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Radiographic cup anteversion measurement corrected from pelvic tilt

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ABSTRACT

The purpose of this study was to develop a novel technique to improve the accuracy of radiographic cup anteversion measurement by correcting the influence of pelvic tilt. Ninety virtual total hip arthroplasties were simulated from computed tomography data of 6 patients with 15 predetermined cup orientations. For each simulated implantation, anteroposterior (AP) virtual pelvic radiographs were generated for 11 predetermined pelvic tilts. A linear regression model was created to capture the relationship between radiographic cup anteversion angle error measured on AP pelvic radiographs and pelvic tilt. Overall, nine hundred and ninety virtual AP pelvic radiographs were measured, and 90 linear regression models were created. Pearson's correlation analyses confirmed a strong correlation between the errors of conventional radiographic cup anteversion angle measured on AP pelvic radiographs and the magnitude of pelvic tilt ($P < 0.001$). The mean of 90 slopes and y-intercepts of the regression lines were −0.8 and −2.5°, which were applied as the general correction parameters for the proposed tool to correct conventional cup anteversion angle from the influence of pelvic tilt. The current method proposes to measure the pelvic tilt on a lateral radiograph, and to use it as a correction for the radiographic cup anteversion measurement on an AP pelvic radiograph. Thus, both AP and lateral pelvic radiographs are required for the measurement of pelvic posture-integrated cup anteversion. Compared with conventional radiographic cup anteversion, the errors of pelvic posture-integrated radiographic cup anteversion were reduced from 10.03 (SD = 5.13) degrees to 2.53 (SD = 1.33) degrees. Pelvic posture-integrated cup anteversion measurement improves the accuracy of radiographic cup anteversion measurement, which shows the potential of further clarifying the etiology of postoperative instability based on planar radiographs.

1. Introduction

Malpositioning of the cup in total hip arthroplasty (THA) can potentially cause impingement and dislocation [1–3]. Radiographic assessment of cup orientation is critical to identify possible causes of postoperative instability. The cup orientation is determined by its circular cup rim, which is a three dimensional concept intraoperatively. However, its orientation in practice is measured by two planar parameters post-operatively, the cup inclination (IN) and the cup anteversion (AV) [2]. The cup IN and the cup AV are measurements of cup orientation in the coronal plane and the sagittal plane, which are determined by the elliptical projection of the circular cup rim on a planar anteroposterior (AP) pelvic or hip radiograph. The cup IN is defined as the angle between the major axis of the ellipse and the line connecting bilateral tear drops of acetabula on an AP pelvic radiograph, which can be measured directly on AP pelvic radiographs. The cup AV can be calculated from the ratio between the lengths of the minor and major axes of the ellipse, using trigonometric equations [2–4]. Unlike cup IN, the measurement of cup AV is however relatively more complicated [5]. Computed tomography (CT)-based cup AV measurement was reported with a higher accuracy [6,7]. However, CT-based cup AV is different from commonly accepted definitions reported by Murray [8], and the accuracy of measurement on CT images is still affected by pelvic tilt [6–9]. Thus, post-processing is required to minimize the influence of pelvic tilt [4–7,10]. Besides, CT-based measurement brings additional radiation and costs [4,9,11].

Radiographic cup AV measurement is routinely performed on an AP pelvic radiograph. Pelvic posture, which has a direct impact on the appearance of cup profile shown in Fig. 1, can influence the measurement of radiographic cup AV [2]. Pelvic tilt, rotation and obliqueness, illustrated in Fig. 2, are commonly applied to describe

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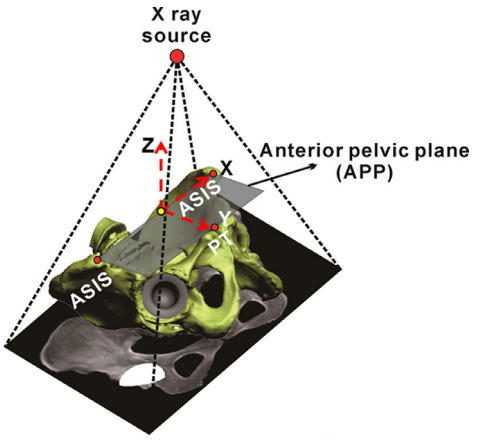

Fig. 1. Virtual pelvic-cup model and AP virtual pelvic radiograph generated from a virtual X-ray source. The three dimentional coordinate system is illustrated on the virtual pelvic model. Red dots are bilateral anterior superior iliac spines(ASIS) and the middle point of bilateral pubic tubercles(PT). The yellow dot is the middle point of bilateral ASISs. *X* axis is defined as the line from right ASIS to left ASIS. Y axis is defined as the line from the middle point of bilateral ASISs to that of bilateral PTs. *Z* axis is defined as the line perpendicular to the plane determined by *X* and *Y* axes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. Basic rotations of a pelvis used to define its posture. Pelvic tilt is defined as a rotation around the pelvic horizontal axis, pelvic rotation is defined as a rotation around the pelvic longitudinal axis, and pelvic obliqueness is defined as a rotation around the pelvic sagittal axis.

pelvic posture. Pelvic tilt is defined as a rotation around the right–left axis, also called pelvic horizontal axis (*X* axis), pelvic rotation is defined as a rotation around the top-down axis, also called pelvic longitudinal axis (*Y* axis), and pelvic obliqueness is defined as a rotation around the back-forward axis, also called pelvic sagittal axis (*Z* axis) [12]. Previous studies have shown significant intra- and inter-subject differences in pelvic posture measured in the supine position, inevitably affecting the accuracy of radiographic cup AV measurement [9,11]. As shown in Fig. 1, the anterior pelvic plane (APP), defined by the plane passing through the bilateral anterior superior iliac spines (ASIS) and the middle point of pubic tubercles (PT), is a reliable anatomic reference to describe pelvic posture [2,11–13]. The most adopted pelvic posture for an optimal measure of the radiographic cup AV and IN is defined when the patient is lying supine on the table with the APP parallel with X-ray film [2,12]. With this alignment, the radiographic cup AV and IN can be accepted to be the true cup orientation. Perfect alignment between APP and the X-ray film is not easy to control clinically. The main focus of the current study is to improve accuracy of radiographic measurement of cup AV taking pelvic tilt into consideration. Clinically, patients might have both pelvic tilt and rotation when capturing radiographs. Pelvic rotation is relatively easy to control by making the line connecting bilateral ASISs parallel to X-ray table. Due to the uneven body fat distribution between ASISs and PTs, control of pelvic tilt is considerably more difficult. Thus, the authors believe pelvic tilt is the main source of error in the radiographic measurement of cup AV. Even though the amount of pelvic tilt can be measured on a lateral radiograph, the link between the magnitude of pelvic tilt and its effect on the measurement of radiographic cup AV has not been clarified [12–15].

Conventionally, as we see, the measurements of cup AV on planar radiographs are not accurate due to varying individual pelvic postures. The objective of this study is to develop a simple tool which surgeons can apply to correct errors in radiographic AV measurement created by influences of pelvic tilt. In the course of this work, we apply a validated method for the calculation of pelvic tilt, which is an input parameter to our proposed AV measurement method. With this input parameter along with the proposed method, we are trying to demonstrate the effectiveness of the proposed pelvic posture-integrated radiographic AV measurement.

2. Materials and methods

2.1. Method overview

The general idea is to propose a technique which corrects the measured radiographic cup AV on AP pelvic radiographs from the influence of the pelvic tilt to obtain a corrected assessment of the true radiographic AV. This takes the form of the following equation to calculate the proposed posture-integrated radiographic cup AV with better accuracy (Eq. (1)):

$$\theta_P = \theta_C + (CP_{tilt} \cdot \theta_{tilt} + K_{tilt}) \quad (1)$$

where θ_P is the proposed posture-integrated radiographic cup AV; θ_C is the conventional radiographic cup AV measured directly on the AP pelvic radiograph; θ_{tilt} is the pelvic tilt angle measured conventionally on the lateral pelvic radiograph; and CP_{tilt} and K_{tilt} are the general correction parameters for pelvic tilt that are determined in this study using a collection of simulated radiographs.

The following provides an overview of the general approach. 3D models were generated based on skeletal anatomy segmented from CT scans and CAD-generated acetabular cups. Cups were placed into the acetabulum over a physiologic range of cup AV and IN and computer-generated radiographs were created for each condition. From these models, cup AVs were assessed with conventional methods. The errors were assessed and a regression model of the errors as a function of pelvic tilt was used to develop the technique for radiographic AV correction. The technique was tested on several additional computer-generated models, first calculating pelvic tilt and radiographic cup AV conventionally, then applying the correction tool.

2.2. Participants

Virtual pelvic radiographs were generated from CT volume data of real patients, as illustrated in Fig. 1. Using a helical CT scanner (Light Speed 16, GE Medical System, USA) at intervals of 1.25 mm, pelvic CT scanning was performed on 3 male and 3 female subjects, who were diagnosed with end-stage hip osteoarthritis but without other pelvic pathology. The mean age was 55 (50–70) years. The mean height was 168 (160–175) cm. The mean weight was 63 (58–74) kg. They were recruited after obtaining approval from the institutional review board and informed consent from the patients.

2.3. Computer modeling and virtual cup placement

Using region grow, threshold and object separator modules, 3D virtual pelvic models were reconstructed based on the CT data using Analyze® (Mayo Clinic, Rochester, MN), a medical image processing software package. A virtual radiography environment was then created and each virtual pelvic model was realigned to the optimal posture with the APP parallel to virtual X-ray film [2,16]. A series of hemispherical cup models with appropriate outer diameters were created with a computer-aided design (CAD) software called Solidworks® (Dassault Systemes, Velizy, France), and these were then

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