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Two-Dimensional and Three-Dimensional Cup Coverage in Total Hip Arthroplasty with Developmental Dysplasia of the Hip

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ABSTRACT

We analyzed the mean difference and correlation between 2D cup coverage measured from different projections and three-dimensional (3D) cup coverage to investigate their precise relationship in total hip arthroplasty (THA) among patients with developmental dysplasia of the hip (DDH). We created DDH–THA models on six foam pelvic models. 3D cup coverage was measured using a motion capture system and imaging software. Digitally reconstructed radiographs with predetermined pelvic rotations were simulated using image processing software at three different angles of rotation around the long body axis (0°, 25° and 45°). 2D cup coverage was then measured on these reconstructed radiographs. The 3D technique showed excellent intra-observer ($\kappa > 0.98$) and inter-observer ($\kappa > 0.99$) reliability. The 2D technique tended to overestimate the real cup coverage by about 15%. The smallest difference between 2D and 3D cup coverage occurred when 2D measurement was performed on the radiographs with 45° of pelvic rotation toward the operated side (14.50%, $P < 0.0001$), meanwhile, the highest correlation coefficient between 2D and 3D cup coverage was also observed when the 2D measurement was performed on the radiographs at this same pelvic rotation ($r = 0.67$, $P = 0.0003$). Published recommendations regarding the minimum cup coverage based on 2D measurement should be interpreted cautiously. The minimal cup coverage, as an intra-operative 3D parameter related to the long term fixation of the cup component, should be more accurately determined with intra-operative measurement.

1. Introduction

Total hip arthroplasty (THA) is considered to be the standard treatment for patients with end-stage hip diseases. Due to insufficient bone stock, the acetabulum cannot provide full coverage of the acetabular component among patients with developmental dysplasia of the hip (DDH; Charnley and Feagin, 1973; Sanchez-Sotelo et al., 2002; Spangehl et al., 2001). Inadequate cup coverage leads to abnormal stress distribution along the bone–implant interface and limits viable host bone for bone ingrowth (Anderson and Harris, 1999; Hartofilakidis et al., 1996; Jasty et al., 1995; Schuller et al., 1993). Thus, insufficient cup coverage is considered to be a negative factor leading to cup loosening (Chougle et al., 2005; Hartofilakidis and Karachalios, 2004; Hartofilakidis et al., 1998)

Various radiographic evaluation techniques of cup coverage have been proposed based on the measurement on anteroposterior (AP) pelvic radiographs (Anwar et al., 1993; Sarmiento et al., 1990; Silber and Engh, 1990; Sugano et al., 1995). In Silber's study, the percentage of the coverage provided by the autograft was determined by measuring the circumference of the cup in contact with the graft on an AP pelvic radiograph. Similarly, cup coverage could also be defined by the percentage of area of the cup covered by host bone. Using similar measurement techniques, previous studies recommended that the minimum value of cup coverage required to ensure long-term survival of cup component should be above 70% (Anderson and Harris, 1999; Dorr et al., 1999; Hartofilakidis et al., 1998; Jasty et al., 1995).

Previously, various 2D radiographic parameters were proposed to measure the coverage of the native femoral head (Tonnis, 1976; Wiberg, 1953). However, these techniques provided limited information, since they used 2D representations of the complex 3D geometry around acetabulum. A new computed tomography (CT) based computer-assisted technique should be applied to better measure the 3D coverage (Dandachli et al., 2008). Similarly, the current 2D cup coverage has never been validated with the 3D cup coverage. Thus, the precise relationship between 2D and 3D cup coverage is unknown. Further, differences in 2D cup coverage measured from radiographs of different projections are unknown.

In this study, physical models consisting of a foam pelvis and acetabular cup were used to compare 2D radiographic measurements

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of cup coverage with different projections with 3D measurements performed on the same models to clarify the mean difference and the correlation between 2D and 3D measurements. The 3D measurement is based on a new technique using an optical digitization system and computer aided design software. We sought to answer the following questions: (1) Are there significant differences between 2D and 3D cup coverage measurements? (2) How much is the magnitude of these differences? (3) Which projection results in 2D measurements that most closely match the 3D cup coverage?

2. Methods

2.1. Preparation of models with DDH related bony defect

The most common pattern of the bony defect among DDH patients is located at the anterosuperior portion of the acetabulum (Hartofilakidis and Babis, 2009; Hartofilakidis and Karachalios, 2004; Hartofilakidis et al., 1988; Karachalios and Hartofilakidis, 2010; Fig. 1A and B). To make a close approximation of this specific deformity, a bony defect was created with a hemispherical reamer at the anterosuperior portion of the acetabulum on 6 normal foam pelvic models (Sawbones™, Vashon, WA, USA). The acetabulum, originally of 57 mm diameter, was reamed to a diameter of 58 mm. A 59 mm S-ROM™ cup (Depuy, Warsaw, IN) was impacted into place and secured with one screw. Cup orientation was guided by periacetabular bony landmarks. Cup inclination was controlled by making the inferior cup rim flush with the acetabular notch. Cup anteversion was controlled by making the inferoposterior cup rim flush with the lowest point of the acetabular sulcus of the ischium (Fig. 1C and D).

2.2. Computer assisted measurement of 3D cup coverage

2.2.1. Digitization of representative points

The pelvic models were mounted on a rigid table, which was stationary relative to the position sensor of an Optotrak Certus™ capture system (NDI, Ontario, Canada). The distance between the pelvic model and position sensor was 2.25 m, where, according to the manufacturer's information, the 3D resolution was 0.01 mm. 6 evenly-spaced red points on the outer edge of cup rim and 20 green points along bone-implant border were digitized for each model using a probe (Fig. 2A and B). The digitization was repeated three times, and the cup coverage measurements were repeated three times using the three separate digitizations.

2.2.2. Computerized cup modeling and 3D measurement

For each model, digitized data sets were loaded into Solidworks™ 2009 (Dassault Systemes, Velizy, France) to create computerized cup models. Firstly, a face-plane was created in Solidworks™ 2009 based on the 6 points digitized from the cup rim. Secondly, to simulate the cup rim, a circle was analytically fit by picking three of the six points digitized on the cup rim. To minimize error introduced by manual digitization, the circle was given a diameter equal to the known cup diameter (59 mm) and was used to choose the optimal three points on the edge of cup rim. Subsequently, a 3D hemispheric cup model was reconstructed based on this circular rim. The 20 points digitized on the bone-implant border were loaded into the program and projected onto this hemispheric cup surface (Fig. 2C). A spline curve intersecting the projected points separated covered and uncovered area. The region of interest (ROI) was selected and its surface area was calculated using existing Solidworks™ 2009 functions (Fig. 2D). Two investigators (L.W. and H.K.) performed 3D measurements independently. Both observers had some background using computer assisted software.

2.3. Digitally reconstructed radiograph (DRR) free of metallic artifact

2.3.1. CT scanning

Two paired sets of CT scans of each pelvic model (with and without cup) were collected using a helical CT scanner −140 kV, 340 effective mAs, pitch = 0.8, rotation = 1 s, collimation 32 × 0.6 mm^2 with z-flying focal spot enabled (Siemens Definition, Siemens Healthcare, Forchheim, Germany). During scanning, the pelvic models were laid in a supine position with a cushion placed on each side for stability. The images were reconstructed using a medium kernel (B40) to produce CT slices 0.6 mm in thickness (resolution, 512 × 512 pixels) with a 354 × 354 mm^2 field of view around pelvic model. In order to improve the quality of digitally reconstructed radiography (DRRs), paired CT images (with and without cup) were registered to generate a merged model, which was free of metallic artifact.

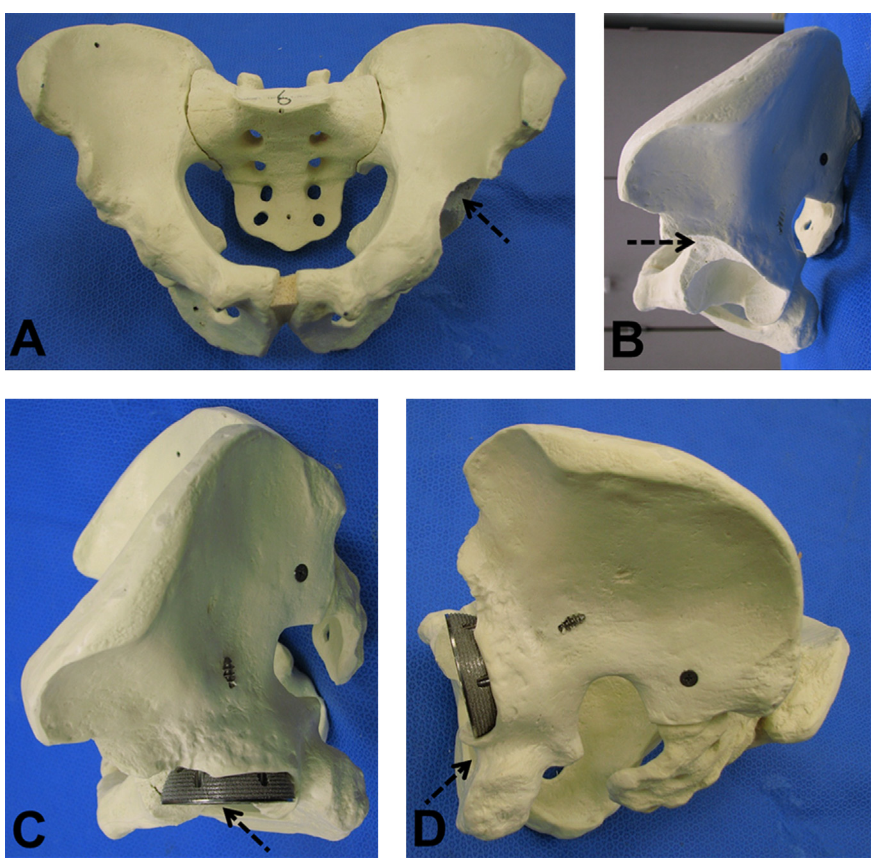

Fig. 1. AP and lateral views of a foam pelvic model with anterosuperior bony defect (A and B), and the cup orientation was guided by peri-acetabular bony landmarks, including acetabular notch for cup inclination (C) and the lowest point of the acetabular sulcus of the ischium for cup anteversion (D).