Joints

Evaluation of RSA set-up from a clinical biplane fluoroscopy system for 3D joint kinematic analysis

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Abstract

Purpose: dinamic roentgen stereophotogrammetric analysis (RSA), a technique currently based only on customized radiographic equipment, has been shown to be a very accurate method for detecting three-dimensional (3D) joint motion. The aim of the present work was to evaluate the applicability of an innovative RSA set-up for *in vivo* knee kinematic analysis, using a biplane fluoroscopic image system. To this end, the Authors describe the set-up as well as a possible protocol for clinical knee joint evaluation. The accuracy of the kinematic measurements is assessed.
Methods: the Authors evaluated the accuracy of 3D kinematic analysis of the knee in a new RSA set-up, based on a commercial biplane fluoroscopy system integrated into the clinical environment. The study was organized in three main phases: an *in vitro* test under static conditions, an *in vitro* test under dynamic conditions reproducing a flexion-extension range of motion (ROM), and an *in vivo* analysis of the flexion-extension ROM. For each test, the following were calculated, as an indication of the tracking accuracy: mean, minimum, maximum values and standard deviation of the error of rigid body fitting.
Results: in terms of rigid body fitting, *in vivo* test errors were found to be 0.10±0.05 mm. Phantom tests in static and kinematic conditions showed precision levels, for translations and rotations, of below 0.1 mm/0.2° and below 0.5 mm/0.3° respectively for all directions.
Conclusions: the results of this study suggest that kinematic RSA can be successfully performed using a standard clinical biplane fluoroscopy system for the acquisition of slow movements of the lower limb.
Clinical relevance: a kinematic RSA set-up using a clinical biplane fluoroscopy system is potentially applicable and provides a useful method for obtaining better characterization of joint biomechanics.

Keywords: biplane fluoroscopy, radiostereometry, kinematics, knee, roentgen stereophotogrammetry, RSA.

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Introduction

Quantitative assessment of three-dimensional (3D) *in vivo* skeletal kinematics is crucial to determine joint function. A precise and reliable method able to measure joint kinematics might provide clinically relevant information about the functional behavior of the joint from injury to rehabilitation.
Traditional, non-invasive motion analysis methods use either optoelectronic or video-based systems to track markers attached to the skin, but skin motion artifacts can introduce large errors, making these methods unsuitable for many applications.
In recent decades, non-invasive quantitative evaluation of knee joint kinematics has been performed using motion capture, single-plane or biplane fluoroscopy or radiography (1-13). Some Authors have also assessed bone motion during functional activities, such as weight-bearing flexion, single-legged hop and jump-cut maneuvers (1, 5, 6, 14).
The most popular technique is fluoroscopy, used to track 3D computer models of the tibia and femur bones (e.g. derived from CT examinations) or the tibial and femoral components of a total knee prosthesis (from CAD files), which are matched to the two-dimensional features of the acquired fluoroscopic images (15-17). The main problem is the occurrence of errors in out-of-plane translations and rotations, which

affects the applicability of the method for measuring the 3D components of a movement (18-20).
First, Li et al. (4) performed *in vivo* studies of joint kinematics matching MRI-based bone models or prosthetic CAD models to biplane fluoroscopic images, using series of static fluoroscopic acquisitions. Next, this technique was further developed to measure dynamic knee joint motion (21, 22).
Stereoradiographic imaging, which uses markers implanted in bones, and the dynamic version, known as dynamic roentgen stereophotogrammetric analysis (RSA), can provide extremely accurate quantitative 3D motion assessment.
The purpose of the present work was therefore to evaluate the applicability of a new dynamic RSA set-up for *in vivo* analysis of knee kinematics, using a standard clinical biplane fluoroscopic image system. To this end, the Authors describe the set-up as well as the proposed protocol for clinical knee joint assessment and evaluate the accuracy of the kinematic measurements.

Methods

Set-up
The fluoroscopy system (Biplane Advantx LC LPN+; GE Healthcare, Little Chalfont, UK), consisting of two coupled C-arms equipped with 32-cm diameter image intensifiers able to rotate around a common center, was used for the acquisitions.
We defined two different C-arm configurations: one suitable for capturing knee motion in a supine position and the other suitable for examination of weight-bearing movements (**Fig. 1**).
The configuration of X-ray devices in standard anterior-posterior and lateral orthogonal projections allowed adequate visualization of the implanted markers during passive laxity testing, pivoting motion and active flexion-extension movements.
The focal spot dimension was set at 0.6 mm. The source-detector distance was 110 cm, and the source-object distance was 70 cm.
The radiological parameters were set automatically by the exposure system.
All the movements were performed as slowly as possible, in order to reduce blur motion artifacts on the acquired images (23).
The RSA technique requires a calibration step for the 3D reconstruction of the X-ray foci as well as the image plane positions with respect to a laboratory coordinate system. This calibration was performed by

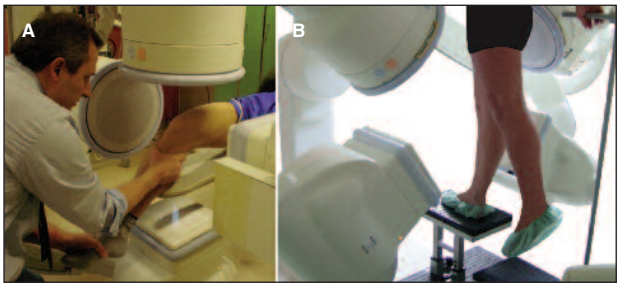

Fig. 1. Configurations of the biplane fluoroscopic system for: supine examinations (A) and weight-bearing examinations (B).

acquiring biplanar images of a specially created calibration phantom in the same X-ray device position used for the motion tests, as well as images of a calibration grid for the distortion calibration. The calibration phantom consists of a 200-mm acrylic cube containing metallic microspheres (0.8 mm in diameter) at known locations (16 fiducial and 16 control markers for each view). The distortion calibration grid consists of a Perspex plate with a chequered 7-mm pattern of embedded 2-mm diameter steel balls.
The acquired images were processed using Model-Based RSA 3.0 (MBRSA, Medis Specials b.v., Leiden, The Netherlands) and MATLAB (MathWorks Inc., Natik, MA, USA) software.
Both the biplanar calibration phantom and the distortion calibration grid were custom made, using a CNC milling machine to position the microspheres and steel balls.
Joint motion was assessed by tracking the markers fixed in the articular bones.

Protocol
The analysis performed can be subdivided in three main phases:
- *in vitro* test in the biplanar set-up under static conditions (static X-ray) to validate the calibration process without experimental noise due to motion artifacts and to assess the intrinsic performances of the set-up. In this experiment 20 static pairs of images were obtained by the biplanar fluoroscopic set-up by randomly positioning a marked (0.8 mm tantalium beads) lower limb phantom (Sawbones, Pacific Research Laboratories Inc., Vashon, USA) within the field of view.
- *in vitro* tests under dynamic conditions (fluoroscopy), to assess the best performances of the set-up during motion, without loss of contrast due to tissue artifacts. In particular the phantom was moved through the knee flexion-extension range of motion (ROM). A 56-frame biplane fluoroscopy sequence was recorded.
- *in vivo* analysis (fluoroscopy), performed in order to

test the system performance in clinical conditions. In this phase, 3 patients in supine positions were examined analyzing the full flexion-extension ROM. Two of them had previously undergone anterior cruciate ligament reconstruction surgery, and 1 total knee replacement surgery.

In each patient, four or more markers were implanted, during surgery, in both the distal femoral and proximal tibial epiphysis using an appropriate needle equipped with a piston (**Fig. 2**). The biplane fluoroscopic sequences contained 40-51 frames.

Patients gave their informed consent to participate in the study, which had previously been approved by the institution's ethics committee.

The data processing protocol comprises the following steps: 1) distortion correction for sequence images; 2) calibration of the biplane system configuration relative to a global reference 3D coordinate system; 3) acquisition of 3D coordinates of bone markers; 4) extraction of kinematic data. Custom software in MATLAB was developed for distortion correction, adopting a global bipolynomial technique (24): optimized bipolynomial transformation was computed from the acquired distorted images of the calibration grid captured at each examination session at the chosen C-arm configuration. This transformation served to correct each image in the recorded sequences of the corresponding configuration. The MBRSA software was used for the 3D system calibration (from calibration cube images) and for the acquisition of 3D coordinates of bone markers for each sequence frame. MATLAB was then used for kinematic analysis of knee motion. The joint coordinate system used for kinematic analysis is the one described by Grood and Suntay (25) and recommended by the International Society of Biomechanics.

For each test the following were calculated, as an indication of the tracking accuracy: the mean, minimum, maximum values and standard deviation (SD) of the error of rigid body fitting (e_{RB}) as defined by Selvik (26). In particular, differences in marker positions at test *versus* a reference time were considered. Moreover, only for the *in vitro* test, the translational and rotational zero motion accuracy were measured in all phantom tests. To this end, the eight markers within the bone model were divided into two groups of four markers, thus defining two rigid bodies. The mean value and SD of the translational (Tx, Ty, Tz) and rotational (Rx, Ry, Rz) components of relative motion between these two rigid bodies inside the phantom were calculated. In particular, y was considered an in-plane direction

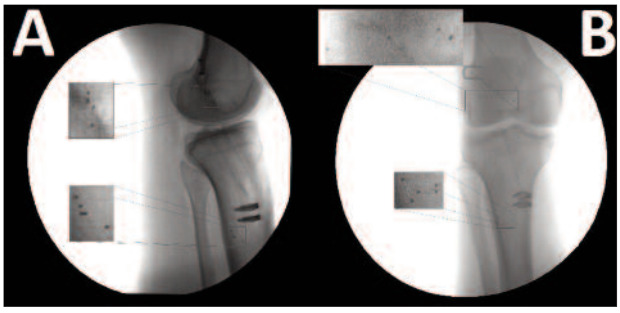

Fig. 2. Lateral (A) and frontal image (B) from a biplane fluoroscopic sequence of an ACL reconstructed knee, tested with a dynamic RSA study in a supine set-up. Tantalum markers are inserted in both the tibia and the femur. Markers in the bones are enlarged (270%).

for both views and the anterior-posterior projection was contained in the z-plane. Given that the two rigid bodies were inside the same phantom, zero motion was to be expected.

Results

In the biplane fluoroscopy set-up in static conditions, the e_{RB} showed the same variance (SD=0.02 mm) as shown by the standard RSA method. Moreover, the dynamic phantom tests (**Tab. 1**) and the *in vivo* analysis (**Tab. 2**) showed similar e_{RB} values: 0.12±0.06 mm and 0.10±0.05 mm, respectively.

The results of the relative zero motion phantom test, for both the static and the kinematic phantom, are reported in **Table 3.**

One tibial marker model was excluded from the study as not enough markers were visible during motion.

Discussion

The most important finding of the present work is that the suggested set-up allows satisfactory acquisition and quantification of slow movements of the lower limb.

The similarity between the SD found in the first phase (static, X-ray) and in the second phase (static, fluoroscopy) of the study suggests that it is possible to extract a reliable marker configuration from a static fluoroscopic RSA scene. The finding of similar e_{RB} results in *in vitro* and *in vivo* testing shows that *in vivo* data can be expected to show the same rotational and translational accuracy as is found for phantom tests.

It can be assumed that worse SD values during the dynamic analysis were due to poor synchronization

Table 1. Results of errors of rigid body fitting (e_{RB}) for phantom tests (n=number of pairs of images/frames analyzed).

	N	mean e_{RB} (mm)	SD e_{RB} (mm)	min e_{RB} (mm)	max e_{RB} (mm)
In vitro static X-ray	20	0.04	0.02	0.01	0.07
In vitro fluoroscopy	20	0.06	0.02	0.02	0.10
In vivo fluoroscopy	56	0.12	0.06	0.03	0.33

Table 2. Results of errors of rigid body fitting (e_{RB}) for *in vivo* tests (n=number of pairs of frames analyzed).

Bone markers model	*N*	Mean e_{RB} (mm)	SD e_{RB} (mm)	min e_{RB} (mm)	max e_{RB} (mm)
Patient 1 (tibia)	40	0.06	0.02	0.02	0.12
Patient 1 (femur)	40	0.12	0.05	0.03	0.23
Patient 2 (tibia)	51	0.06	0.01	0.04	0.10
Patient 2 (femur)	49	0.14	0.02	0.10	0.19
Patient 3 (tibia)	24	0.15	0.07	0.06	0.35
Total	204	**0.10**	**0.05**	**0.02**	**0.35**

Table 3. Results of relative zero motion phantom test (n=number of pairs of frames analyzed). Mean values indicated with (*) differed significantly from zero.

	Tx (mm)	Ty (mm)	Tz (mm)	Rx (°)	Ry (°)	Rz (°)
Kinematic phantom (n=56)						
Mean	-0.03	-0.20*	-0.03	-0.07	-0.02	0.05*
SD	0.24	0.45	0.36	0.30	0.13	0.16
Min	-0.69	-1.37	-0.67	-0.64	-0.34	-0.29
Max	0.73	0.56	0.76	0.55	0.23	0.47
Static phantom (n=20)						
Mean	-0.02	-0.04*	0.04*	0.03	0.00	0.11*
SD	0.07	0.04	0.08	0.13	0.11	0.08
Min	-0.17	-0.14	-0.08	-0.25	-0.19	-0.04
Max	0.13	0.03	0.23	0.25	0.19	0.25

between the two images. This would also explain the fact that a higher SD was found for Rx than for the other rotations and for Ty and Tz than for Tx: the movement of the phantom, mimicking a flexion-extension movement, was mostly contained in the sagittal plane of the phantom leg, which corresponded to the *x*-plane. Despite this, a more homogeneous distribution of errors within the three directions has been found in kinematic RSA compared with the values reported for the single-plane fluoroscopy method. According to the literature for single-plane fluoroscopy, both with bone markers (27, 28) and with 3D surface model registration (16, 29), translations in the out-of-plane direction are detected with a precision that is one order of magnitude worse than for in-plane translations. The experimental investigation performed was limited to the supine biplane set-up.

As a future application, analogous experiments in a weight-bearing set-up will be performed to show that no additional calibration errors are introduced when changing the configuration of the fluoroscopy system. Moreover, a further study will be performed in order to assess repeatability in defining the joint coordinate system (25, 30). The anatomical reference frames were defined only once and then used for all the images of the patient by rigid body transformations based on marker positions. From those frames the joint coordinate system should be obtained to compute the six-degrees-of-freedom motion of the knee.

In conclusion, the present study, using a clinical bi-

plane fluoroscopy system, allowed an initial *in vivo* and *in vitro* validation of a kinematic RSA set-up. The analysis underlines its potential applicability as a useful method allowing better characterization of joint biomechanics. The method relies on full 3D data acquisition without the unreliable components of the measured movement, such as the translation in the out-of-plane direction seen in single-plane fluoroscopy. The set-up should allow the acquisition of slow movements of the lower limb, both in supine and weight-bearing positions.

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References

1. De Frate LE, Sun H, Gill TJ, et al. In vivo tibiofemoral contact analysis using 3D MRI-based knee models. J Biomech. 2004;37:1499-1504.
2. Hosseini A, Van de Velde S, Gill TJ, et al. Tibiofemoral cartilage contact biomechanics in patients after reconstruction of a ruptured anterior cruciate ligament location of cartilage contact. J Orthop Res. 2012;30:1781-1788.
3. Hosseini A, Van de Velde SK, Kozanek M, et al. In-vivo time-dependent articular cartilage contact behavior of the tibiofemoral joint. Osteoarthritis Cartilage. 2010;18:909-916.
4. Li G, DeFrate LE, Park SE, et al. In vivo articular cartilage contact kinematics of the knee: an investigation using dual-orthogonal fluoroscopy and magnetic resonance image-based computer models. Am J Sports Med. 2005;33:102-107.
5. Van de Velde SK, Bingham JT, Hosseini A, et al. Increased tibiofemoral cartilage contact deformation in patients with anterior cruciate ligament deficiency. Arthritis Rheum. 2009; 60:3693-3702.
6. Deneweth JM, Bey MJ, McLean SG, et al. Tibiofemoral joint kinematics of the anterior cruciate ligament-reconstructed knee during a single-legged hop landing. Am J Sports Med. 2010; 38:1820-1828.
7. Tashman S, Kolowich P, Collon D, et al. Dynamic function of the ACL-reconstructed knee during running. Clin Orthop Relat Res. 2007;454:66-73.
8. Tashman S, Araki D. Effects of anterior cruciate ligament reconstruction on in vivo, dynamic knee function. Clin Sports Med. 2013;32:47-59.
9. Tashman S, Anderst W. In-vivo measurement of dynamic joint motion using high speed biplane radiography and CT: application to canine ACL deficiency. J Biomech Eng. 2003;125:238-245.
10. Chaudhari AM, Briant PL, Bevill SL, et al. Knee kinematics, cartilage morphology, and osteoarthritis after ACL injury. Med Sci Sports Exerc. 2008;40:215-222.
11. Moro-oka TA, Muenchinger M, Canciani JP, et al. Comparing in vivo kinematics of anterior cruciate-retaining and posterior cruciate-retaining total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc. 2007;15:93-99.
12. Moro-oka TA, Hamai S, Miura H, et al. Dynamic activity dependence of in vivo normal knee kinematics. J Orthop Res. 2008;26:428-434.
13. Taylor KA, Cutcliffe HC, Queen RM, et al. In vivo measurement of ACL length and relative strain during walking. J Biomech. 2013;46:478-483.
14. Miranda DL, Fadale PD, Hulstyn MJ, et al. Knee biomechanics during a jump-cut maneuver: effects of sex and ACL surgery. Med Sci Sports Exerc. 2013;45:942-951.
15. Komistek RD, Dennis DA, Mahfouz M. In vivo fluoroscopic analysis of the normal human knee. Clin Orthop Relat Res. 2003;410:69-81.
16. Banks SA, Hodge WA. Accurate measurement of three-dimensional knee replacement kinematics using single-plane fluoroscopy. IEEE Trans Biomed Eng. 1996;43:638-649.
17. Mahfouz MR, Hoff WA, Komistek RD, et al. A robust method for registration of three-dimensional knee implant models to two-dimensional fluoroscopy images. IEEE Trans Med Imaging. 2003;22:1561-1574.
18. Banks SA, Hodge WA. Implant design affects knee arthroplasty kinematics during stair-stepping. Clin Orthop Relat Res. 2004;(426):187-193.
19. Fantozzi S, Catani F, Ensini A, et al. Femoral rollback of cruciate-retaining and posterior-stabilized total knee replacements: in vivo fluoroscopic analysis during activities of daily living. J Orthop Res. 2006;24:2222-2229.
20. Dennis DA, Komistek RD, Mahfouz MR, et al. Multicenter determination of in vivo kinematics after total knee arthroplasty. Clin Orthop Relat Res. 2003;(416):37-57.
21. Li G, Van de Velde SK, Bingham JT. Validation of a non-invasive fluoroscopic imaging technique for the measurement of dynamic knee joint motion. J Biomech. 2008;41:1616-1622.
22. Varadarajan KM, Moynihan AL, D'Lima D, et al. In vivo contact kinematics and contact forces of the knee after total knee arthroplasty during dynamic weight-bearing activities. J Biomech. 2008;41:2159-2168.
23. You BM, Siy P, Anderst W, et al. In vivo measurement of 3-D skeletal kinematics from sequences of biplane radiographs: application to knee kinematics. IEEE Trans Med Imaging. 2001;20:514-525.
24. Gronenschild E. The accuracy and reproducibility of a global method to correct for geometric image distortion in the x-ray imaging chain. Med Phys. 1997;24:1875-1888.
25. Grood ES, Suntay WJ. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. J Biomech Eng. 1983;105:136-144.
26. Selvik G. A stereophotogrammetric system for the study of human movements. Scand J Rehabil Med Suppl. 1978;6:16-20.
27. Garling EH, Kaptein BL, Geleijns K, et al. Marker Configuration Model-Based Roentgen Fluoroscopic Analysis. J Biomech. 2005;38:893-901.
28. Ioppolo J, Börlin N, Bragdon C, et al. Validation of a low-dose hybrid RSA and fluoroscopy technique: determination of accuracy, bias and precision. J Biomech. 2007;40:686-692.
29. Hoff WA, Komistek RD, Dennis DA, Gabriel SM, Walker SA. Three-dimensional determination of femoral-tibial contact positions under in vivo conditions using fluoroscopy. Clin Biomech. (Bristol, Avon). 1998;13:455-472.
30. Wu G, Cavanagh PR. ISB recommendations for standardization in the reporting of kinematic data. J Biomech. 1995; 28:1257-1261.