Journal of JSEM, Vol.10, Special Issue (2010) 247-250

Accuracy Verification of Image-Matching in a Setting Method for the Stem during Total Hip Arthroplasty

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(*Received 5 February 2010; received in revised form 12 June 2010; accepted 12 June 2010*)

Abstract

Currently, stem insertion during total hip arthroplasty (THA) is not well controlled. The present study investigated a method for improving stem setting in accordance with preoperative planning using a three-dimensional (3-D) computed tomography (CT) model of the femur and RGB images of the excised femoral head. We utilized three femoral heads removed during THA and modeled each head using three spherical acrylic markers. Each femoral head was osteotomized using a parallel jig and three rectangular images of the osteotomized head were taken using a CCD camera. Each femoral head was then set on a camera base and RGB images were taken from three orthogonal directions using the CCD camera. The B-images of the femoral head and the 3-D bone model were processed through image-matching software using an automatic outline extraction and downhill simplex method. The position of the contralateral side of the jig, related to the femur, was measured using a 3-D measuring system in order to validate the accuracy of the image-matching. However, since validation of the accuracy of the image-matching is difficult once the femoral head is excised, a six-degree-of-freedom board was used to facilitate the accuracy validation.

Key words

Controlled Stem Setting Method, Total Hip Arthroplasty, Image-Matching, Femoral Head, Downhill Simplex Method

1. Introduction

Improper setting of an artificial hip joint during THA is associated with increased risk of dislocation and re-operation, poor clinical performance, and limited durability. According to circumstances, components setting position shift more 5mm, 5deg in comparison with the preoperative plan. For this reason, development of an intraoperative support system is the focus of much current research. However, many of these methods have not been applied clinically due to lack of installation accuracy and increased cost of operation.

We previously reported the development of a three-dimensional (3-D) leg alignment assessment system [1-4] that constructs a 3-D bone geometric model using CT. The computed radiographic (CR) image and the 3-D femur model are matched by software, and hip joint alignment is analyzed resulting in precise preoperative planning by setting an artificial hip joint CAD model in a suitable position (Fig.1).

The present study investigated a method of improving stem setting in accordance with preoperative planning using a 3-D femur model and RGB images of an excised femoral head using the 3-D leg alignment assessment system.

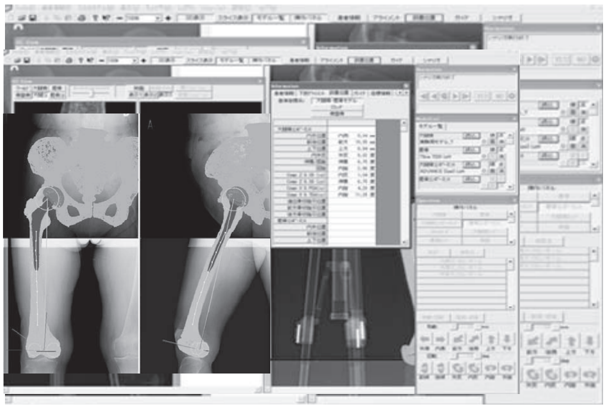
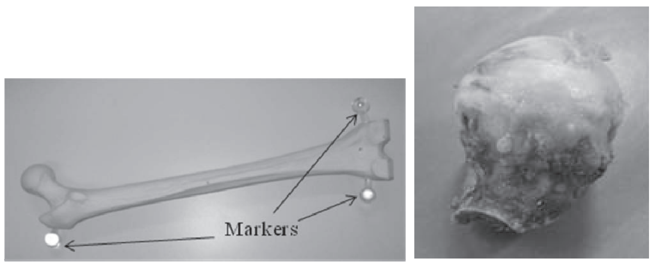


Fig. 1 Three-dimensional leg alignment assessment system.

2. Materials and Methods

2.1 Materials

In this experiment, a spherical acrylic marker was attached to the medial condyle, the lateral condyle, and the great trochanter of three model left femurs (Saw Bones, 1121, WA, USA). The length of the left femora of the models ranged in size between 35 and 42 cm in length and their femoral heads ranged in size between 45 and 52 mm in diameter (Fig.2 (a)). Moreover, femoral heads removed from three patients during THA (Fig.2 (b)) were also used as experimental material after obtaining informed consent from the patients in accordance with our institutional review board guidelines.



(a) (b)

Fig. 2 Experimental materials
(a) Model femur with three acrylic markers attached.
(b) Femoral head from a patient who underwent THA.

2.2 Methods

2.2.1 Osteotomy

Our 3-D bone model utilized 3-D analysis software (ZedViewer, LEXI, Tokyo, Japan) and CT images of the model femora and femoral heads.

A parallel jig consisting of two sheets, pin wires and a bone saw were used for the osteotomy. The parallel jig was fixed to the femoral neck by the pin wires, and the osteotomy was performed using the bone saw. The excised femoral head was then placed upon a photographic device (Fig.3). The RGB images of the femoral head from three orthogonal directions were obtained using a CCD camera (PL-A742, PixeLINK, Ottawa, Canada). The resolution of the CCD camera was 1280 × 1024 pixels.

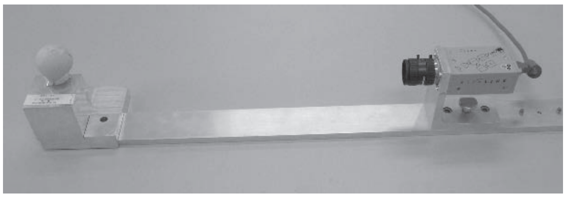


Fig.3 Photographic device.

2.2.2 Calibration

The projection matrixes were computed by the calibration [5]. Verification of the accuracy of the projection matrixes was performed using the following procedures. The calibration frame to which 30 spherical markers were attached (in a spiral orientation) was photographed from three orthogonal directions (sagittal, axial and coronal) using the CCD camera and the three orthogonal projection matrixes were computed (Fig.4). The coordinate value of the marker reconstructed from the projection matrixes was compared with the coordinate value of the marker measured by a 3-D coordinate measuring machine (BH504, Mitutoyo, Kawasaki, Japan) to within 1.0 µm of accuracy and the error was calculated. The average error was found to be within 0.01 mm and the maximum error was within 0.24 mm (Table 1).

Table 1 Calibration Errors of three orthogonal directions.

	X-axis	Y-axis	Z-axis
Maximum	0.17mm	0.24mm	0.11mm
Minimum	-0.08mm	-0.16mm	-0.19mm
Ave.*	-0.01mm	0.02mm	0.01mm
S.D.**	0.11mm	0.13mm	0.11mm

*Ave: Average
** S.D.: Standard Deviation

2.2.3 Image-matching

Image-matching using RGB images of the femoral head in the three orthogonal directions and a 3-D bone model was performed by image processing. The procedure is schematically shown in Fig.5. In the initial part of the process, color decomposition was performed on the RGB images and automatic contours extraction processing [6] was performed on the B-image until a clear concentration difference was observed between the femoral head and the background. Then, image-matching between the 3-D bone model and the B-image was performed by the downhill simplex method, which is a multidimensional optimization method that utilizes contour information (Fig.6). In the model bone, the original position of the parallel jig coordinate system was computed based on the coordinate values of the femoral markers (analysis values).

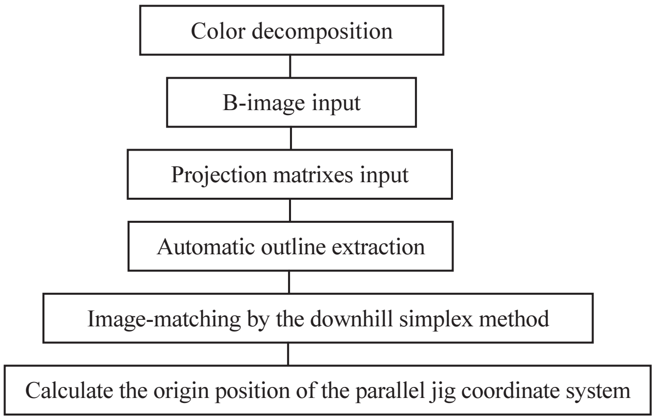
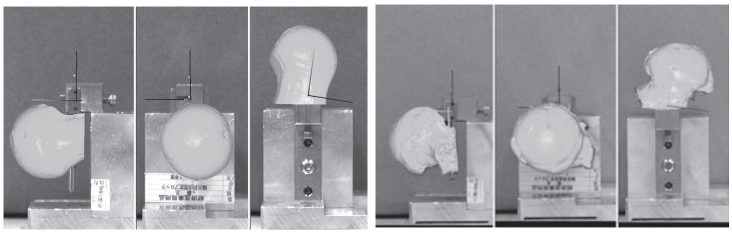


Fig. 5 Flow diagram showing image-matching stages.



(a) Model Femur (c) Actual femoral head

Fig.6 Image-matching processing.

2.2.4 Accuracy validation of image-matching

Verification of the accuracy of the image-matching was performed for the three model bones. The coordinate values for the parallel jig and three ball markers were measured using the 3-D coordinate measuring machine (Fig.7), and the original position of the parallel jig coordinate system was computed (true value). The mean squared error was calculated from this true value and the analysis value.

However, the validation of the accuracy of the above-mentioned method was difficult using the excised femoral heads. Thus, a six-degree-of-freedom board was used to validate the accuracy of the excised femoral head image-matching. The method performed image-matching to the femoral head rotated in the direction of the y-axis at 0 degrees, 3 degrees, 5 degrees, and 7 degrees (Fig.8) and the coordinate value of the 3-D bone model was computed. The error in both translation and rotation was calculated based on the bone model-coordinate value of 0 degrees.

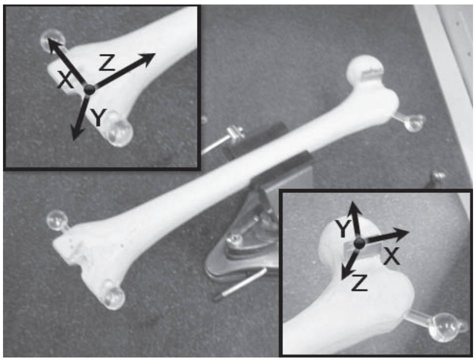
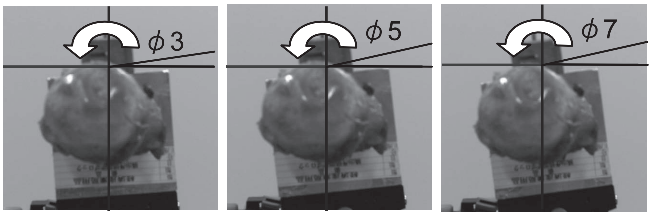


Fig.7 Three-dimensional measuring technique.



3 degrees 5 degrees 7 degrees

Fig.8 The femoral head rotated at arbitrary angles.

3. Results and Discussion

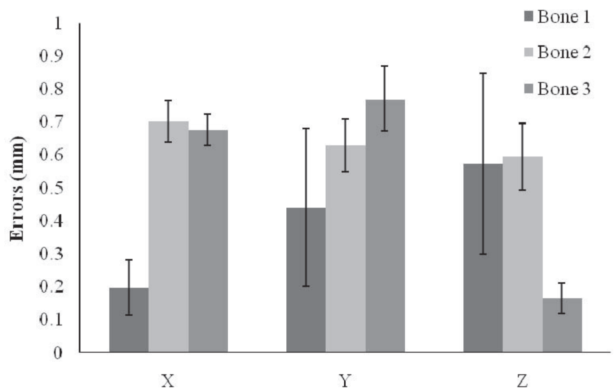
Translational and rotational maximum errors of the model femora and the excised femoral heads were calculated from the jig coordinate system. The translational maximum errors of the model femora were 0.75 ± 0.06 mm in the x-axis, 0.77 ± 0.10 mm in the y-axis and 0.59 ± 0.10 mm in the z-axis, while the rotational maximum errors were 0.75 ± 0.03 degrees in the x-axis, 0.71 ± 0.08 degrees in the y-axis, and 0.72 ± 0.10 degrees in the z-axis (Fig.9). Moreover, it was found that the translational and rotational errors of the excised femoral heads were within 1 mm and 1 degree, respectively (Fig.10). The cause that variations produced to the error of each angle is because outline information to use for image-matching was affected by the soft tissue. We think that it's necessary to add the operation to remove influence of some soft tissues in future.

In conventional research, image-matching between RGB images and a 3-D bone model is usually performed using reference points such as the center of the femoral head, the femoral neck and the fovea [7-8]. However, such research is fraught with problems such as calibration imprecision and lack of reproducibility. Therefore, a spiral type frame was developed for use in calibration. Moreover, in order to improve reproducibility, automatic contour extraction and the downhill simplex method were utilized for image-matching.

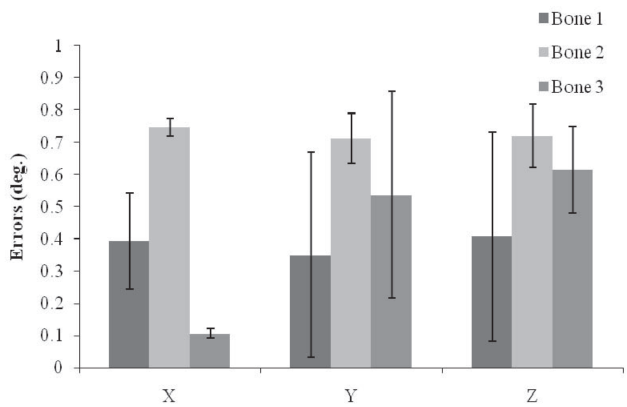
As a result, the errors in image-matching were reduced to within 1 degree for rotation and to within 1 mm for translation. Processing time from image photography of the femoral head to image-matching was also reduced to less than 3 minutes. Kai et al (2007) developed image-matching method that used the reference points of the femur [7]. However, their method was not automatic, and the translational errors were more than 3mm. Thus, our automated image-matching method offers better accuracy and time efficiency than conventional methods.

Our methodology using the excised femoral head is also safe and hygienic. The excised femoral head with its cartilage defects and bone deformation is suitable for CT modeling. Furthermore, it is noninvasive and the controlled stem setting method during THA using image-matching is suitable for most clinical applications.

Future aims include shortening the processing time and data accumulation with improvements in both the photographic device and software. In addition, we plan to produce a new jig to allow us to set a stem inside the femoral medullary cavity. The targeted value of the stem setting is errors range within 2degrees, 2mm needed in the clinical application.



(a)



(b)

Fig.9 Translational (a) and rotational (b) errors between the analysis value and the true value using automatic image-matching.

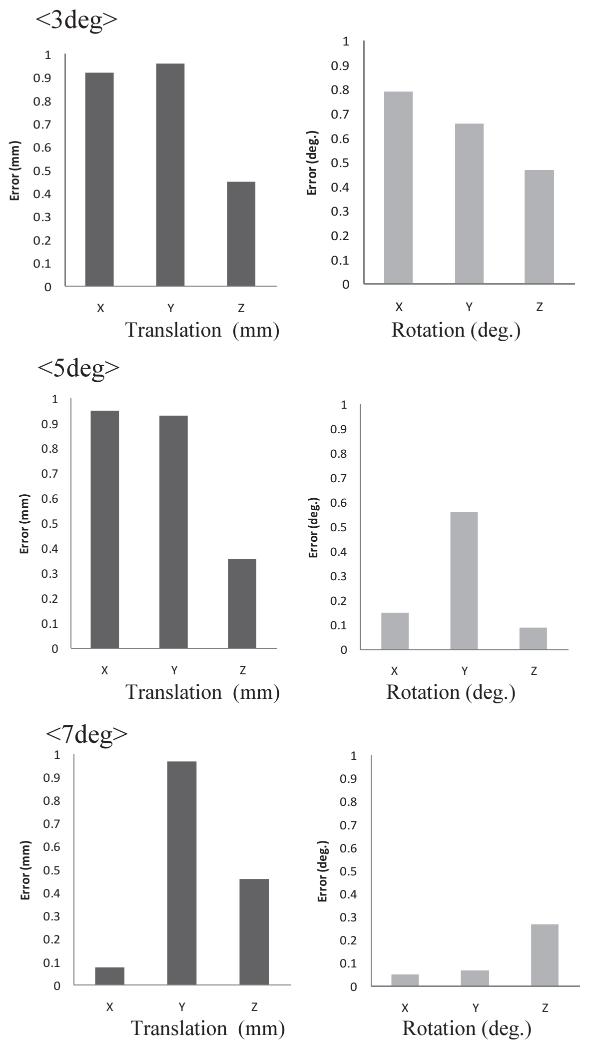


Fig.10 Translational and rotational errors of the excised femoral heads.

4. Conclusion

We have developed a more controlled stem setting method during THA using the 3-D leg alignment assessment system, and we have validated the accuracy of the image-matching. Our results can be summarized as follows:

(1) The image-matching between our 3-D bone model and the femoral head image was processed using the downhill simplex method. As a result, the translational errors of the model femora were 0.75 ± 0.06 mm in the x-axis, 0.77 ± 0.10 mm in the y-axis and 0.59 ± 0.10 mm in the z-axis, while the rotational errors were 0.75 ± 0.03 degrees in the x-axis, 0.71 ± 0.08 degrees in the y-axis, and 0.72 ± 0.10 degrees in the z-axis. In addition, the translational errors for the excised femoral heads were within 1 mm and the rotational errors were within 1 degree.

(2) Calibration was processed using a spiral frame. As a result, errors were minimized to within 0.01 mm of the average errors and the maximum error was limited to 0.24 mm.

(3) The photographic device for the femoral head that we developed can take images from three orthogonal directions using the CCD.

In conclusion, we have developed an accurate method for stem setting using a femoral 3-D bone model and B-images of the femoral head.

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