Robust Pelvic Coordinate System Determination for Pose Changes in Multidetector-row Computed Tomography Images

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Abstract

For developing navigation system of total hip arthroplasty (THA) and evaluating hip joint kinematics, 3-D pose position of the femur and acetabulum in the pelvic coordinate system has been quantified. The pelvic coordinate system is determined by manually indicating pelvic landmarks in multidetector-row computed tomography (MDCT) images. It includes intra- and inter-observer variability, and may result in a variability of THA operation or diagnosis. To reduce the variability of pelvic coordinate system determination, this paper proposes an automated method in MDCT images. The proposed method determines pelvic coordinate system automatically by detecting pelvic landmarks on anterior pelvic plane (APP) from MDCT images. The method calibrates pelvic pose by using silhouette images to suppress the affect of pelvic pose change. As a result of comparing with manual determination, the proposed method determined the coordinate system with a mean displacement of 2.6 ± 1.6 mm and a mean angle error of 0.78 ± 0.34 deg on 5 THA subjects. For changes of pelvic pose position within 10 deg, standard deviation of displacement was 3.7 mm, and of pose was 1.28 deg. We confirmed the proposed method was robust for pelvic pose changes.

Key Words : pelvic coordinate system, anterior pelvic plane, MDCT images, total hip arthroplasty

1. Introduction

Quantification of 3-D pose position of the femur and acetabulum is required for evaluating the hip joint kinematics or developing navigation system of total hip arthroplasty (THA) [00]. By analyzing the hip joint kinematics, biomechanics of joint, mechanism of walking on two legs, the cause of joint dislocation, etc. has been studied [0]. To analyze the hip joint kinematics, 2-D/3-D image registration of 2-D X-ray images and 3-D multidetector-row computed tomography (MDCT) images has been used [00]. The methods produce 3-D pose position parameters of the femur and the pelvis in MDCT image coordinate system. Thus, to investigate the relative pose position between the femur and the acetabulum, it requires a definition of pelvic coordinate system.

Pelvic coordinate system is a coordinate system derived from subject's pelvic shape. There are mainly two definitions of the coordinate system. The representative one, and used in this study, is based on anterior pelvic plane (APP) [00]. APP is a tangent plane of the pelvis, and is determined by four pelvic

landmarks that are the right and left anterior superior iliac spines (ASIS), and the right and left pubic tubercles. The other definition of pelvic coordinate system is based on the ASIS and the posterior superior iliac spine (PSIS) [0].

The pelvic landmarks have been determined manually in MDCT images. The manual interaction causes intra- and inter-user variability. Furthermore, subjects' pose in MDCT scanner changes in every image acquisition. In such cases, it is difficult to define the same coordinate system every time. The variability of coordinate system definition affects the hip joint kinematics evaluation and functional test. Furthermore it may cause the serious problem of variability of THA operation. Therefore a robust pelvic coordinate system determination without pose change affect is required.

There are few studies for automated definition of pelvic coordinate system or for automated finding of APP. In order to find the APP, they extract the anatomical landmarks by registering the predefined atlas data with MDCT images of evaluating subject [00]. The other method finds APP by using the mirror plane associated with the left and right ASIS [0]. Although, the conventional methods did not consider about robustness for pelvic pose changes.

This paper proposes a fully automated pelvic coordinate system in MDCT images. The method calibrates the pelvic pose by using silhouette images, and finds the pelvic landmarks and APP. Using the obtained APP and pelvic landmarks, the

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Fig. 1 Pelvic landmarks. A: Anterior, P: Posterior, R: Right, L: Left, I: Inferior, S: Superior.

Fig. 2 MDCT coordinate system.

pelvic coordinate system is defined. This method reduces variability due to pose changes and user interaction. The proposed method was applied to MDCT images of 5 THA subjects, 1 non-THA subject for qualitative evaluation, and to computer-synthesized images for quantitative evaluation.

2. Preliminaries

2.1 Pelvic landmarks

The proposed method determines the pelvic coordinate system by extracting APP. APP is a tangent plane which contacts with the anterior pelvic region. Because the contacting points are pelvic landmarks, APP can be determined by extracting the pelvic landmarks. Fig. 1 introduces location of pelvic landmarks; superior and right landmark is called the right anterior superior iliac spine (ASIS), superior and left landmark is called the left ASIS, inferior and right landmark is called the right pubic tubercle, inferior and left landmark is called the left pubic tubercle, and center of the right and the left pubic tubercles is called pubic joint.

2.2 MDCT images

In this study, MDCT images were acquired from an MDCT scanner (Somatom Plus, Siemens, Germany) with a matrix size of 512 by 512 pixels, a spatial resolution of about 0.75 mm square, number of slice of about 300, and a slice thickness of 1.0 mm. Subjects were scanned with a feet-first supine (FFS) pose in MDCT scanner. MDCT coordinate system is a right-handed coordinate system (X-Y-Z) illustrated in Fig. 2.

In preprocessing, pelvic region is extracted by thresholding using an experimentally determined parameter, Th_{bone} . In addition, in case of THA patients, MDCT images are corrupted by the metal artifact (See Fig. 3). The metal artifact should be removed because it decreases the performance of finding pelvic landmarks. A voxel which satisfied formula (1) is classified into metal artifact, and is removed.

$$card(\{v | v \in \Delta(x), f(v) \geq Th_{bone}\}) \leq Th \quad (1)$$

where x is a voxel of interest, $\Delta(x)$ is a set of neighboring voxels of x , $f(v)$ is CT value of voxel v , and 26-neighbors are used as neighboring voxels. This formula is satisfied when the number of neighboring voxels whose CT value is higher than

(a) Non-THA subject.

(b) THA subject.

Fig. 3 MDCT images.

Th_{bone} is lower than Th . Th is an experimentally determined parameter.

3. Automated determination of pelvic coordinate system

3.1 Overview

The pelvic coordinate system is determined by finding APP, the left and right ASIS, and the pubic joint in MDCT images according to literatures [9][10]. To suppress variability due to pelvic pose change, the pelvic pose is calibrated by using silhouette images. And, from the voxels belonging to pelvic region, contacting points of the pelvic region to APP can be limited to some hundred voxels using a *priori* knowledge. Among the limited voxels, APP is determined by using an optimization technique. Finally, the left and right ASIS and the pubic joint are extracted, and then the pelvic coordinate system is determined. In summary, the proposed method consists of the following steps.

- Step 1) Calibrate pelvic pose using silhouette images.
- Step 2) Limit candidates of pelvic landmarks.
- Step 3) Optimize APP and extract pelvic landmarks.
- Step 4) Determine pelvic coordinate system.

3.2 Calibrate pelvic pose using silhouette images

To suppress the affect of pelvic pose change in MDCT scanner, pelvic pose is calibrated after acquiring MDCT images. The calibration is based on finding a set of rotation angles that faces the largest area of the anterior pelvis to the front (Z-X

Fig. 4 Silhouette images.

plane) and faces the smallest area of the lateral pelvis to the side (Y - Z plane) as shown in Fig. 4.

First, the pelvic region is rotated around Y axis and Z axis so that silhouette image of the pelvic region projected for Y - Z plane becomes the smallest area. The silhouette image is synthesized by formula (2).

$$SI_{\theta}(y, z) = \coprod_x I_{\theta}(x, y, z) \quad (2)$$

where $\coprod_x$ is disjoint union of sets for x and $I_{\theta}(x, y, z)$ is a value (0 or 1) assigned to voxel at $[x, y, z]^T$ in the rotated image with a set of rotation angles θ . $SI_{\theta}(y, z)$ takes a value whether 0 or 1, and means the value assigned at pixel $[y, z]^T$ in the silhouette image. The rotation angle $\theta = [\theta_x, \theta_y, \theta_z]^T$ is found by steepest descent method as follows.

$$\theta^{(k+1)} = \theta^{(k)} - \alpha \begin{bmatrix} 0 \\ \partial f(\theta^{(k)}) / \partial \theta_y^{(k)} \\ \partial f(\theta^{(k)}) / \partial \theta_z^{(k)} \end{bmatrix} \quad (3)$$

$$f(\theta^{(k)}) = \sum_{y, z} SI_{\theta^{(k)}}(y, z) \quad (4)$$

where $\theta^{(k)}$ is k th parameter set of rotation angles, and $\theta^{(0)} = [0, 0, 0]$ is the initial value.

Second, the pelvic region is rotated around X axis so that silhouette image of the pelvic region projected for Z - X plane becomes the largest area by steepest descent method using the following formulas.

$$\theta^{(k+1)} = \theta^{(k)} - \alpha \begin{bmatrix} \partial g(\theta^{(k)}) / \partial \theta_x^{(k)} \\ 0 \\ 0 \end{bmatrix} \quad (5)$$

$$g(\theta^{(k)}) = \sum_{z, x} SI_{\theta^{(k)}}(z, x) \quad (6)$$

$$SI_{\theta}(z, x) = \coprod_y I_{\theta}(x, y, z) \quad (7)$$

3.3 Limit candidates of pelvic landmarks

Location of pelvic landmarks can be limited by the following anatomical (priori) knowledge; (1) the right ASIS area is located in the superior and right area; (2) the left ASIS is located in the superior and left area; (3) the right pubic tubercle is located in the inferior and right area; (4) the left pubic tubercle is located in the inferior and left area. In the limited areas, voxels with the largest Y -coordinate value for each pixel in Z - X plane is extracted as center of candidates for pelvic landmarks. When one or more pixels are given, center of them is used.

For each pelvic landmark, consider a sphere whose radius is r and center is the center of candidates, and voxels in the sphere are extracted as candidates of the pelvic landmark. Candidates for the right ASIS is denoted by V_1 , for the left ASIS is denoted by V_2 , for the right pubic tubercle is denoted by V_3 and for the left pubic tubercle is denoted by V_4 .

3.4 Optimize APP and extract pelvic landmarks

APP is determined from the candidate voxels by using an optimization technique. APP is a tangent plane which is determined by the right and the left ASIS, and either or both of the right or/and the left pubic tubercle because a plane is determined by three points. So, APP is determined by the following formula.

$$(\hat{p}_1, \hat{p}_2, \hat{p}_3) = \arg \min f(p_1, p_2, p_3) \quad (8)$$

$$p_1 \in V_1, p_2 \in V_2, p_3 \in V_3 \cup V_4$$

where $f(p_1, p_2, p_3)$ is a function of counting the pelvic voxels whose location is superior from a plane determined by p_1, p_2 and p_3 . As the result, three points that are located on the right ASIS, on the left ASIS, and on the right or left public tubercle are obtained, and the optimized plane is obtained. Finally, pelvic landmarks are extracted by finding gravity center of voxels of their candidates on the optimized plane, or the nearest voxel to the optimized plane among their candidates when no voxel is on the optimized APP.

3.5 Determine pelvic coordinate system

Using the obtained pelvic landmarks, the pelvic coordinate system is determined. In this study, pelvic coordinate system is defined according to literatures 00. Pelvic coordinate system is a left-handed coordinate system (X_{PCS} - Y_{PCS} - Z_{PCS}). The origin, O_{PCS} , is a pubic joint that is a midpoint of the right and the left pubic tubercles. The X_{PCS} axis is parallel to a straight line connecting the left ASIS and the right ASIS. The Y_{PCS} axis is directed vertically for APP. The Z_{PCS} axis is an outer product of X_{PCS} axis and Y_{PCS} axis. Fig. 5 illustrates the pelvic coordinate system definition.

Fig. 5 Pelvic coordinate system.

4. Experimental results

To assess the proposed method, we have recruited five THA patients (Subject #1 to #5) and non-THA patient (subject #6). All subjects gave their informed consent according to the guidelines approved by Kobe University, JAPAN. Same analysis parameters were used: Th_{bone} was 210 HU; Th was 9 voxels; r was 10mm; α was 1.0×10^{-3} . By applying the proposed method to the acquired MDCT images, APP and the pelvic landmarks were determined. The extracted APP and landmarks for THA subject #1 to #5 and for non-THA subject #6 are shown in Fig. 6. For any subject, the pelvic coordinate system was defined by using the extracted landmarks according to the definition although there are differences in pelvic pose

among subjects. As shown in these figures, the extracted pelvic landmarks located anterior of the pelvis and on the edges. Using the extracted landmarks, APP was determined successfully.

4.1 Evaluation of validity

To evaluate validity of the proposed method, the experimental results were compared with manual determination results by four well-trained orthopaedic doctors. Each doctor indicated the pelvic landmarks in multiplanar reconstruction (MPR) images. For each THA patient and for each doctor, two or more tests were performed to reduce the observer variability. Fig. 7 shows a comparison of the obtained landmarks by the proposed method with those by manual determination for subject #1. Table 1 tabulates the displacement of origin and difference of pose. In this table, a mean of the manually given points was used as ground-truth value. On five THA subjects, the mean $\pm$ standard deviation (SD) of origin displacement was 2.6 ± 1.6 mm, and of pose difference was 0.78 ± 0.34 deg. These results show that the proposed method extracted pelvic landmarks that were similar to those given manually by the orthopaedic doctors.

4.2 Evaluation of robustness for pelvic pose change

To evaluate the robustness for pelvic pose changes with the proposed method, MDCT images of subject #4 were rotated by randomly chosen angles. 200 patterns were synthesized with an angle in which root-squared angle $\phi = \sqrt{\phi_x^2 + \phi_y^2 + \phi_z^2}$ was

Fig. 6 Extracted pelvic landmarks and determined APP with the proposed method. Left: Inferior-superior view, Right: Left-right view, $\bullet$: Pelvic landmarks, and white planes are the determined APP.

less than 30 deg. The proposed method determined the pelvic coordinate system for all patterns. Fig. 8 shows distribution of SD for pelvic pose change. Even if the rotation angle ϕ becomes big, the proposed method obtained a good result that SD is small. The results showed that the SD of origin displacement was 3.7 mm and pose difference was 1.28 deg. This indicates the high robustness of the proposed method for the pelvic pose change.

5. Discussion

Fig. 9 shows distribution of pelvic landmarks that were obtained from randomly rotated MDCT images of a THA subject (subject #1) and of a non-THA subject (subject 6) with a similar manner described in Sec. 4.2. A mean SD for THA subject was 1.5 mm and a mean SD for non-THA subject was 1.0 mm. SD of the extracted pelvic landmarks for non-THA subject was smaller than for THA subjects. The differences indicated that metal artifact effect was still remained and the pelvic region was under-segmented or over-segmented after metal artifact reduction process as shown in Fig. 10. In this study, metal artifact reduction method was based on a spatial distribution of metal artifacts. Because metal artifacts around implants are densely existed, they cannot be removed by the present method. Since few metal artifacts were not removed around the implant, false detection of pelvic landmarks was occurred. They resulted in slightly large SD for THA subjects in comparison with for non-THA subjects.

6. Conclusion

This paper proposed a fully-automated pelvic coordinate system determination method in MDCT images. By automating

Table 1. Displacement of origin and difference of pose in comparison with manual determination results.

	Origin displacement [mm]	Pose difference [deg]
Subject #1	0.69	0.94
Subject #2	1.27	0.46
Subject #3	1.81	0.55
Subject #4	4.69	0.52
Subject #5	4.09	1.35
Subject #6	3.01	0.83

Fig. 8 SD of pelvic landmark for pelvic pose change (right ASIS).

the pelvic coordinate system determination, the intra- and inter-observer variability was removed. And, pose calibration process included in the proposed method extremely reduced the affect of pose change in MDCT scanner. By comparing manual determination method by orthopaedic doctors, the mean origin displacement was 2.6 mm, and the mean pose difference was 0.78 deg on five THA subjects and one non-THA subject. In addition, for pelvic pose change within 30 deg, the SD of origin displacement was 3.7 mm, and pose was 1.28. The differences

Fig. 9 Comparison of performance between THA subject (◆) and non-THA subject (■).

Fig. 10 Results of metal artifact reduction.

will be caused since metallic THA implant was implanted in the subject and metal artifacts in MDCT images were still remained. Therefore, we will investigate the metal artifact reduction method to reduce the variability. And, we will validate the defined pelvic coordinate system in clinical studies. In the future, this method will be applied to estimate hip joint kinematics after THA and to define pelvic coordinate system when THA surgery.

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