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Determining 3D Kinematics of the Hip Using Video Fluoroscopy: Guidelines for Balancing Radiation Dose and Registration Accuracy

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ABSTRACT

Background: Video fluoroscopy is a technique currently used to retrieve the in vivo three-dimensional kinematics of human joints during activities of daily living. Minimization of the radiation dose absorbed by the subject during the measurement is a priority and has not been thoroughly addressed so far. This issue is critical for the motion analysis of the hip joint, because of the proximity of the gonads. The aims of this study were to determine the x-ray voltage and the irradiation angle that minimize the effective dose and to achieve the best compromise between delivered dose and accuracy in motion retrieval.
Methods: Effective dose for a fluoroscopic study of the hip was estimated by means of Monte Carlo simulations and dosimetry measurements. Accuracy in pose retrieval for the different viewing angles was evaluated by registration of simulated radiographs of a hip prosthesis during a prescribed virtual motion.
Results: Absorbed dose can be minimized to about one-sixth of the maximum estimated values by irradiating at the optimal angle of 45° from the posterior side and by operating at 80 kV. At this angle, accuracy in retrieval of internal-external rotation is poorer compared with the other viewing angles.
Conclusion: The irradiation angle that minimizes the delivered dose does not necessarily correspond to the optimal angle for the accuracy in pose retrieval, for all rotations. For some applications, single-plane fluoroscopy may be a valid lower dose alternative to the dual-plane methods, despite their better accuracy.

Video fluoroscopy is an accurate and minimally-invasive technique currently used for the analysis of in vivo joint kinematics. A sequence of fluoroscopic images of the joint of interest is collected while the subject performs a specific motion task. For each frame, the three-dimensional (3D) pose of the joint is retrieved by matching a 3D model of each segment to its two-dimensional (2D) projection in the corresponding image, that is, 2D-to-3D registration [1]. The movement is finally reconstructed from the sequence of registered poses. Fluoroscopy of the hip has been performed to analyze gait on a treadmill [2–5], stair climbing [6], and isolated abduction [2,7].

As with conventional radiography, fluoroscopy imaging involves exposure of the subject to ionizing radiation. According to the As Low As Reasonably Achievable radiation safety principle, all reasonable methods should be used to minimize radiation dose. In video fluoroscopy, a trade-off exists between image quality and radiation exposure. Acquisition of image data at high frame rates for dynamic events requires greater x-ray exposure to increase brightness and obtain the image quality required to achieve sufficient registration accuracy [8]. Furthermore, x-ray imaging of the hip requires typically higher exposure compared with imaging other peripheral joints of the body, because the image contrast is limited by a greater amount of surrounding tissue. However, higher x-ray exposure is associated with increased dose absorbed by the subject [9]. This issue is particularly critical for the hip because of the proximity of the gonads—the risk of biological damage to the gonads attributed by the International Commission on Radiation Protection (ICRP) is 2 times the risk assigned to bladder, liver, and thyroid glands and 8 times the risk assigned to the bone surface, skin, and brain [10]. The radiation dose is doubled when dual-plane fluoroscopy is used to acquire a pair of simultaneous images [4,5] as a means to improve the accuracy in pose retrieval.

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Many in vivo fluoroscopic studies of the hip lack information concerning radiation exposure [2,6,7,11–14] or report only the fluoroscopic settings without dose estimations [4]. The studies that provided values for the absorbed dose [5,15–17] did not explain the method used for their estimations and did not characterize the dependency of the dose on the imaging parameters. Effective dose can be estimated from the product between the kerma-area product, usually provided by the fluoroscope, and a reference dose conversion coefficient (DCC) [18] that is specific for the diagnostic procedure and the irradiated organs [19]. However, the values for the kerma-area product are not validated with in-situ dosimetry measurements and the reference values for the DCC, although derived from Monte-Carlo simulations using anthropomorphic digital phantoms, are not specific for the subject (gender, body mass index [BMI]), for the measurement geometry (distance and position of the patient with respect to the beam), and for the imaging settings (voltage, current, pulse width). For example, Le Heron [20] estimated that for the trunk region the DCC for the lateral and the posteroanterior (PA) radiographic projections are approximately half those corresponding to anteroposterior (AP) projection.

Considering the safety implications of radiation exposure, and the discrepancies in reported radiation dose for current fluoroscopy studies, the first aim of this study was to accurately estimate the radiation dose during hip imaging and to determine the imaging parameters that minimize the dose while providing acceptable image quality. The variable parameters investigated for this analysis were the x-ray voltage and the irradiation angle with respect to the pelvis.

For single-plane use, the fluoroscope must be positioned carefully to obtain sufficient bony details from optimized viewing angles, while minimizing occlusion of surrounding tissues and out-of-plane movement for the analyzed activity [15]. Hence, registration accuracy is influenced by imaging angle and must be considered together with dose minimization. The second aim of this study was to quantitatively investigate the dependence of the registration accuracy on the viewing angle of single-plane fluoroscopy, for a specific motion task.

Material and Methods

Estimation of Dose

Effective dose (Sv) for a fluoroscopic study of the hip was estimated by means of Monte Carlo simulations and dosimetry measurements with an Alderson phantom. Estimations were obtained for 2 different x-ray voltages, 80 kV and 100 kV, and 5 different irradiation angles described in Figure 1. The values for the x-ray voltages were comparable with those used in previous x-ray studies of the hip [4,5,15–17,21]. On the clinical fluoroscope incorporated in the imaging system, tube current is not independently adjustable. The tube current was automatically set by the fluoroscope to 12 mA for both voltages.

Monte Carlo methods with the Geant4 library [22] were used to simulate the x-ray irradiation of a 3D human model with 73 different organs and a voxel size of $2 \times 2 \times 2$ mm^3. Material properties of each organ were assigned according to the tissue composition provided by the ICRP [23]. The x-ray beam used in the simulations was modeled according to the specifications of the used fluoroscope (BV Pulsera, Philips Medical Systems, Switzerland). The beam aperture was 17°. The output of the simulation was the average absorbed dose H_T (Gy) for each organ, a deterministic quantity accounting for the amount of deposited energy. The simulated effective dose E_S was computed as the weighted sum of the absorbed doses over all organs of the body (Equation 1). The organ-specific weighting factors W_T account for the stochastic biological risk associated with radiation exposure and are defined by the ICRP.

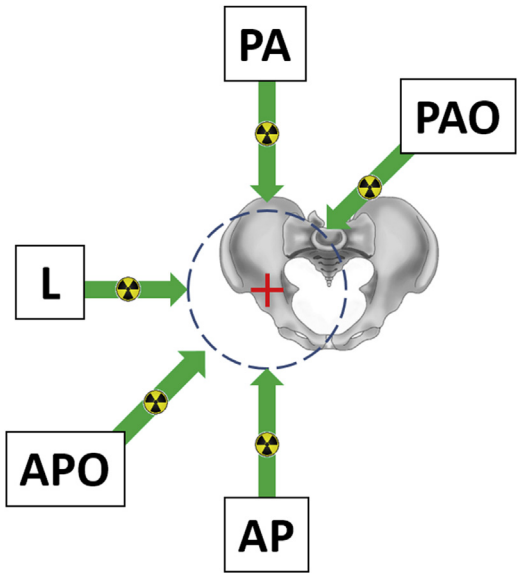

Fig. 1. Top view of a pelvis with the simulated irradiation angles. AP, anteroposterior; L, lateral; PA, posteroanterior; APO, anteroposterior oblique; PAO, posteroanterior oblique.

$$E_S = \sum W_T H_T \tag{1}$$

Simulations at different irradiation angles (Fig. 1) and different x-ray voltages were performed. With experimental setups analogous to each simulation, the entrance dose to an Alderson phantom placed at a distance of 70 cm from the x-ray source was measured while operating the fluoroscope at a frame rate of 25 Hz and pulse width of 8 ms (Fig. 2). For each case, the dose-area product (Gy*m^2) was measured with a dosimeter. The simulated effective dose was then scaled with the ratio of the measured dose-area product $D_M R_M^2$ to the simulated dose-area product $D_S R_S^2$ (Equation 2) to retrieve the estimated effective dose E for each measurement setting.

$$E = E_S \frac{D_M R_M^2}{D_S R_S^2} \tag{2}$$

Because of the different position between the female and the male gonads, simulations for both a female subject (58 kg, 1.66 m, BMI 21 kg/m^2) and a male subject (80 kg, 1.73 m, BMI 27 kg/m^2) were carried out.

In addition, simulations for a shielded male patient were performed to quantitatively evaluate the benefit brought by gonad protection. Shielding was modeled with a 2-4 mm thick lead sheet placed in front of the testes.

Estimation of Registration Accuracy

Pose accuracy for the different viewing angles was evaluated by registration of simulated radiographs of a hip prosthesis during a prescribed virtual motion. Because accuracy is expected to depend on the specific motion task, level walking and sitting on a chair were chosen as activities covering typical range of motion of the hip joint. For each of these, the following procedure was carried out:

1. Realistic motion of the hip was retrieved from the public database www.OrthoLoad.com [24] and applied to 3D models of the cup and the femoral stem of the prosthesis;