. 1.0 x 2.0 mm. Small effective focal spots may provide better details on radiographs but may limit the size of the beam field. The fact that Röntgen ray emission arises from an area and not from a single spot influences the projection of objects and may lead to loss of details on the radiographs. Emitting from the effective focal spot the Röntgen beam diverges and consequently the radiation intensity decreases inversely proportional to the square of the distance.

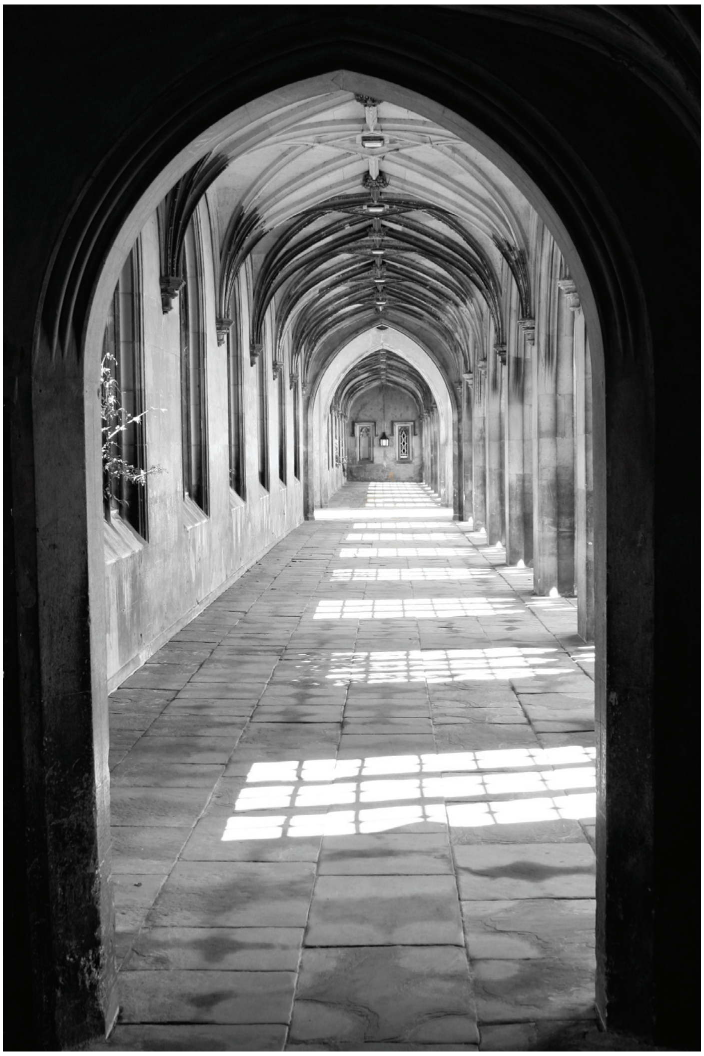
A short description of Röntgen ray interactions

When Röntgen rays pass through a matter the photons loose energy due to reactions between the photons and the atoms in the matter it self(24). The two most important mechanisms are the "photoelectric absorption" and the "Compton scattering". In the first, Röntgen photons interact with electrons and produce ionized atoms. Such atoms are unstable and may be biological harmful. Photoelectric interactions are more likely to occur with matters of high atomic number such as bones of the body.

Compton scattering is the result of interactions between Röntgen photons and electrons resulting in a shift in direction of the photon. Such directional shift may reduce the radiographic picture quality. This is called secondary Röntgen rays and is usually filtered so that only the primary Röntgen rays are making the radiographic picture.

Radiographic pictures are a result of differences in photon density emitted to a radiographic film or a film equivalent. High doses of Röntgen rays result in dark parts of the picture and visa versa. Pictures are therefore the result of differences in exposure between different areas of the film. E.g. bony parts will appear whiter than soft-tissue on radiographs.

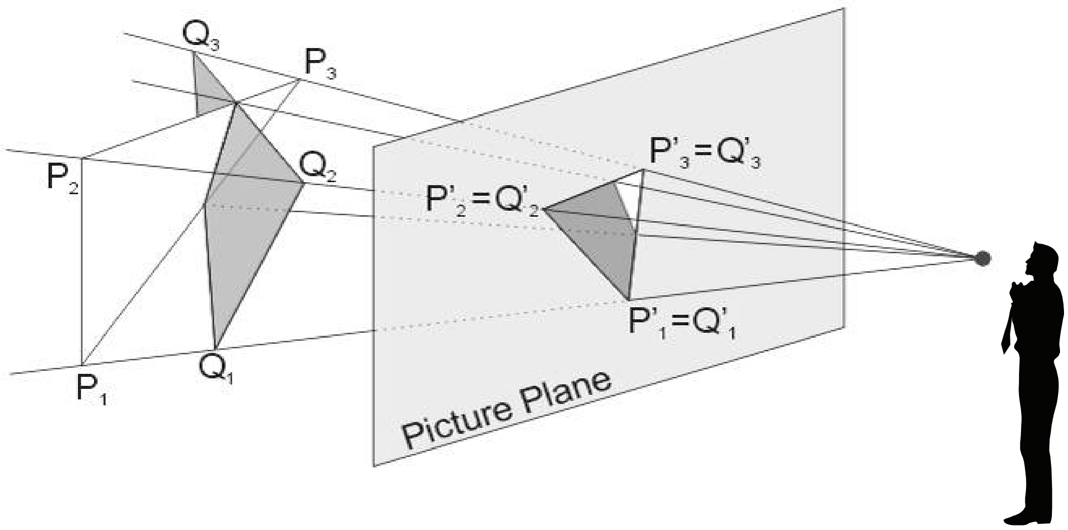
Picture formation



A "one-point perspective", a projection where all parallel lines converges into one single vanishing point.

Three-dimensional objects are transformed into two-dimensional pictures by conventional radiography as in ordinary photography(2,24). Such transformation occurs also when painting or drawing objects and artist have therefore dealt with this phenomenon for several thousand years(1). There are varieties in perspective used when describing the picture formation where most are beyond the scope of this thesis.

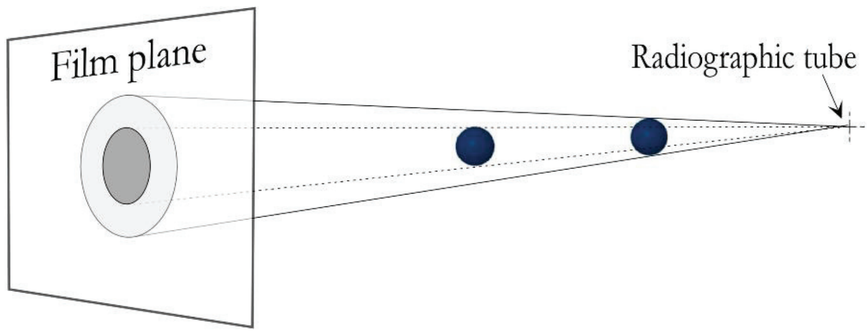
When looking through a window the windowpane itselves can be regarded as a canvas. If the scenery outside was painted exactly on the windowpane, this picture would be identical as the scenery itselves and thereby a transformation from a three-dimensional world into a two-dimensional picture with loss of the dimension of depth as a consequence.



A "one-point perspective" transformation of a three-dimensional object into a two-dimensional picture results in loss of information along one axis, loss of depth.

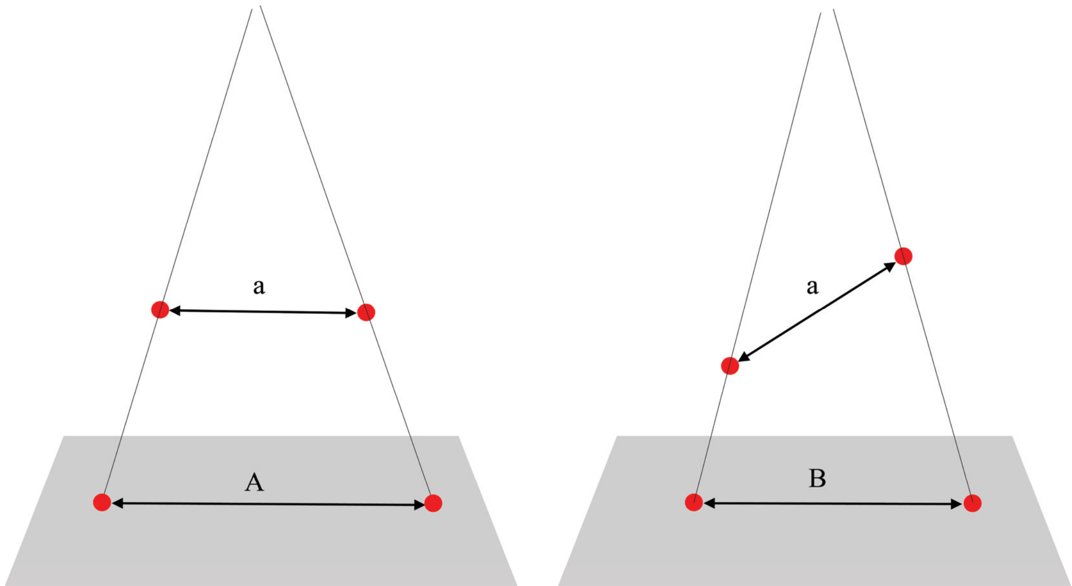
With use of a "one-point perspective" all parallel straight lines in the picture will converge into one single point as when a person observes railroad tracks vanish in the horizon. The more distant objects are, the smaller they appear in the picture. By that a sense of depth are created, a three-dimensional resembling made in a two-dimensional picture.

In a “reverse perspective” objects far from an observer are pictured larger than close objects. Parallel lines will converge to a vanishing point lying in front of the picture. A combination of ”one-point perspective” and “reverse one-point perspective” can be used to describe the three- to two-dimensional transformation that occurs when objects are radiographed. Röntgen rays may in principle be defined as emitted from a single point source. The radiographic film can be described as a canvas. All rays will converge to one single point with the canvas representing the observer’s eyes. Objects far from the canvas, closer to the photon source will create larger shadows on the canvas than objects closer to the canvas as seen in a “reverse one-point perspective”. Consequently magnification of the radiographed objects occurs on the radiographs. Larger distance between the object and the film (OFD), leads to higher magnification than short distances. Furthermore two radiographs obtained at 90 degrees angle are needed to view all three dimensions.



The sizes of the projections of two balls, both with same diameter are influenced by the OFD. Here, the FFD is maintained constant. Objects more distant from the film plane are projected with larger size then closer objects.

Distortion



Example of size distortion.

Image distortion is a misrepresentation of size or shape of an object being radiographed. It can be classified into two groups; size and shape distortion(24). Size distortions are caused by the effect of the object-film distance on the radiographic magnification. Different anatomical structures inside e.g. a human pelvis have different distances to the radiographic film. In a pelvic radiograph obtained in supine position anatomical structures such as the pubic symphysis are further away from the film than the sacroiliac joints and consequently projected with higher magnification. Shape distortions may depict an object with shortening or elongation. Shortening occurs when an object e.g. a human femur is aligned with its long axis oblique with the radiographic film when obtaining a radiograph. The central Röntgen beam represents those photons emitted from the exact centre of the focal spot in the Röntgen tube. All other beams have angulations related to the central beam. These angular differences depict elongations of objects or part of an object not directly placed under the central beam. The two- dimensional formation is consequently affected both by the orientation of the object in relation to the film and the focusing of central beam in relation to the object (73).

The human pelvis

The human pelvic can be described as a bony ring upon which the vertebrae rest and where the pelvis itself rests upon the lower limbs(10). The pelvic ring is a structure composed of four bones; the two hipbones, the sacrum with the coccyx attached. Each hip bone is a fusion of three separate bones; the ilium, the ischium and the pubic bone where the fusions take place in the triradiate cartilage in the acetabulum(71). The fusions are completed in adults. The pelvis is divided along the linea terminalis into the greater and the lesser pelvis. The greater pelvis has an incomplete bony ring while the ring completed of the lesser pelvis. The pelvic construction is a compromise between mechanical stability and the permission of different anatomical structures to pass through. The largest "structure" passing is a human foetus during child birth and this is the main reason of the gender based differences found in anthropometric pelvic dimensions. For males, the antroposterior diameter of the pelvic inlet usually exceeds the maximum transverse diameter(50). For females, however, the maximum transverse diameter usually is equal to or exceeds the antroposterior diameter. Gender specific pelvic differences are to some extent present in childhood but are mainly developed during the adolescent growth period (51). Also there are racial differences in pelvic geometry (38). People of African origin have larger antroposterior/ transverse ratios than Caucasians (72). There are also variations in pelvic geometry within the same gender. Three dimensional analysis shows asymmetry of the human pelvis(6,19). For both males and females, dimensions on the left side of the sacral bone were significantly greater(62).In the present study possible effects caused by pelvic asymmetry were to be minimized in the process of identifying useful parameters able to describe pelvic rotations. A symmetrical pelvic phantom was therefore constructed. Lead markers representing defined reference points were embedded into the phantom symmetrically related to the sagittal plane through the "symphysis", represented by a lead marker itselves.

The human pelvis is a complex three-dimensional structure which consequently affects the picture formation both by the spatial orientation as well the alignment related to the Röntgen central beam. Furthermore, the tube-film distance and object-film distance will influence the radiographic magnification.

As time goes by, an example of clinical use of sequential pelvic radiographs

Several aspects of orthopaedic surgery totally depend on radiography for diagnostic purposes, per-operative evaluations as well as post-operative controls (34,67). Sequential radiographs are commonly used to describe the progression of a condition such as osteoarthritis; a condition typically progressing during several years. Typically a patient suffers from hip pain(23). Clinical and radiographic examinations reveal some osteoarthritis of the hip joint, but initially the condition can be treated by analgesics and physical therapy. As the conditions evolve additional radiographs may be obtained until a total hip replacement is performed. Clinical follow up may continue for decades where possible loosening of the prosthesis is investigated. The wear rate of the acetabular components and possible osteolysis are examined as well. Consequently, several pelvic radiographs are obtained and comparisons between corresponding radiographic measurements are made. Both the spatial orientations of the pelvis and the Röntgen beam focusing affect the picture formation and thereby influence the radiographic measures made(8,13-15,36,41,42,56,63,66,70,74,75,78). Differences between corresponding measures made on the sequential radiographs may be caused by the imaging process itself rather than changes in clinical setting. Errors caused by the imaging process itself should therefore be described and accounted for when sequential radiographs are compared.

Methods to describe pelvic orientation

Several methods have been used to evaluate pelvic orientation based on standard supine pelvic AP radiographs. Some methods identify pelvic radiographs obtained with the pelvis in an unacceptable orientation and thereby permitting such radiographs to be excluded. The “Foramen Obturator Index” and the “Symphysis-os ischium angle” were defined to make such evaluations. Ranges of these indexes were defined by measuring a clinical material. Radiographs with measures outside the defined limits were thereby excluded when studying congenital hip dysplasia(76). Influence of rotation around two axes, the correlation between the indexes and amount of rotation and the effect of altered radiographic focusing were not evaluated. The effects of pelvic rotations upon radiographic parameters of acetabular dysplasia have been described. The association between the foramen obturatorium index and rotations were described but not quantified. The effect of various inclination upon the foramen obturatorium index and the symphysis/ os ischium angle were not investigated nor the effect of altered radiographic focusing.

The distance between the symphysis and the sacrococcygeal-joint has been used to evaluate pelvic inclination(70). With measurements from 86 standard antroposterior radiographs, the normal range of this distance was determined. Four cadaver pelvic specimens were radiographed with various inclinations. The association between the inclination and the selected distance was quantified. The effect of rotation around a vertical axis or altered radiographic focusing was not described.

In the process of investigating suitable radiographic measures we also (among other) investigated effects of pelvic rotations on the length of the line from the pelvic symphysis to the midpoint of the line between the caudal parts of the sacroiliac joints Also the relations between pelvic orientations and the angle between the “pubis-sacrum” line and the IS interconnecting line was investigated. Both the length of the “pubis-sacrum” and the angle between the two lines were rejected used since both were influenced by simultaneously pelvic rotations. Effects caused by pelvic rotations around one axis could therefore not be distinguished from effects caused by rotations around the other. This made us look for other methods to quantify pelvic rotations and we consequently ended up employing the two rotation ratios.

The "Pelvic-tilt index" was used in a study of radiographs of 16 dysplastic hips, all in patients between 3 and 8 years of age (41). A linear correlation between the index and pelvic inclination was found. The pelvic tilt index was not evaluated on patients older than 8 years and the effect of rotation around a vertical axis or altered radiographic focusing was not described.

A method to simulate the acetabular coverage of femoral heads was developed(46). The pelvic tilt could be estimated if the radiographic tube to film distance and the focus of the central beam on the radiograph were taken into account. No validation of the method was performed.

None of these previous methods have taken into account the possible influence of simultaneous rotation around two axes and altered radiographic focusing.

The "Ein Bildt Röntgen Analyse (EBRA)", is a computerized method to measure migration in hip sockets(49). Pelvic positions were defined by a system of parallel and rectangular tangents on defined pelvic structures. A comparability algorithm dividing sequential radiographs into groups with acceptable differences in pelvic positions and migration of the hip socket was than measured. The differences in spatial position were arranged into acceptable or not acceptable groups but not quantified.

Radiostereometry (RSA) can detect rotations around and translocations along three axes with high accuracy but requires insertion of small spherical tantalum markers into the bones as well as the implants, special radiographic examinations and computer software(69).

Pelvic rotations can also be measured precisely with use of three dimensional CT(59,60).

Summary of the background for the present study

We felt that the previously published methods assessing pelvic positioning by radiography had shortcomings. Some were inaccurate; some were complicated or required invasive deposition of small tantalum markers. Some employed advanced CT examinations. Consequently a new method able to quantify pelvic rotations between standard sequential radiographs obtained from the same pelvis was developed. The method should preferably be based on data from a large number of pelvic radiographs obtained from a selection of persons each with several radiographs obtained in different, defined pelvic orientation. With such data, the method should be able to describe effects caused by the natural variation in pelvic geometry(20,38,45,50,51,72). Practical and ethical considerations made such approach impossible. Consequently another method was employed to acquire the data needed. These data were acquired with the use of anthropometric pelvic dimension data used in computer simulation of virtual pelvic radiographs.

Computer simulation has been employed in studies related to various aspects of planar radiographic analysis. A model based RSA method used simulation to determine the position and orientation of prosthesis from its projection (40,77). The same technique has been employed with different algorithms in medicine as well as in the field of computer aided design (CAD). Our simulations of virtual radiographs were based on the same principle. Radiographic measurements were used since there are significantly differences between direct linear pelvic measures obtained from specimens and the corresponding radiographic measurements(68). Consequently, direct anthropometric pelvic three-dimensional measurements were transformed into virtual two-dimensional measurements by computer simulation.

Aims of the present study

The primary aim of the present study was to develop a new method that describes altered pelvic orientation when pairs of sequential standard pelvic AP radiographs are compared.

Standard supine pelvic AP radiographs were to be employed since these are commonly used and thereby available both in prospective and in retrospective perspectives.

The method had to be easy in use with no special tools needed.

The inter- and intra-observer accuracy should be high.

The accuracy of the method had to be high enough making useful clinical applications possible.

The ideal method should be able to detect rotations around two axes separately unaffected of simultaneous rotations around both axes.

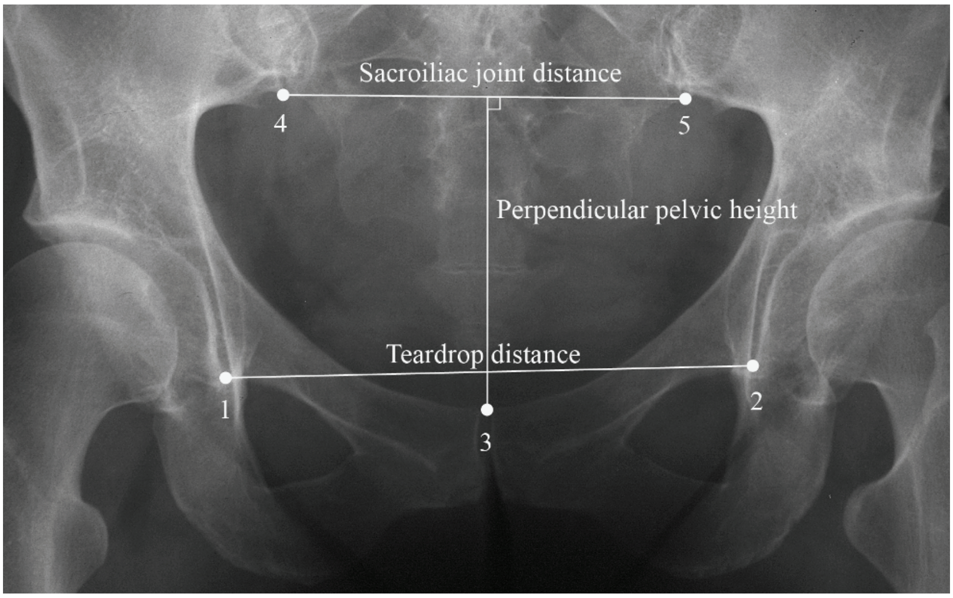
Ideally, the method should also be unaffected by altered conditions in the radiographic laboratory such as altered focusing, altered settings of the focus-film distance and object-film distance within and ranges used in clinical setting for these parameters.

Specific aims of the study:

1. To define robust parameters able to detect pelvic rotations separately around two axes, (paper 1).
2. To describe the correlation between pelvic rotations and the parameters, (paper 1).
3. To derive formulas stating the correlation between pelvic rotations and differences in the two parameters when two radiographs are compared (paper 1).
4. To describe the parameters ability to discriminate effects caused by rotations from effects caused by altered radiographic focusing, (paper 1).
5. To develop a computer program able to simulate radiographs of objects defined by a defined number of points, (paper 2).
6. To describe effects of different settings of the parameters in the virtual radiographic laboratory on the selected virtual radiographic measured, (paper 2).
7. To implement the former described rotation formulas into clinical use, (paper 3).
8. To investigate if implementing gender and pelvic-size adjustments would improve the accuracy in the clinically use the formulas, (paper 3).
9. To validate the accuracy of the use of the five radiographic reference points upon which the two parameters are based, (paper 4).
10. To quantify pelvic rotational difference found in a clinical material by comparisons of sequential radiographs, (paper 4).
11. To validate the overall accuracy of the method based on rotational differences found in the clinical material, (paper 4).

Summary of papers

Paper 1

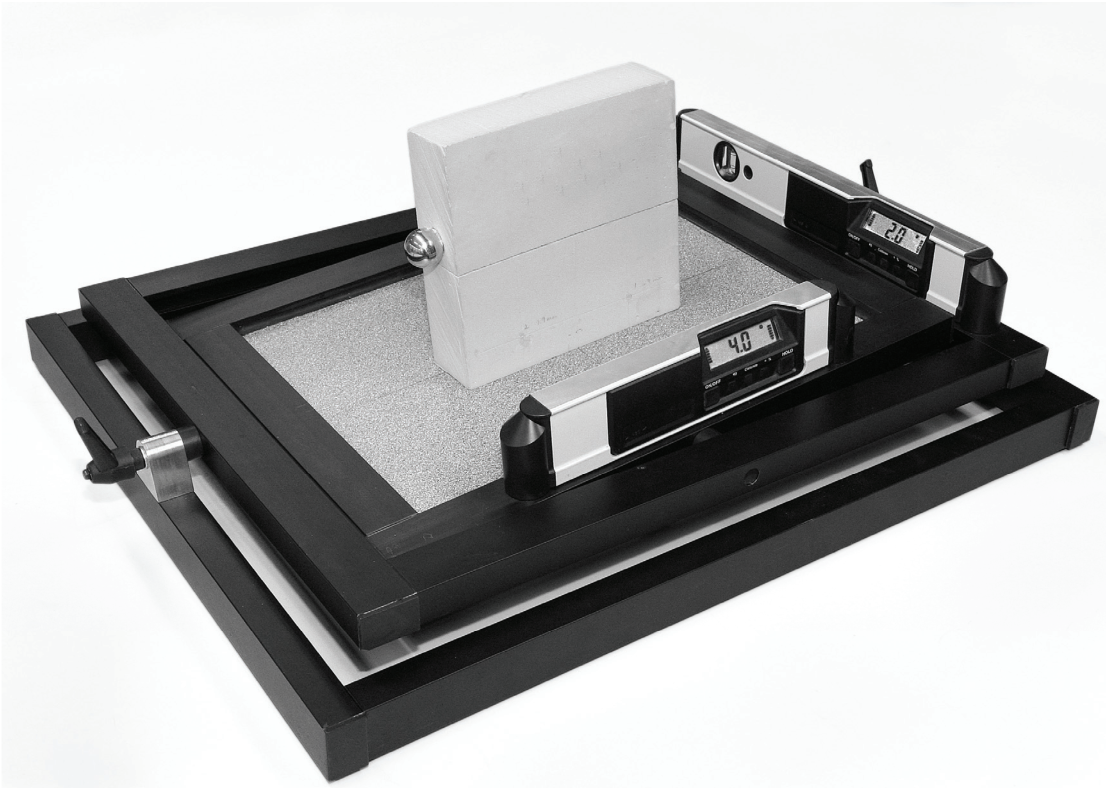


A standard pelvic AP radiograph with marking of the five reference points and the three interconnecting lines.

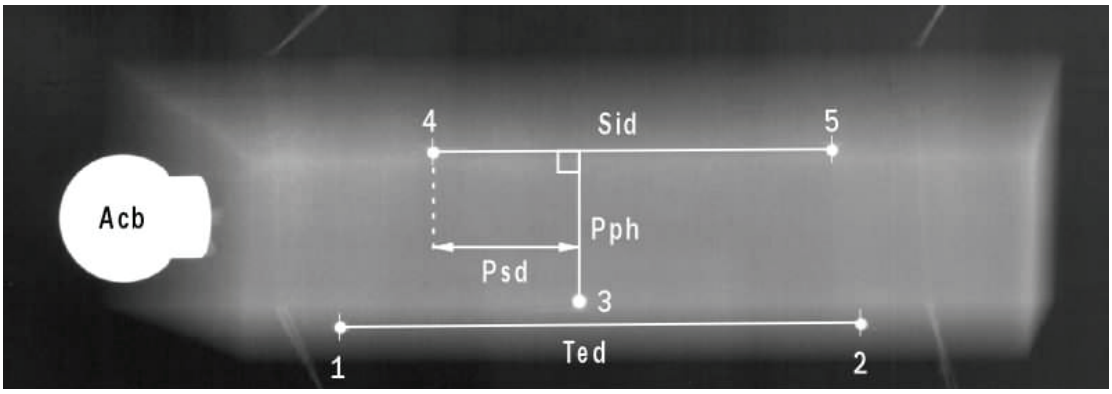
The aim of this study was to define and characterize parameters able to describe pelvic rotations. Two ratios, named the Transversal Rotation Ratio (TRR) and the Vertical Rotation Ratio (VRR) were defined based on radiographically projections of five defined anatomically pelvic reference points; (1-2) the middle of the caudal part of the pelvic teardrops, (3) the cranial midpoint of the pubic symphysis and (4-5) the middle of the caudal part of the sacroiliac joints, defined as the most caudal point on the curve of the sacral articular margin. Three interconnecting lines were then defined: (a) The teardrop distance as the length of the line between points 1 and 2. (b) The sacroiliac joint distance was defined as the length of the line between points 4 and 5 and (c) the perpendicular pelvic height as the perpendicular distance from point 3 to the line between points 4 and 5. The definitions of the two RR were based on these three lines: The TRR was defined as the ratio between the perpendicular pelvic height and the pelvic teardrop distance. The perpendicular pelvic height divides the sacroiliac joint distance into two parts. VRR was defined as the ratio between the right part and the total length of the sacroiliac joint distance. Effects caused by pelvic rotations and effects caused by translocations (movement relative to the central Röntgen beam) were analyzed using a pelvic phantom.

The phantom was based on three-dimensional measures from a pelvic model and represented an idealized human pelvis.

A tilt table was specially constructed with a top that could rotate around two orthogonal axes, and the phantom was mounted on the tilt table and then radiographed in an ordinary radiographic laboratory with 33 different defined orientations and with 16 different defined radiographic focusing.



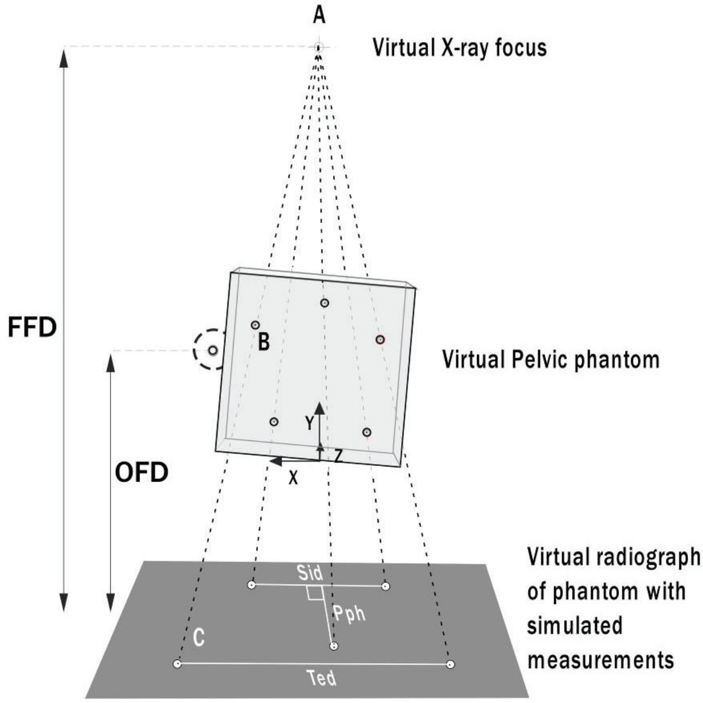
The pelvic phantom mounted on the special constructed tilt table.



A radiograph made of the pelvic phantom in which the five reference points were represented by lead markers. The interconnecting lines, used to define the two Rotation Ratios are illustrated. TRR = Pph / Ted VRR = Psd / Sid

A linear correlation between pelvic rotations around one axis and the corresponding Rotation Ratio were found with almost no influence of simultaneously rotation around the other axis. A linear correlation was also found between altered radiographic focusing along one axis and the non-corresponding Rotation Ratio. Formulas were derived stating the correlation between differences in the RR and phantom rotations. The study disclosed that effects caused by phantom rotations could not be distinguished from effects caused by altered radiographic focusing.

Paper 2

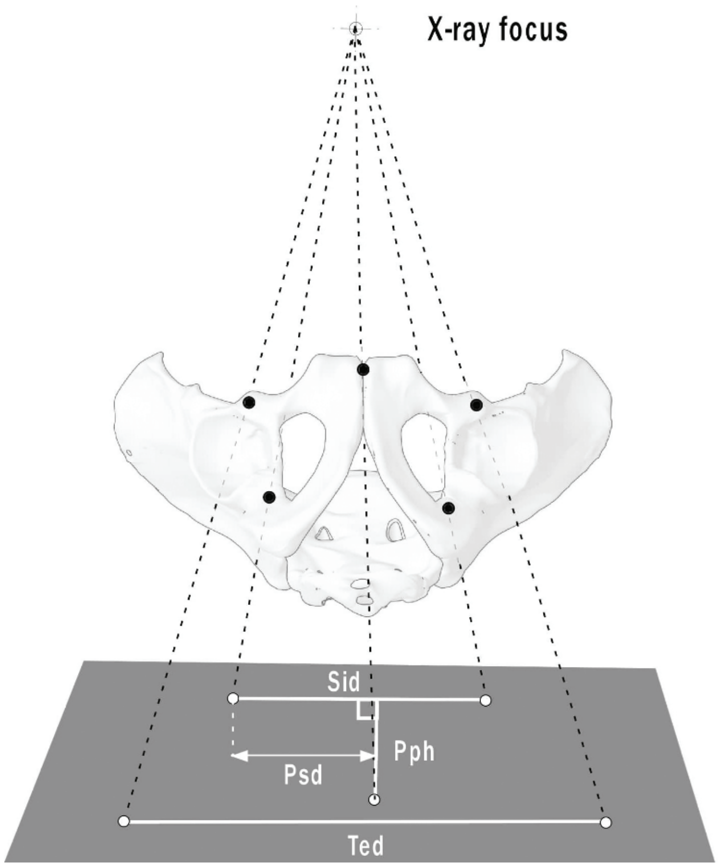


The virtual pelvic phantom placed in the virtual radiographic laboratory.

The aim of this study was to develop and verify a computer program design to simulate virtual radiographs of rigid three-dimensional bodies. The program computes the transformation from an arbitrary three-dimensional rigid point object into a two dimensional image. The object orientation, the radiographic beam centre, the FFD and the OFD could be defined independently in this “virtual radiographic laboratory”. This computer program was used for radiographic simulation of a virtual pelvic phantom representing a duplicate of the real phantom employed in paper 1. The virtual model was orientated and virtually radiographed according to the procedure followed in the pelvic phantom study. Virtual radiographic measures were compared with the corresponding real measures obtained in the phantom study. The computer simulation program was found to be accurate to both linear and angular virtual measurements.

In the second part of the study, computer simulation was used to quantify the influence of some principal parameters on the radiographic formation. The effects from; a) variations in the FFD and the OFD distances, b) variations in the radiographic focusing and c) variations in pelvic spatial orientations were described on four virtual radiographic measures.

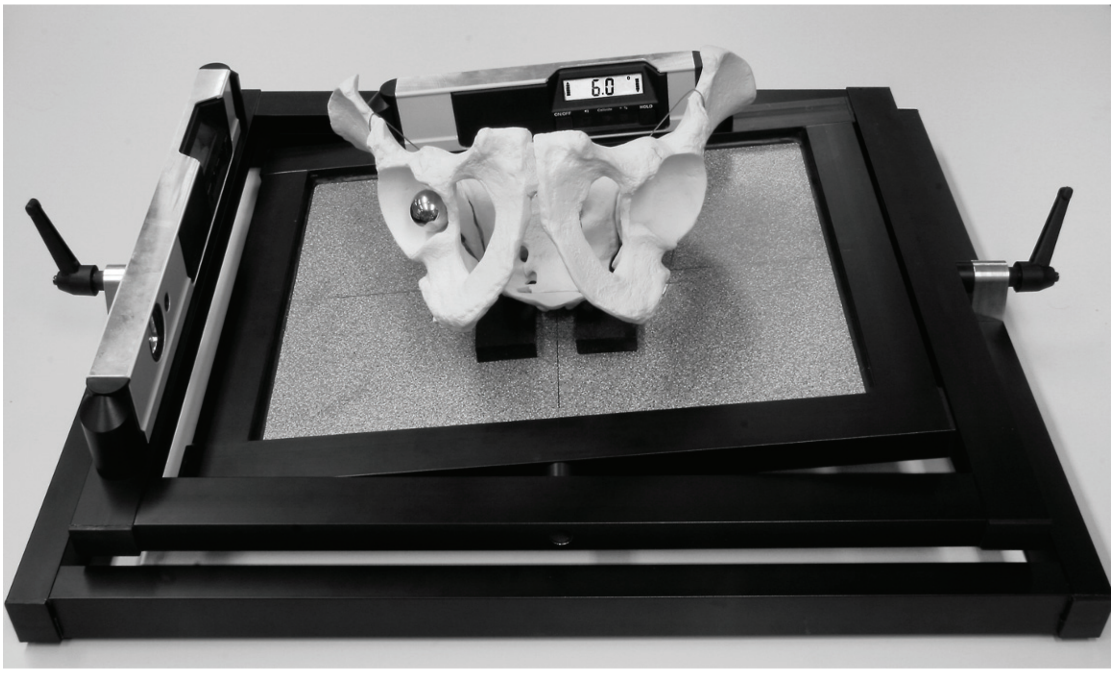
Paper 3



A virtual radiograph with radiographic distance of a pelvic represented by three-dimensional data of the five reference points. The three-dimensional data were obtained from a real pelvic specimen.

The aim of this study was to expand the basic qualities of the formulas developed in paper 1 into clinical use. Effects caused by the natural variation in pelvic geometry had to be implemented. The teardrop distances were measured in a clinical material consisting of 262 standard supine pelvic radiographs of 46 patients. The mean distance of females were found to be significant larger than males (120 mm vs. 112 mm). The computer simulation program (described in paper 2) was employed in simulation of virtual radiographic measures based on actual pelvic dimensions data obtained from the Hamann-Todd Osteological Collection. Virtual radiographic measurements from 4653 virtual radiographs of 141 carefully selected pelvic specimens were used to develop the clinically formulas. Adjustments based on gender and pelvic sizes (represented by the teardrop distance) were implemented in the formulas in order to increase the accuracy for the method.

Paper 4



A pelvis mounted on the specially constructed tilt table.

The Rotation Ratios Method can be described as an algorithm with both manual and mathematical steps to be made in order to calculate pelvic rotations. The aim of the study was to validate the accuracy of the different steps involved. Rotational differences in a clinical material (the same material presented in paper 3) were calculated with the RRM. The 97.5 percentile of rotational differences were 3.4 degrees to vertical rotations and 9.7 degrees to transversal rotations and the percentiles were defined as limits of rotational differences used in the validation. Five pelvises were sequentially mounted on the tilt table and radiographed in an ordinary radiographic laboratory, orientated and radiographed in the same manner as the pelvic phantom (described in paper 1) and as the simulations of virtual pelvic radiographs (described in paper 3).

A Picture in Picture (PiP) facility was implemented in the measurement program that enabled the user to view markings made on the first radiograph when marking the corresponding reference points on the second one. The effect of the PiP facility was evaluated by repeated measurements on radiographs from the clinical material with no significant improvements found. Effects of pelvic rotations on the projection of the reference points were investigated. In three of the five pelvises, lead markers were placed close to the anatomical structures responsible for the reference points on the radiographs. 99 radiographs of the three pelvises were analyzed twice, first with use of the reference points and second with use of the markers. The differences in the radiographic measures were compared. The reference points were found easy to identify and little influenced by pelvic rotations within the ranges of pelvic movement investigated.

The validations of the formulas were made by use of the radiographs obtained from the five pelvises. Real rotational differences between pairs of pelvic orientations were compared with the corresponding rotational differences calculated with the RRM. The mean differences between calculated and real pelvic rotations were 0.0 degree to vertical rotations with standard deviation of 0.5, 0.6, and 0.7 in the three series. For transversal rotations the mean differences were 0.1 degree with standard deviation of 0.7 in all the three series.

The inter observer and intra observer repeatability were investigated and found to be reasonably high.

General Discussion

Material and Methods

Paper 1

One pelvic model, one pelvic phantom, a specially constructed tilt table, and a computer program designed to perform measurement on digitized radiographs were used.

The investigation took place in idealized situation since basic qualities of defined parameters where to be described based on radiographic projections of pelvic anatomical structures. A pelvic model (Sawbones) was used to determine the three-dimensional positions of five reference points; the caudal part of the pelvic teardrops(21), the cranial midpoint of the pubic symphysis and the caudal part of the sacroiliac joints, defined as the most caudal point on the curve of the sacral articular margin. These points were selected due to their large three-dimensional spread inside the pelvis and the evident projections they make on standard pelvic AP radiographs. Based on the projection of the five reference points, the two rotation ratios TRR and VRR were defined. The definitions were based on two-dimensional radiographic measurements and not three-dimensional pelvic distances. Effects on TRR and VRR caused by rotations (changes in the orientation of the pelvic phantom) and effects caused by translocations (movement of the pelvic phantom relative to the central radiographic beam) were described and related to an orthogonal coordinate system with 3 axes (x, y, and z). The x-axis was defined as transversal, y axis as antroposterior (AP) and z axis as vertical.

Three dimensional analysis has demonstrated asymmetry of the human sacral bone(62). For both males and females, dimensions on the left side were significantly greater. Also a radiograph of the pelvic model disclosed asymmetry. Consequently a pelvic phantom was constructed using solid rigid polyurethane. Lead markers were embedded symmetrically representing the reference points where the positions were based on the three-dimensional coordinate date obtained from the corresponding points in the pelvic model. The use of phantoms has served a variety of purposes in radiographic imaging, such as describing normal and pathological anatomy(37,57,61,64), describing the position and migration of implants (25,27) and validation new measuring methods(28,54). In the present study, the phantom represented an idealized human pelvis which excluded factors related to pelvic asymmetry and inaccuracy of marking the reference point on radiographs.

The tilt table was specially constructed with a top that could rotate around two orthogonal axes, denominated vertical and transversal. Rotations were measured by digital inclinometers with ±0.3 degrees accuracy. The phantom was mounted on the table with its vertical and transversal axes corresponding to the rotating axes of the table. The pelvic start orientation was similar to pelvic orientation found in a supine position(9) defined relative to the plane of McKibbin(55) with 5 degrees reclination. The phantom was radiographed in an ordinary radiographic laboratory. The phantom was radiographed in incremental rotations of 2.0 degrees from -10.0 to +10.0 degrees around the vertical axis. Subsequently two additional series of radiographs were taken

in the same manner, one with -5.0 degrees and one with +5.0 degrees rotation around the transversal axis, all together 33 radiographs. Thereafter the phantom was realigned into the start orientation. New radiographs were taken with translocations of 10 mm along the vertical axis in the ranges from -50 mm to +50 mm from 0 mm to + 50 mm along the transversal axis, a total of 16 radiographs.
The radiographs were digitized and analysed using a constructed measurement program, programmed in Labview .The five reference points were marked manually on each radiograph (by OAF), and the TRR and VRR for each picture were automatically calculated.

The pelvic phantom was radiographed under clinical relevant condition. Still, the use of the pelvic phantom represented an unrealistic condition compared to clinical pelvic radiographs. The depicting of the reference points were unrealistic clear leaving the marking of these points presumable too reliable compared with clinically pelvic radiographs. The advantage of employing the phantom was the ability to minimize possible errors due to pelvic asymmetry and uncertainty of the radiographic markings of the reference points when describing the basic qualities of the two rotation ratios. The three-dimensional measures used to define each reference point in the phantom were based on measurements made on one single pelvic model. These facts were all limitations when implementing the results from the pelvic phantom study into clinical application. Only the basic qualities of the two rotation ratios were regarded valid in clinical settings and only valid inside the ranges of pelvic movements investigated. The Rotation Ratios Method is not able to distinguish the effects caused by rotations from translocations on pelvic radiographs. In clinical practise, altered pelvic position together with altered radiographic focusing might occur in radiographic sequences. However, we believe that standardized radiographic focusing is easier to achieve than standard pelvic positioning and therefore altered pelvic orientation is considered to be the most important factor. Radiographs to be compared should consequently have the same radiographic focusing.

In order to define useful parameters, we investigated several other radiographic measurements that were rejected. Changes in the distance of the line from the symphysis to the midpoint of the sacroiliac-joint interconnecting line and changes in the angle between these two lines were both sensitive markers for rotations but were influenced by simultaneous rotation around two axes. With use of the pelvic model and four pelvic specimens, changes in the projected areas of foramen obturatoria and the projected area of the pelvic inlet were examined. Changes in the projected areas were highly sensitive to rotations and translocations. However with use of this method we were not able to differentiate rotation along one axis from the other, translation along one axis from the other or rotations from translocations.

Paper 2

The first part of the study was a virtual copy of the pelvic phantom study presented in paper 1. The computer program was designed to simulate virtual radiographs of rigid point objects where the program can be regarded as a “virtual radiographic laboratory”.

With the virtual phantom orientated in a virtual radiographic laboratory the radiographic ray paths could be described mathematically. The spatial position of the radiographic focus, the focus-film distance (FFD) and the object-film distance (OFD) were in addition essential for the calculation of projection points in the film plane and for estimation of the radiographic magnification. A Röntgen ray from the focus of the radiographic ray tube, point A ($A_{x,}$ $A_{y,}$ A_z), intersecting an arbitrary point B ($B_{x,}$ $B_{y,}$ B_z), in the phantom, will hit the roentgen film plane at point C ($C_{x,}$ $C_{y,}$ C_z), where

$\overrightarrow{AC} = \frac{FFD}{FFD - BFD} \cdot \overrightarrow{AB}$, and BFD is the B-Film Distance along the y-axis

This calculation was performed on all phantom points for a given orientation to obtain a set of projected points representing the virtual radiograph.

The radiographic magnifications in the real phantom study were defined as the ratio of the radiographic measured size to the true size of the acetabular ball. Virtual radiographic magnifications were, as in the phantom study expressed as

$\frac{FFD}{FFD - OFD}$ (25) where *OFD* is specified as the distance from the film plane to a steel ball of 28.0 mm. This OFD changed as the phantom was rotated, which influenced the radiographic magnifications.

The simulation of phantom reorientation requires calculation of rotations about several axes in order to determine the new three-dimensional of each of the five virtual markers and the virtual acetabular ball in order to calculate their corresponding two-dimensional virtual film projections. The virtual pelvic phantom was defined as a rigid body as described earlier. Rotations of a right handed coordinate system with rigid object about the x, y and z axes are described with three matrices (33).

A reorientation of the phantom was described by a primary transversal rotation about the x axis followed by a secondary vertical rotation about the z-axis. This combined rotation was expressed with a rotation matrix R', where $R' = R'_z R'_x$

A point represented by original coordinates **p** (x, y, z) , was after a given rotation described with its new coordinates **p'** (x', y', z') according to the following relation:

p' = R'**p,** where

$$R' = \begin{bmatrix} \cos(\theta_z) & -\cos(\theta_x)\sin(\theta_z) & \sin(\theta_x)\sin(\theta_z) \\ \sin(\theta_z) & \cos(\theta_x)\cos(\theta_z) & -\sin(\theta_x)\cos(\theta_z) \\ 0 & \sin(\theta_x) & \cos(\theta_x) \end{bmatrix}$$

This matrix was used on all points constituting the pelvic phantom to calculate the new spatial point positions for each orientation, and for the following determination of the projected image points.

The effects from different radiographic focusing were determined by adjusting the coordinates of the object points relative to the radiographic focus and then use the virtual ray tracing technique to determine the image projection points. Movement of the phantom in one direction was equivalent to an opposite movement of beam centring. A point represented by original coordinates **p** (x, y, z) , was after a given translation T described with its new coordinates **p'**(x',y',z') according to the following relation:

$\mathbf{p'} = \mathbf{p} + T$;   where T is the translational matrix $\lfloor T_x \quad T_y \quad T_z \rfloor$

A virtual pelvic phantom was defined and "placed" inside the virtual laboratory. The virtual phantom was a virtual duplicate of the real phantom employed in the real pelvic phantom study. Virtual pelvic movements identical to those carried out in the real phantom study were simulated and virtual radiographs obtained corresponding to those obtained in paper 1, a total of 49 virtual radiographs. Radiographic measurements of the two sets of corresponding radiographs, the real and the virtual were compared with the real measurements defined as "gold standards". The differences between virtual and real measurement were used to validate the accuracy of computer simulation of pelvic radiographs.

Four sets of 49 corresponding virtual and real radiographic measurements were compared. These were; the teardrop distance (Ted), the sacroiliac joint distance (Sid) similar to the definition in paper 1. The pelvic height (Pht) was defined as the distance from the marker representing the pelvic symphysis to the midpoint of Sid. The pubosacrale angle (Psa) was defined as the angle between the Pht and Sid. The Psa was introduced in the present study to examine the ability to simulate angle measures and not distances only. The accuracy of the simulation technique was validated by comparisons between corresponding virtual and real radiographic measurers.

In the second part of the study the "virtual radiographic laboratory" was employed to describe situations outside the ranges used in the real pelvic phantom study. A selection of combinations was made where effects caused by variations in the FFD and OFD distances, radiographic focusing and spatial phantom orientations. The four radiographic measures obtained for the standardized radiographic condition with the phantom in a neutral orientation served as reference values. The respective measures obtained under different conditions were presented as percentage deviation from the reference values.

The “virtual radiographic laboratory” represents a simplification of a clinical laboratory. In the virtual laboratory all virtual Röntgen rays are emitted from a single point in contrast to emission from “the effective focal spot” found in radiographic tubes. Effects caused by the “Compton scattering” is not accounted for and the virtual Röntgen rays are absorbed totally or not at all when passing through the virtual pelvic phantom. The virtual radiographs consequently became unrealistic in terms of contrast and sharpness. The virtually projection of the reference points were defined mathematically with no need for manual markings. Possible errors due to the manual markings, necessary on real radiographs, were therefore eliminated. Also the assumption of a rigid body may to some extent be unrealistic. The clinical projections of the reference points are a composition of different anatomical elements. The use of projected reference points may be impaired by variation in pelvic orientations or radiographic focusing as in contrast to the virtual radiographing. The “virtual radiographic laboratory” is merely a research tool designed to simulate radiographs of rigid bodies e.g. parts of the skeleton where basic effects caused by object movements and radiographic focusing together with variations in FFD and OFD can be described. Despite the limitations listed, we found such a research tool most useful and important due to the ability of generating large amounts of radiographic data that otherwise were impossible to obtain due to ethical and methodical obstacles.

Paper 3

A clinical material of pelvic radiographs from 46 patients and anthropometric data recorded from 141 pelvises in an anatomical collection were used. The computer program designed to perform measurements on digital radiographs and the computer program designed to simulate radiographs of virtual rigid bodies were employed.

The pelvic teardrop distance was measured on radiographs obtained from the clinical material of 46 patients, 27 females and 19 males. For each patient, a minimum of three pelvic radiographs were analyzed, (mean 5.7, range 3 – 10) total 262. All patients had total hip replacement (THR) with non-cemented acetabular cups and known diameter of the prosthetic femoral head. The radiographs were digitized and then analysed using a constructed measurement program earlier described in paper 1. The teardrop distance was calculated for each gender.

The "virtual radiographic laboratory" described in paper 2 was used to simulate virtual pelvic radiographs including virtual radiographic measurements.

Anthropometric dimension data obtained from the Hamann-Todd Osteological Collection were used(35). This collection consists of more than 3.000 human skeletons of documented age, sex and race and a selection of 141 pelvises were employed in the present study. On each of the specimens, 123 surface landmarks hade been measured manually with ± 0.5 mm accuracy into an orthogonal three axial coordinate system using a stereotactic measurement device(65). A selection of these landmarks was used, representing the anatomical structures of which the radiographic projections are used in the RRM.

Pelvic rotations were related to a three-dimensional orthogonal coordinate system similar to the one described in paper 1 and employed in paper 1 and 2.

The pelvises were simulated rotated in incremental steps of 2.0 degrees from -10.0 to + 10.0 degrees around the vertical axis and virtually radiographed in each position. Subsequently 2 series of virtual radiographs were simulated in the same manner, one with -5.0 degrees and one with +5.0 degrees rotations around the transversal axis. 33 virtual radiographs of each of the 141 pelvises were made, a total of 4653.

The VRR and TRR were calculated on each of the virtual radiographs. The correlation between vertical rotations and the VRR together with the correlation between transversal rotations and the TRR were analyzed separately for each pelvis. Scatter plots with regression lines were used. The slope of the two regression lines (ßTRR and ßVRR) and the teardrop distance from all the pelvises were analyzed with use of simple linear regressions. Two analyses examined the correlation between the teardrop distance and the ßTRR while two other analyses examined the correlation between the teardrop distance and the ßVRR. The regression formulas were expressed as:

a) $\beta TRR = k_{transversal} * \text{teardrop distance} + C_{transversal}$

b) $\beta VRR = k_{vertical} * \text{teardrop distance} + C_{vertical}$

Two sets of the two formulas were calculated for each gender. The k`s represents the slopes and the C`s represents the intersections in the formulas. The values of the slopes and intersections were used to calibrate the Rotation Ratios Method for clinical use.

The necessary radiographic data were obtained by the application of pelvic anthropometric data and computer simulation. Data from 33 different defined pelvic orientations were obtained of each pelvis in a selection of 141 from a collection of more then 3000 human skeletons. The combination of anthropometric dimension data used in computer simulation solved a major puzzle in the development of the RRM. Without such approach we were unable to implement the basic method described in paper 1 into clinical use. The pelvic selection used was primarily chosen according to a North American population and this selection may not be representative for other populations. To our knowledge there are no skeletal collections in Europe with comparable size as the Hamann-Todd collection. An alternative approach to acquire pelvic dimension data could have been three-dimensional pelvic reconstructions based on pelvic CT examinations. Given a relative large number of such examinations, a selection representing a population could have been made and additional virtual examinations could have been performed. The racial differences between Caucasians and Afro-Americans were accounted in the present study since the pelvic collection used was a mixture of both. The Rotation Ratios method should consequently not been used in other ethnic groups. The RRM is based on data from simple linear regression analysis. The variations in pelvic geometry lead to somewhat broad 95% prediction intervals when calculating vertical pelvic rotations. Geometric variation are commonly found in human pelvises (7,12,22,38,44,50,51). Other methods, based on standard pelvic radiographs describing pelvic rotations or orientation are probably influenced by these variations as well(53). Gender based geometric differences were to some extent corrected by developing separate formulas to each gender. Multiple regression analyses, one related to vertical pelvic rotations and another to transversal rotations could have been presented. Such analyses were performed but no improvement in the prediction ability compared to simple regression analyses was found. Consequently four formulas were presented and hopefully such presentation made the method easier to grasp.

Paper 4

The Rotation Ratios Method, the computer program designed to perform measurements on digital radiographs, and the tilt table were employed. An experimental material of 165 radiographs obtained from five skeletal pelvises together with a clinical material consisting of 262 pelvic radiographs from 46 patients, were investigated.

The RRM requires manual markings of the five reference points as earlier described. The two Rotation Ratios were defined; the TRR and the VRR. Rotational differences between pairs of pelvic radiographs obtained from the same pelvis can be calculated based on the differences of the two ratios together with the teardrop distance of the pelvic investigated. A complex of anatomical structures forms the pelvic teardrop shadows and the caudal part of the sacroiliac joints(21,29). There are natural variations in the shape of the teardrops. The appearance is influenced by pelvic rotations and some rotations will make a shift in position of the teardrop relative to the ilioischial line(12). The radiological anatomy of the sacroiliac joint is complex due to the spatial configuration of the joints. The joint is composed of three portions oriented in different planes and are projected as two lines on AP radiographs with the anterior portion of the joint projected as the lateral one as the joints diverges inferiorly. Pelvic rotations might influence the projections of the tear drops and the sacroiliac joints, and consequently impair the accuracy the use of the reference points. The possible influence caused by pelvic rotation on the accuracy of the use of the points were investigated by a Picture in Picture facility (PiP), the use of radio opaque markers and by repeated measurement made by a single or two observers.

The PiP facility is used to improve surgical navigation(5,11). The PiP was employed in the present study to allow the investigator to see markings made on the first radiograph when the corresponding markings were made on the next. The effect of the PiP facility was evaluated by repeated measurements on radiographs from the clinical material.

In three of the five pelvises, lead markers were placed close to the anatomical structures responsible for the reference points on the radiographs. While altered pelvic orientation might lead to a masking or distortion in the projection of the reference points, the markers should be unaffected of such phenomena and thereby serve as the "gold standard". 99 radiographs of the three pelvises were analyzed twice, first with use of the reference points and second with use of the markers. The difference in the teardrop distance, the sacroiliac joint distance and the perpendicular pelvic height between the two sets of measurements was calculated.

One observer measured the radiographs from the five pelvises twice in order to evaluate the intraobserver repeatability. The calculated rotational differences from the first series were compared with the corresponding differences from the second. Two observers measured the radiographs to describe the interobserver repeatability. The limits of agreement of intra- and inter-observer measurements were calculated. The qualities of the reference points in respect to various pelvic orientations should be described sufficiently by these three procedures.

Rotational differences in a clinical material were calculated with use of the RRM. The material is the same as described in paper 3, containing 262 standard supine pelvic radiographs obtained from 46 patients. All patients had total hip replacement (THR) with non-cemented cups, leaving the teardrop shadows unaffected by the surgery in contrast to when cemented cups are implanted. The 97.5 percentiles of pelvic rotations found in the clinical material were used as references when validating the formulas in the RRM. For each patient, a minimum of three pelvic radiographs were analyzed, (mean 5.7, range 3 – 10) using the RRM. For each patient the first of the sequential radiograph was chosen as the base line and compared with each of the other radiographs. The base line radiographs were obtained some days after the surgery as a routine. Post-operative surgical pain might have contributed to more extreme pelvic orientations which may explain the findings of the pooled means different from zero. However, the use of post operative radiographs may be useful and therefore included in the method validation. The 97.5 percentiles were selected as reference values and thereby excluded the 2.5 % highest values of pelvic rotations.

Five pelvises, three male and two female were radiographed in an ordinary radiographic laboratory employing the same tilt table as in the pelvic phantom study (paper 1). The five pelvises were sequentially mounted on the tilt table with the vertical and transversal axis aligned to the corresponding axis of the table. The pelvises were rotated and radiographed as in the pelvic phantom study with 33 radiographs obtained from each pelvis, a total of 165. Pelvic rotations were calculated by the RRM. The formulas in the Rotational Ratios Method were then validated by pair wise comparisons between known (real, measured by the inclinometers mounted on the tilt table) and calculated pelvic rotations of the pelvises. 2640 comparisons could be made inside the ranges of pelvic movement initially included in the development of the RRM. The number of comparisons were reduced to those rotational differences expected to be relevant based on the results from the clinical material. Five pelvises were employed in this paper, four anatomical specimens and one pelvic model representing an “arbitrary Caucasian male”. A more thorough clinical validation of the RRM should ideally have been performed. Series of clinical pelvic radiographs, obtained with various defined pelvic orientations of a relative large number of persons should preferably have been made. Real pelvic rotations could then have been compared with the corresponding calculated rotations. Such approach is difficult due to ethical and practical considerations. Also, radiographs of the five pelvises were made without effects caused by soft tissue as in contrast to clinical pelvic radiographs. The reference points were consequently projected somewhat unrealistic clear on the radiographs in this experimental material.

Statistics

The statistical software SPSS 13.0 for Windows (SPSS Inc. Chicago, US) including Sample Power 2.0 was employed. The Spearman rank correlations (r_s) were used to measure the degree of statistical association between Rotation Ratios and rotations. The results were considered significant at $p < 0.05$. Scatter plots with regression lines were used to describe the correlations. Q-Q plots were used to verify normality of the test data. Two sided t-test was used to analyse the differences of the teardrop distances between the genders. The results were considered significant at $p < 0.05$. The agreements between different measuring methods and the limits of interobserver and intraobserver repeatability were described according to the procedure described by Bland and Altman (17,18). The correlations between the Rotation Ratios and teardrop distance were analyzed by Simple Linear Regression correlation analysis. Pearson correlations with interpretations were used measuring the linear association (26). Wilcoxon Signed Rank test was used to evaluate the effect of the Picture in Picture facility.

Results

Paper 1

Rotations

Transversal Rotation Ratios were plotted against 3 various transversal orientations of the phantom, each included 11 different vertical orientations. A significant linear correlation between TRR and transversal orientations was found with use of Spearman rank correlation ($r_s = 0.94$). Vertical Rotation Ratios were plotted against 11 various vertical orientations, each with 3 different transversal orientations. Significant linear correlation between VRR and vertical orientations was found ($r_s > 0.99$). Consequently, rotations around one axis can be measured almost without influence of rotations around the other.

The differences in the TRR (ΔTRR) and the VRR (ΔVRR) can be calculated when pairs of phantom radiographs are compared. Formulas describing the relations between phantom rotations and these differences were derived.

Consequently, transversal and vertical phantom rotations can be calculated separately when two radiographs are compared.

Translocations

Vertical and Transversal Rotation Ratios were plotted against translocation along the vertical axis. We found a significant linear correlation between vertical translocations and the Rotation Ratios. Vertical translocations had no influence on VRR but did influence the TRR; this based on the differences in the slope of the regression lines. The Vertical and Transversal Rotation Ratios were plotted against the translocation along the transversal axis. We found a significant linear correlation between transversal translocations and VRR and a non linear correlation between transversal translocations and TRR. Transversal translocations had no influence on TRR but did influence the VRR.

Consequently, translocation along one axis can be measured without influence of simultaneous translocation along the other axis.

It is not possible to separate translocations from rotations by use of the Rotation Ratios within the limits of the movements examined in this study. A 50 mm translation along the vertical axis will be interpreted as 2.8 degrees rotation around the transversal axis and a 50 mm translation along the transversal axis will be interpreted as 2.7 degrees rotation around the vertical axis related to the pelvic phantom examined.

Paper 2

The differences between the simulation of the pelvic teardrop distance, pubosacrale angle and the sacroiliac joint distance from the data the phantom study are presented.

	Phantom orientations		Radiographic focusing	
	Mean	**± SD**	**Mean**	**±SD**
Teardrop distance (mm)	-1.1	± 0.3	-1.2	± 0.7
Pubosacral angle (mm)	-0.3	± 0.3	0.8	± 0.4
Pelvic height (mm)	-0.4	± 0.4	-1.1	± 0.4
Sacroiliac joint distance (mm)	-0.7	± 0.4	-0.9	± 0.5

Differences between simulated and real radiographic quantities obtained from 33 different phantom orientations and 16 different levels of radiographic focusing

Effects caused by pelvic rotations and pelvic translocations could be simulated with high accuracy. It is important to note that the simulated virtual radiographs were produced in an unrealistically perfect radiographic environment where several factors related to measurement were not accounted for. Inaccuracy related to the orientation and alignment of the phantom relative to the defined coordinate system will affect the elevation of the acetabular ball when the phantom is rotated, and consequently influence on the projected ball size and thereby the radiographic magnification. All simulated linear measures were underestimated. We believe this is caused by an underestimation of the radiographic magnification in the radiographic study. The steel ball, used as reference was projected somewhat smaller in the pelvic phantom study than it should have been theoretically. A point representation for the virtual focal spots was used, whereas diagnostic radiographic tubes have focal spots of varying sizes (24), a factor that also would blur the projected ball edge. However, we found that the total differences were within an acceptable range and consequently concluded that any rigid object represented by a number of points with known spatial positions could be simulated with high accuracy, when the imaging conditions in the roentgen laboratory were known.

Result from the second part of the study is presented as the deviation from the values obtained under a standardized condition, presented in percentages.

	Radiographic settings		**Radiographic focusing**		**Phantom orientations**	
	OFD (70-150mm) FFD (900-1500mm)		Cranio-caudal (-100-100mm) Medio-lateral (-50 - 50mm)		Transversal (-14º-- 14º) Vertical (-10 º- 10 º)	
Deviation in:	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Teardrop distance (%)	-0.1	0.1	0.0	0.0	-4.4	1.3
Pubosacral angle (%)	0.0	0.0	-15.4	15.4	-83.9	83.9
Pelvic height (%)	-1.0	1.4	-33.0	17.7	-83.3	87.3
Sacroiliac joint distance (%)	-3.2	2.8	0.0	0.0	-3.7	1.6

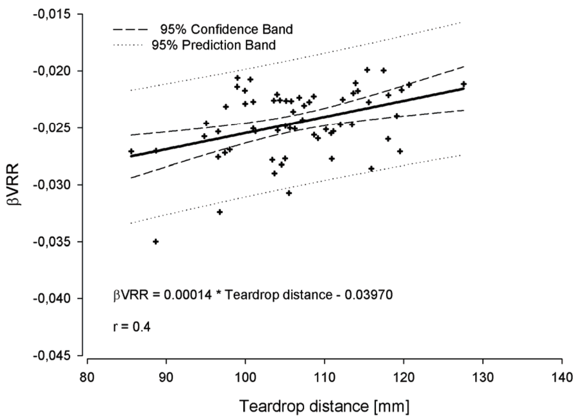
Min and max deviations from neutral values found by simulation of different radiographic settings, radiographic focusing and phantom orientations for a phantom with a left side positioned acetabular ball.

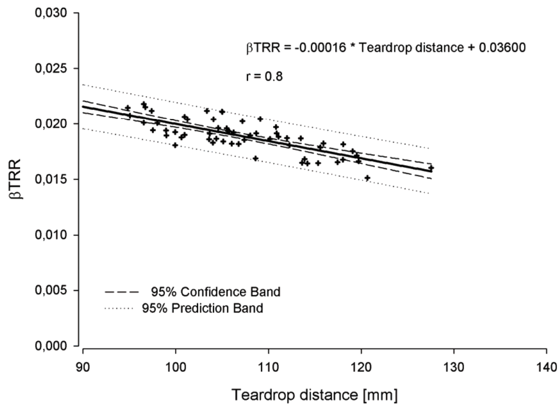
Focus-Film Distance (FFD) and beam centering are together with object rotations factors that are considered to have major influence on the appearance of the projected image(48). Our simulation showed that change in phantom orientation had considerable effects upon all four parameters. Radiographic focusing is normally performed according to standardized routines, but errors related to inaccuracy in focusing in the use of pelvic radiographs for hip related measures are examples that could influence the resulting image. The simulation showed that the variations in focusing did not influence the estimation of neither the teardrop distance nor the sacroiliac joint distance. The pubosacrale angle was mainly influenced by sideways movement of the central beam. The pelvic height was on the other hand mostly affected by the transverse movement, where a caudal transfer projected a greater part of the pelvic inlet resulting in a higher estimation of the pelvic height.

Simulation of different values of FFD and OFD reflected the variety of settings used in different hospitals due to different standards and routines(27), and also accounted for the natural variation in pelvic anatomy and soft tissue thickness that may affect the OFD during radiography(47). The measured parameters were, however, little influenced by these two factors, and maximum deviation was 3.2%. We believe the observed deviations were related to the previously described variations in radiographic magnification ratio within the phantom. The difference in height above the film plane between the magnification marker (steel ball) and each parameter was constant, but the relative difference in magnification ratio increased with lower values of FFD. It seems likely that this contributed to the observed variations.

Paper 3

The mean teardrop distance in females was 120 mm (range 104-133 mm) and in males 112 mm (range 100–124 mm) in the clinical material. The difference of 8 mm between the means of the two sexes was found to be statistically significant ($p < 0.01$). Separate regression analyses of each gender were consequently made when data from the 4653 virtual pelvic radiographs were analyzed. Four simple regression analyses were performed, separate for gender and rotational axes. A significant linear correlation between teardrop distances and the four simple linear regression lines ($p < 0.01$) were found. The Pearson correlations were 0, 4 describing the correlation between teardrop distance and the vertical rotation regression lines for both genders. This is to be interpreted as “fair”. The correlation between teardrop distance and the transversal rotation regression lines were 0, 8 for both genders. This is to be interpreted as “moderately strong. The variation of the teardrop distance only partly explains the observed variations in the transversal rotation regression lines (64 %) and the vertical rotation regression lines (16%). We believe this is caused by the natural variation in pelvic depth/transversal ratio found in the selected pelvises from the Hamann-Todd collection The predictability of the Rotation Ratios Method is better when applied to transversal rotations than to vertical rotations. A measured transverse rotation of 2 degrees is within the 2 ±0.2 degree interval and a vertical rotation of 2 degrees within the 2±0.7 interval. Transversal rotations are probably of more clinical importance than vertical, representing variations in pelvic inclination. The values of the constants in the regression equations were used in the formulas of the Rotation Ratios Method.





The regression analysis between teardrop distance and ßVRR and ßTRR respectively, for males. The 95% Confidence bands and Predictions bands are outlined.

Fig 6 A

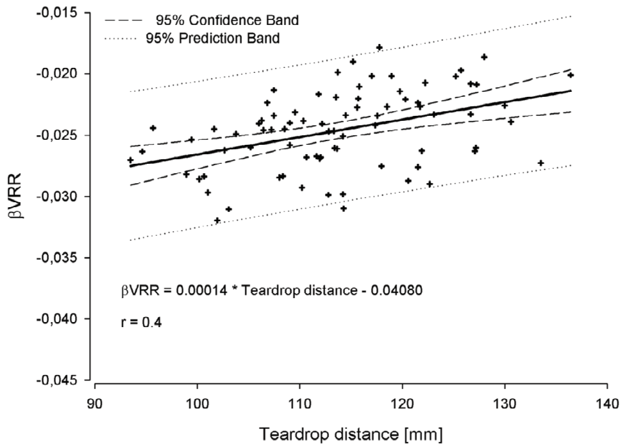
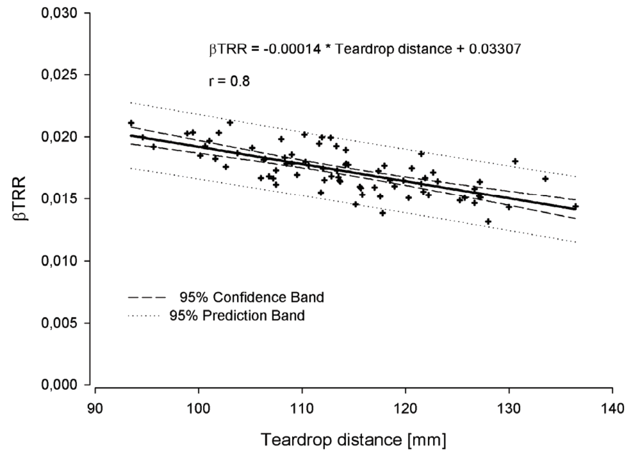


Fig 6 B



The regression analysis between teardrop distance and ßVRR and ßTRR respectively, for females. The 95% Confidence bands and Predictions bands are outlined

Paper 4

Only small improvements were found when the Picture in Picture function where employed, none of them found to be statistically significant.

The limits of agreement between the use of the reference points and the use of lead markers were small. The interobserver and intraobserver repeatability coefficients were equal for pelvic rotations around both axes and both were reasonably good. Consequently the selected reference points seem to be easy to identify and little influenced by pelvic rotations.

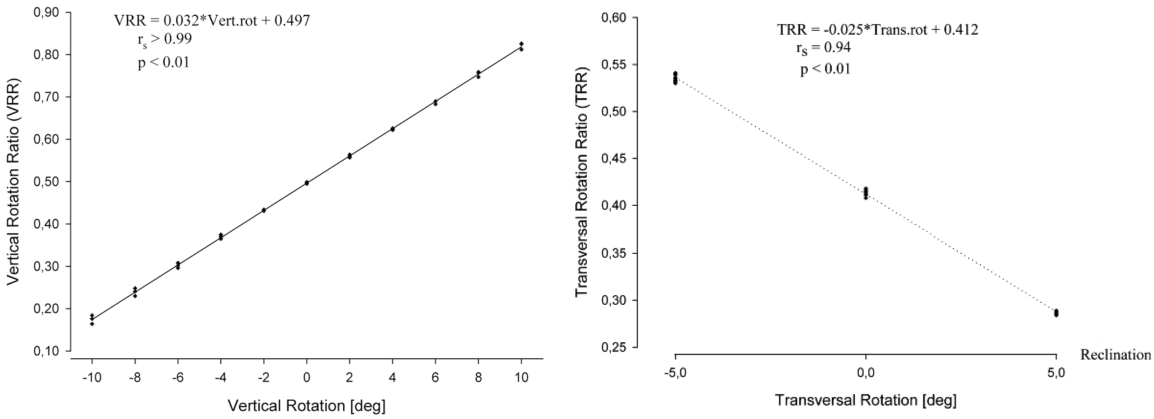
The pooled means of pelvic rotations in the clinical material were 0, 2 degrees to vertical rotations and 0, 3 for transversal rotations.

The 97.5 percentiles of rotational differences found in the clinical material were 3.4 degrees for vertical and 9.7 for transversal rotations. These values served as references when comparisons between real and calculated pelvic rotations in the experimental material were made.

The mean differences between calculated and real pelvic rotations were 0.0 deg (SD 0.6) for vertical rotations and 0.1 deg (SD 0.7) for transversal rotations of 165 radiographs obtained from the five pelvises in the experimental material.

Additional characterization of the two Rotation Ratios

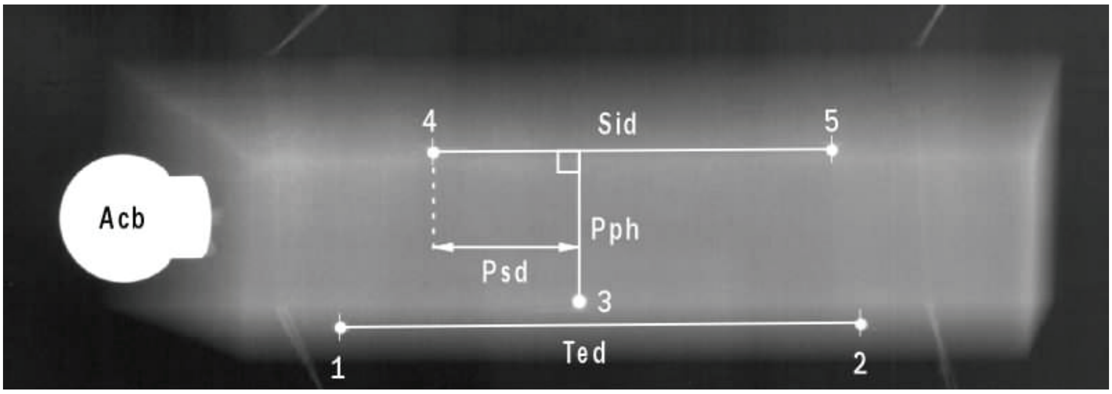
The two Rotation Ratios were defined and characterized with use of a pelvic phantom inside the ranges of phantom orientations of -10.0 to +10.0 degrees around the vertical axis and -5.0 to +5.0 degrees around the transversal axis, presented in paper 1. Two main characteristics where found. First, there were linear correlations between phantom rotations and the corresponding Rotation Ratio. Second, simultaneously rotations around both axes could be quantified separately.



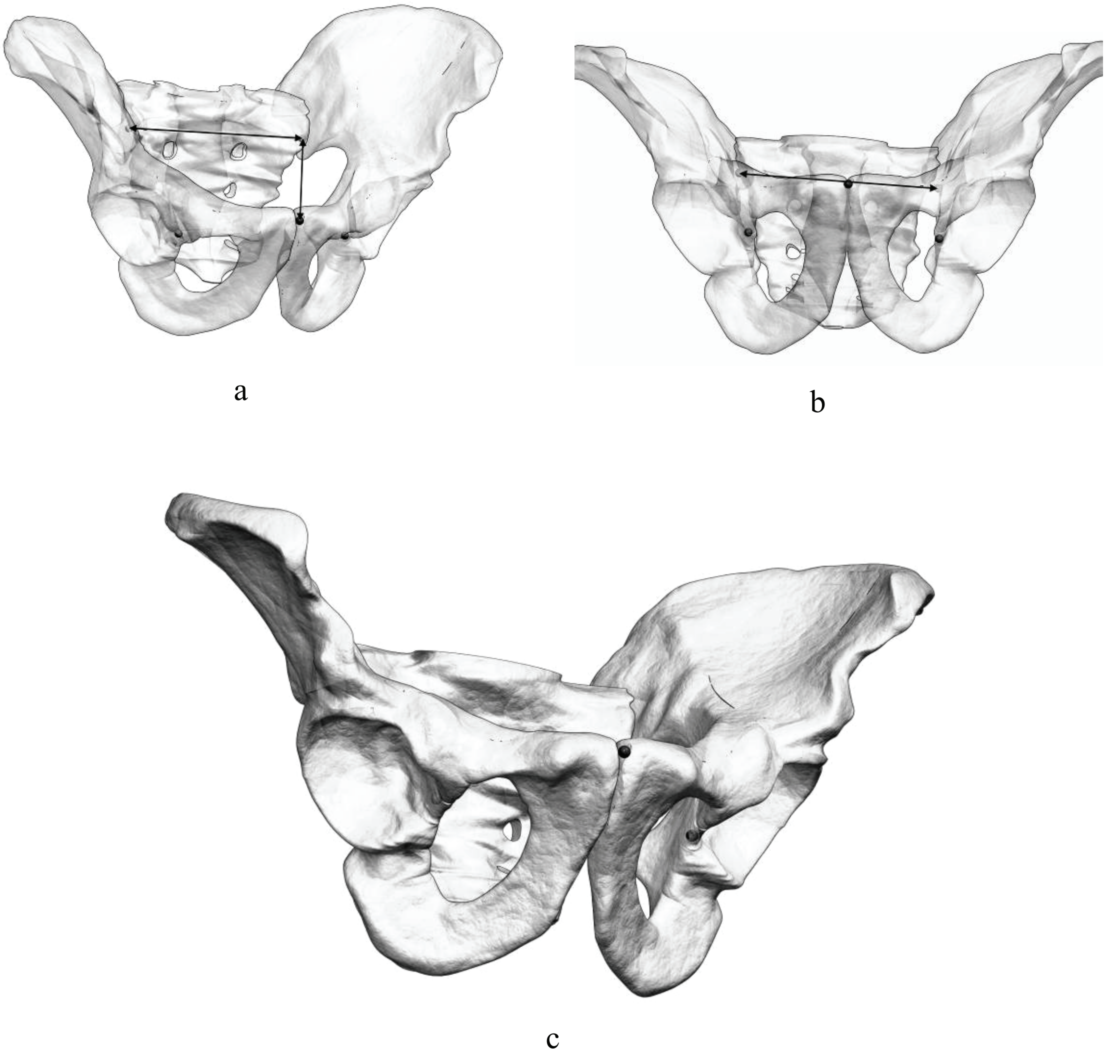
Graphs showing the relations between phantom orientations and the Rotation Ratios: (a) Plot with 3 different transversal orientations, each with 11 different vertical orientations. (b) Plot with 11 different vertical orientations, each with 3 different transversal orientations. The Spearman rank correlation ($r_{s)}$ is used. The phantom rotations were inside the -10.0 to + 10.0 interval of vertical orientations and inside the -5.0 to + 5.0 interval of transversal orientations.

The Vertical Rotation Ratio is defined as; Psd / Sid. The VRR reach it limits as when the perpendicular line from marker 3, representing the projection of the pubic symphysis, ends in marker 4 or 5, representing the caudal projection of the sacroiliac joints,. In these cases the VRR becomes 0 or 1.

The Transversal Rotation Ratio is defined as; Pph / Ted. The limit of TRR is when marker 3 is projected on the Sid. The Pph then becomes 0 and consequently the TRR becomes 0 as well. Transversal rotations in the other direction increases the Pph until unrealistic clinical pelvic orientations occur.



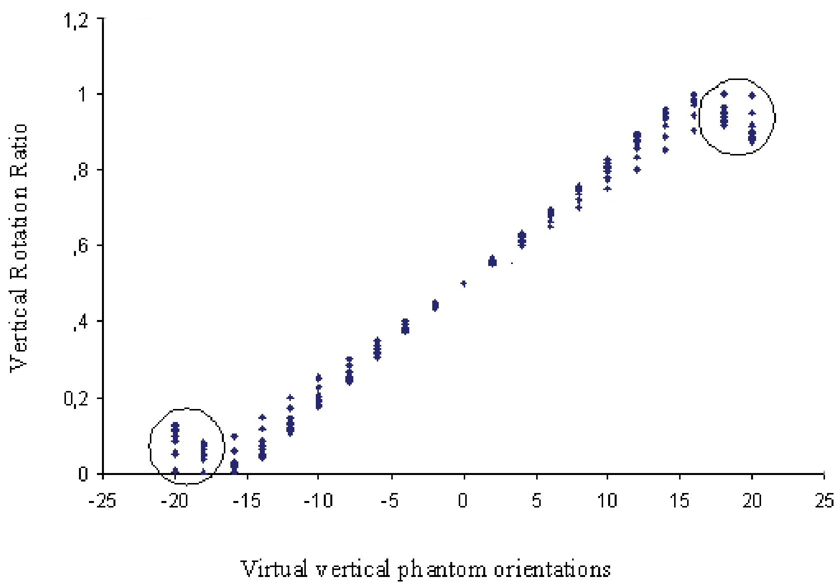
The Rotation Ratios were defined as:
Vertical Rotation Ratio; VRR = Psd / Sid.
Transversal Rotation Ratio; TRR = Pph / Ted.



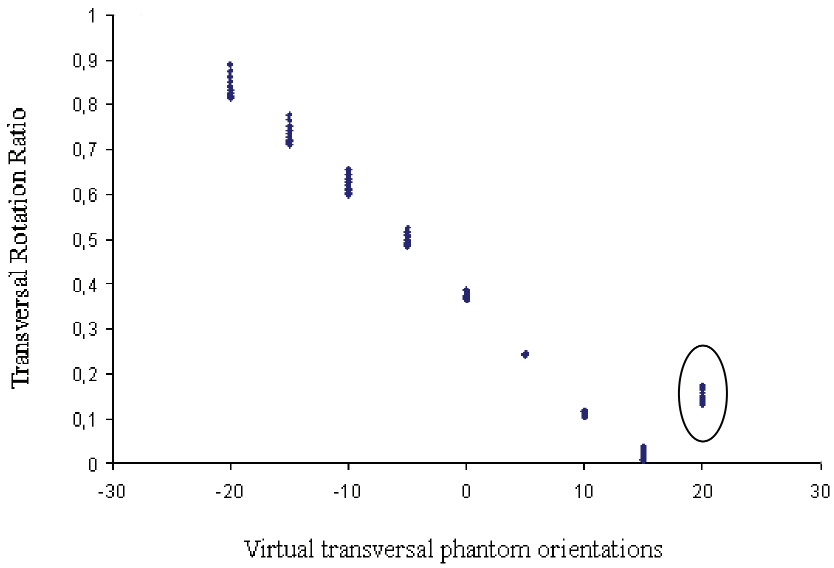
An illustration of three pelvic orientations; a) describes the orientation when the VRR reaches one of its limit, b) when TRR reach one of its limits and c) the combined orientation of a and b.

An additional study was performed to characterise the Rotations Ratios outside the earlier described ranges of phantom orientations. The virtual pelvic phantom and the computer simulation program presented in paper 2 were employed.

Virtual phantom radiographs were made inside the ranges of phantom orientations of -20.0 to +20.0 degrees around the vertical axis and -20.0 to + 20.0 degrees around the transversal axis. The results are presented in the two following figures.



The plot presents effects caused by virtual phantom orientations on the Vertical Rotation Ratio. Each cluster describes effects caused by simultaneously orientations inside the -20.0 to + 20.0 degrees interval around both axes. Phantom orientations outside the -18 to + 18 degrees interval of vertical orientations, makes the VRR invalid.



The plot presents effects caused by virtual phantom orientations on the Transversal Rotation Ratio. Each cluster describes effects caused by simultaneously orientations inside the -20.0 to + 20.0 degrees interval around both axes. Transversal phantom orientations larger than +15 degrees, makes the TRR invalid.

The Vertical Rotation Ratios are valid inside the -18 to + 18 degrees interval of vertical orientations. The Transversal Rotation Ratios are valid to pelvic orientations smaller than +15 degrees. The lower limit of the VRR seems to be determined by practical considerations when obtaining AP radiographs.

The five reference points, on which the two Rotation ratios are based, are projections of defined pelvic structures. These projected points are lost when pelvic orientations becomes to “extreme”. In paper 4, we described the loss of the teardrop shadows when vertical rotations became more then ± 4 degrees.

In conclusion, it seems reasonably to assume that the two Rotation Ratios will be applied well inside the ranges of their validity.

Future perspectives

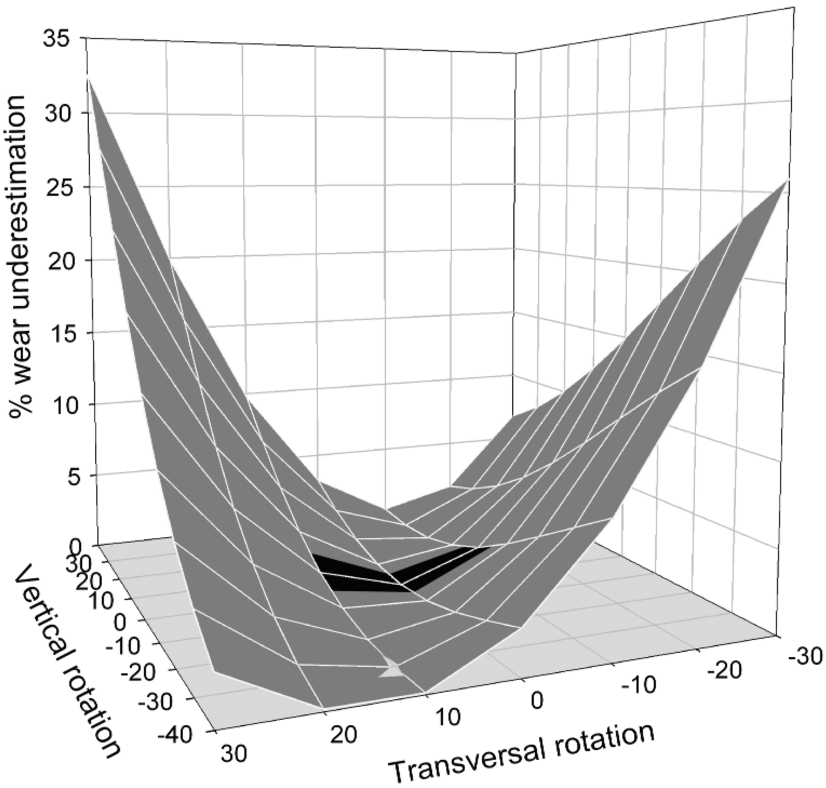
The Rotation Ratios Method has so far been used in one study:

"Polyethylene acetabular wear in hip prostheses;

Computer simulated quantification of error caused by changes in pelvic orientation and wear direction."

(Accepted for publishing in Acta Orthopaedica)

The effects caused by pelvic rotations and wear direction on wear measurements were quantified.



The gray shaded part of the graph describes the percentages of wear underestimation within larger ranges of pelvic rotations than those found clinically and thereby describes the theoretical effect of pelvic rotations on wear measurements. The darker part of the graph describes the levels of wear underestimation found within the ranges of clinical pelvic rotations described in paper 4. Variation in pelvic orientations induced a maximum of 2.6 percent wear underestimation with a mean of 0.4 percentages. Variation in wear direction induced a maximum of 42.0 percent underestimation with a mean of 8.5 percentages. A mean of 8.9 percentages of wear underestimation was found when varying both pelvic orientations and wear directions simultaneously.

Thereby, variations in pelvic orientations, one among several other sources of error in wear measurements, was described and quantified.

My detour in orthopaedic research then ended with a description of an almost neglectable source of error in polyethylene wear measurements in total hip replacements.

The Rotation Ratios Method could be employed in all patients treated with total hip replacement. The acetabular cup position should be optimal as when patients are in erect position. In this position, the main load is applied on the bearing surfaces of the prosthesis. Incorrect positioning of the acetabular cup is associated with dislocation, impingement and increased amount of polyethylene wear(16,31,32,43,52).For some patients the pelvic inclination may change moving between supine and erect posture

(30). Such possible change in pelvic inclination could be quantified pre-operative and corrected per-operatively when positioning the acetabular cup by comparing radiographs obtained in both postures. Such corrections could be made with use of standard operative techniques. However, with use of a per-operative computer aided guiding system such corrections may prove more useful since such technique facilitate a higher accuracy in cup positioning.

Practical instructions of the Rotation Ratios Method are presented as an appendix presented in paper 3.

Summary and conclusions:

1. Two rotation ratios based on five markings on standard pelvic AP radiographs were defined where each ratio describes pelvic rotations around the corresponding rotational axis unaffected of simultaneously rotations around the other.
2. Both rotation ratios were linearly correlated with the corresponding pelvic rotation inside the examined ranges of pelvic orientations.
3. Formulas able to describe rotations of a defined pelvic phantom when comparing pairs of radiographs were derived.
4. The rotation ratios were not able to discriminate effects caused by pelvic rotations from effects caused by altered pelvic focusing inside the ranges of pelvic movements investigated. Pelvic rotations around one axis are interpreted as pelvic translocations along the other.
5. A computer program representing a virtual radiographic laboratory was constructed and simulation of virtual radiographic measurements could be made with high accuracy.
6. Effects of different settings in the virtual laboratory on selected virtual radiographic measures were quantified.
7. Clinical formulas describing the relation between pelvic rotations and the rotational ratios were developed and made clinical application of the Rotation Ratios Method possible.
8. Correction related to gender and pelvic size represented by the teardrop distance was examined and both variables were implemented into the method since both increased the method accuracy.
9. Markings of the five reference points were little influenced by pelvic variations in pelvic orientations. They were easy to identify on radiographs and proved useful in defining the two rotation ratios.

10. Pelvic rotational differences were described in a clinical material and pelvic rotations inside the 97.5 percentiles of pelvic rotations were used when validating the Rotation Ratios Method.
11. The Rotation Ratios Method is an algorithm with both manual and mathematical steps to be made. The accuracy of each different step as well as the overall accuracy of the method allows the Rotation Ratios Method to be used clinically.

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