

## 2D-3D GA MATCHING BETWEEN CT AND ROENTGEN IMAGING OF SCAPULA FOCUSING ON ACROMION AND ANGULUS INFERIOR

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**ABSTRACT.** *A dynamic 3D motion analysis of bones in vivo is one of very interesting themes. We used GA (genetic algorithm) for 2D-3D matching of 3D position and rotation of a scapula and a 2D contour of a scapula in a Roentgen image as a previous research. The name of our software is GANESHA (Genetic Algorithm with Numeric Engine for SHoulder Ability). Our system measures position and rotation (6 DOF) of a scapula. However, a search in 6-dimension space is very difficult. We here propose a method to measure 2 DOF with fixed 4 ( $= 2 \times 2$ ) DOF. 4 DOF are calculated from 2D positions of an acromion and an angulus inferior which are observed with stability in Roentgen images and are pointed by user operations. It is easier for users to search in 2D space than to search in 6D space.*

**Keywords:** Shoulder joint, Scapula, 3D space analysis, 6 DOF, Dimensionality reduction

**1. Introduction.** A dynamic 3D motion analysis of bones in the living human body is one of interesting issues for health science and surgical treatment. A scapula plays one of important roles in a shoulder joint. However, a scapula has a pale shadow in Roentgen images. So it was difficult to extract 6 DOF (degrees of freedom) of a scapula automatically. We noted that the scapula resembles a flat triangle plate in 3D. Especially positions of an acromion and an angulus inferior of a scapula as two of three angles of a triangle are easy to find in 2D Roentgen images. So we propose to search 2 DOF with fixes 4 DOF (two by 2D positions of an acromion and an angulus inferior) in the process to identify 3D positions and 3D directions of a scapula. It is easier to search 2 DOF than to search 6 DOF.

Voight and Thomson [1] reported that the role of the scapula and rotator cuff tendon is significant in rehabilitation after shoulder injury. Sugamoto [2] pointed out that three dimensions of bone and joints have important meaning in rehabilitation. Oyama et al. [3] measured the motion of the scapula with a magnetic tracking device attached to the surface of the body. Seitz et al. [4] measured the motion of the scapula in motions such as pitcher pitching in professional baseball using a magnetic tracking device. Seitz et al. showed the results that the standard error was 1.9 degrees. However, the measurements of Oyama et al. and Seitz et al. are the dynamics of the body surface. There are fat and muscle between the scapula and the surface. The measured values are different

from the true position and direction of the scapula. Nagamoto et al. [5] used MRI to determine the three-dimensional position and orientation of a living human vertebra. In addition, Fujisawa et al. [6] measured the scapula using MRI. An MRI used by Nagamoto and Fujisawa needs much time to take one imaging. Therefore, the data of imaging by MRI imaging is insufficient for Voight, Sugamoto, and Oyama to know the desired bone dynamics.

Yamazaki et al. [7] proposed a method to measure the motion of artificial knee joints by performing 2D-3D matching on the roentgens of the artificial knee joints in the knee. In addition, Nakajima and Ikebuchi [8] proposed a method of 2D-3D matching of Roentgen and CT images of the shoulder blade using ES (evolutional strategy) approximating GA.

Although 2D-3D matching of bone has been proposed in the past, the scapula has a special situation among bones. Since the scapula has less calcium, the X-ray image has a low derivative value of the contour. Furthermore, when the standing position is photographed from the front, it often overlaps the calcaneal rib or clavicle, and the contour is determined by differentiating from the image. In addition, contours of ribs and clavicle appear strongly at derivative values higher than the threshold, and it is difficult to extract contours of the scapula alone. Therefore, it is necessary to perform model-based matching using ES and GA in order to correct errors due to them.

In order to use GA and ES for 2D-3D matching with X-ray images and Roentgen images, it is necessary to place a 3D model outline in a place close to the outline of the target bone in the Roentgen image as its initial value. However, since 3 DOF models generally require 6 DOF, it is necessary to specify 6 parameters. However, manually specifying the numerical values of these parameters is a difficult task as it is a search in a six-dimensional space until the contours match. Therefore, the authors focused on the acromion and lower horn that can be detected visually even in the Roentgen image from the front. The two-dimensional parameters of these two parts can fix 4 DOF. Then we propose a method to manually search for 2 DOF by combining it with 1 DOF of anterior-posterior-posterior-fold and 1 DOF of rotation angle around acromion-angulus inferior axis, and correct manual error by automatic search using GA. Ikeda et al. [10] only used automatic search, and in this method, it was possible to analyze the scapula easily and accurately by adding manual search to the previous step of automatic search.

Matsuki and Wada [9] measured the posture of the scapula by driving lead beads into the scapula. Contours of beads are sharper and easier to measure than the contour of the scapula, but the surgical insult that strikes the bead is a drawback. Our work need not lead beads and can be applied to human bodies in vivo. Ikeda et al. [10] measured 6 DOF of artificial ankle joints from two-view X-ray images. Their targets were artificial joints with sharp edges. Comparatively we applied our method to shadows of scapulae with pale edges. And our method need not two-view but one-view. It is one of advances of our method, too.

This paper is organized as follows: Section 2 describes our method. Section 3 describes an experiment on CG scapula images and an experiment on Roentgen images in vivo, and Section 4 shows a consideration. Section 5 describes conclusions.

**2. Method.** GANESHA is a software that we developed. A medical staff of orthopedics and rehabilitation operates it and gives initial values of 6 DOF. After that GA automatically finds out the best matching of differential of a Roentgen image and CAD edges from CT data.

**2.1. Manual designation of shoulder and lower corners.** An example of a radiograph taken of the human scapula is shown in Figure 1. The shadows of the ribs are so sharp that the position of the scapula is hard to find. However, if operator looks carefully, he (she) can find a margo medialis (i.e., an inside edge of a scapula).



FIGURE 1. Roentgen of chest

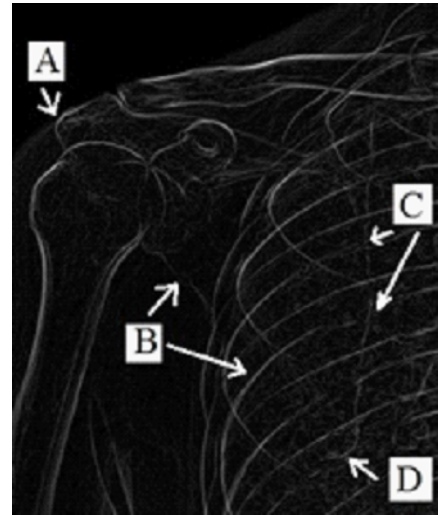


FIGURE 2. Differential of Roentgen

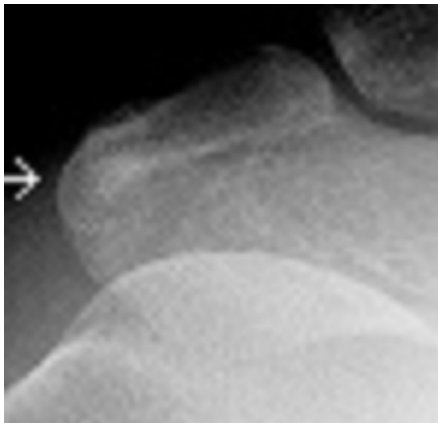


FIGURE 3. Acromion

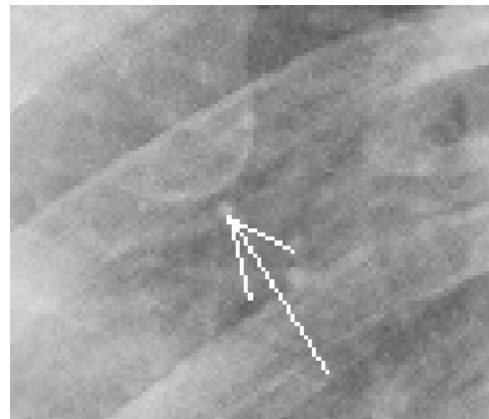


FIGURE 4. Angulus inferior

Figure 2 shows a differential image. The image has value of the root of the sum of squares of Sobel differentials in the horizontal and vertical directions. ‘A’ shows an acromion. ‘B’ shows a margo lateralis. They partially overlap with ribs. Then it is difficult to extract its total line. ‘C’ shows a margo medialis. However, the outline of the margo medialis is broken because the change in pixel value of an outline of a rib is larger than the change of it. ‘D’ shows an angulus inferior. There are an angulus superior (an upper corner) and upper edges in the scapula, but they overlap the contours of ribs and a clavicle (i.e., a collarbone) and are difficult to find out. The arrow in Figure 3 shows the tip of the enlarged acromion. An angulus inferior and other shapes are shown in the arrow in Figure 4. These two can be easily distinguished from other bones.

Figure 5 shows that the X-ray and CT data contours are superimposed in GANESHA. The surfaces of CT data are converted to STL form of a set of small triangle pieces (facets) by the software MIMIC made by MATERIALIZE Inc. In our method, these facets are projected by perspective manner along the X-ray with imaging parameters (focal length and DPI), and the boundary between the background area and the projected area (occlusion contour) becomes a contour. Figure 5 in this paper is a monotone image, but in the software, the Roentgen image is monotone, and the contour of the scapula is green. This CT data were measured from the subject before a measurement. By superimposing this one CT on several Roentgen images, 6 DOF of CT can be obtained for each Roentgen image. The user can use the mouse to specify the acromion and lower corner positions on

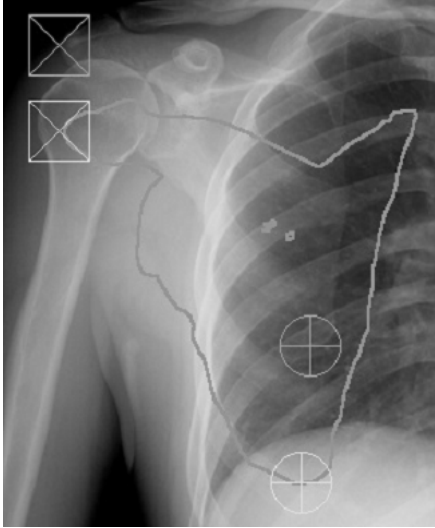


FIGURE 5. Points of acromion and angulus inferior

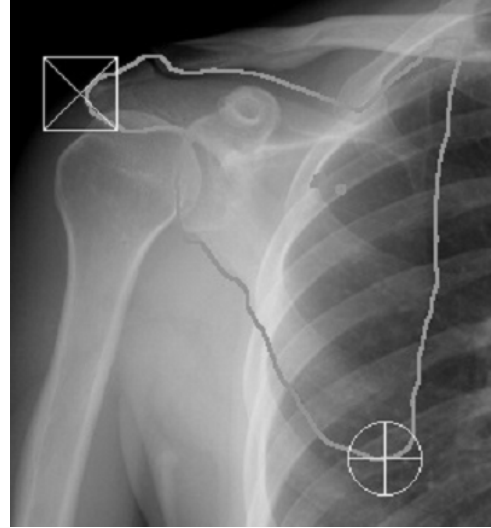


FIGURE 6. Translation and rotation of CT using acromion and angulus inferior

the Roentgen, and the acromion and the angulus inferior on the CT are the outermost ends of the CT data. The leftmost point for a left shoulder and the rightmost for a right shoulder are acromia. The lowest point is an angulus inferior. When a scapula slants or tilts, the lowest point of scapula in 2D Roentgen image is slightly different from the projected point of the bottom of 3D scapula in CT data. However, a 3D shape of a scapula is almost similar to a flat and triangular plate, we think that we can neglect these differences. This is a special case due to the shape of the scapula. And these small differences are corrected by the automatic matching after. Here, a 3D position vector identified as an acromion in CT data is  $\mathbf{V}_a$ , and a three-dimensional vector identified as an angulus inferior is  $\mathbf{V}_i$ . Let the 6 DOF parameters of this position and direction movement be  $(x, y, z, \alpha, \beta, \gamma)$ .  $(x, y, z)$  is a 3D translation vector in world coordinates, where a variable  $x$  is the  $x$ -axis of the Roentgen image and in the frontal Roentgen parallel to the lateral and positive towards the right. A variable  $y$  is parallel to vertical and positive down,  $z$  is parallel to AP (antero-posterior) and positive to the patient's back.  $(\alpha, \beta, \gamma)$  is a rotation angle vector. A variable  $\alpha$  is an angle around the lateral axis (sagittal plane). A variable  $\beta$  is for vertical axis (transversal plane). A variable  $\gamma$  is a rotation angle around AP axis (coronal plane). The  $(x, y)$  coordinates are in the same direction as the  $(XY)$  coordinates of the X-ray image. Among them, the movement with designating the acromion and the lower corner does not change  $\alpha$  and  $\beta$  but changes the other four parameters. Let  $\mathbf{v}_a$  and  $\mathbf{v}_i$  be the two-dimensional vectors of the results of perspective projection of  $\mathbf{V}_a$  and  $\mathbf{V}_i$  on the Roentgen image plane respectively. A vector  $\mathbf{v}'_a$  is a 2D position vector of the angulus inferior found in Roentgen image. A vector  $\mathbf{v}'_i$  is a 2D position vector of the acromion found in Roentgen image. A distance  $|\mathbf{v}_i - \mathbf{v}'_i|$  is the distance between the vectors  $\mathbf{v}_i$  and  $\mathbf{v}'_i$ . A distance  $|\mathbf{v}_a - \mathbf{v}'_a|$  is the distance between the two-dimensional position vectors  $\mathbf{v}_a$  and  $\mathbf{v}'_a$ .

$$d = |\mathbf{v}_a - \mathbf{v}'_a|^2 + |\mathbf{v}_i - \mathbf{v}'_i|^2 \quad (1)$$

The value of  $d$  in Equation (1) is minimized, and  $(x, y, z)$  and  $\gamma$  are determined by the steepest gradient method, but it is necessary to determine two more DOF.

Figure 7 shows a side view of the CT data of the scapula. Figure 7(a) shows the scapula seen from the side of the human body during CT imaging, and the arrow indicates one of the CT coordinate axes. In Figure 7(a), the horizontal direction of the figure is the antero-posterior axis of the human body, but the posture when lying on the CT bed and

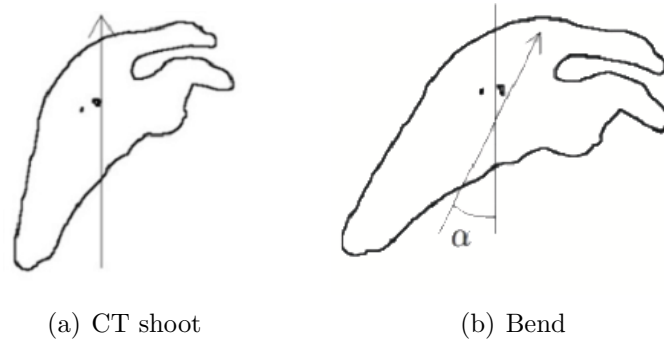


FIGURE 7. Angle of scapula around lateral plane

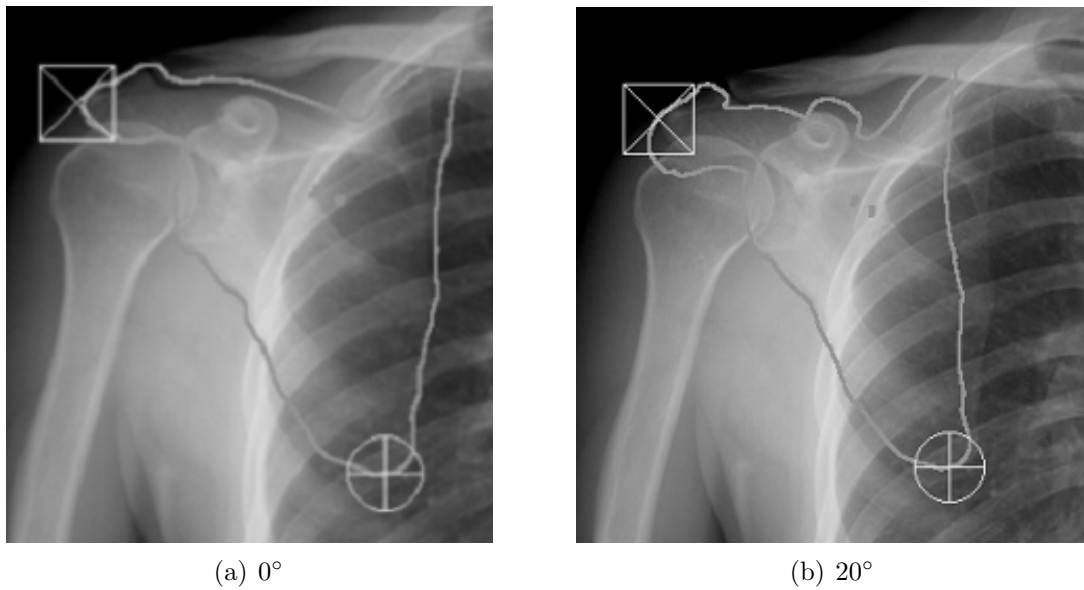


FIGURE 8. Rotation  $\delta$  around axis of acromion and angulus inferior

when taking a Roentgen is different from Figure 7(b). The vertical line in Figure 7(b) shows the line along the vertical axis in the X-ray image plane, the horizontal axis is the direction of the X-ray line. The X-ray body is bent forward at an angle of  $\alpha$  from the vertical axis when taking a CT. An operator can designate the best  $\alpha$  in order to align the CT contour with the outline of the scapula in this X-ray image. In the process of Figure 5, this  $\alpha$  remains unchanged at 0. After this, one more DOF must be specified. The rotation angle  $\beta$  around the vertical axis of the subject is specified at  $(x, y, z, \alpha, 0, \gamma)$  specified in Figure 5 and Figure 7  $(x, y, z, \alpha, \beta, \gamma)$ . The positions of the acromion and the angulus inferior move, so if you specify the rotation angle  $\delta$  around the 3D (acromion-angulus inferior) axis with the GANESHA GUI, the 6 DOF of the scapula shown in Figure 8 is calculated again the most appropriate  $(x', y', z', \alpha, \beta', \gamma')$  satisfying  $\delta$  while preserving the positions of the acromia and angulus inferior, and  $\alpha$  in Figure 7 as a new 6 DOF. The values of  $\alpha$  and  $\delta$  are specified by an operator. The operator may change the values of  $\alpha$  and  $\delta$  for CT contour to be close to the curve of the margo medialis shown as C in Figure 2.

$$g_i(x) = \sin(x/a) \exp(-x^2 / (2\sigma^2)) \tag{2}$$

The central part of the shoulder blade data of CT is thin in calcium, so holes are sometimes opened during CAD data conversion as blobs shown in the center of Figure 7(a) near the vertical line. However, they are artifacts and not real holes.

2.2. **Automatic matching by GA.** After the initial 6 DOF obtained manually, these are automatically optimized by GA. The evaluation is matching of the CT contour to overlap the 2D outline of CG of the 3D scapula CT data and differential of the Roentgen image. The software calculates by convolution of the pixel values of the Roentgen image and the Gabor function as shown in Figure 10(a) along a normal line as shown in Figure 9. The convolution means a matching of the contour and the differential.

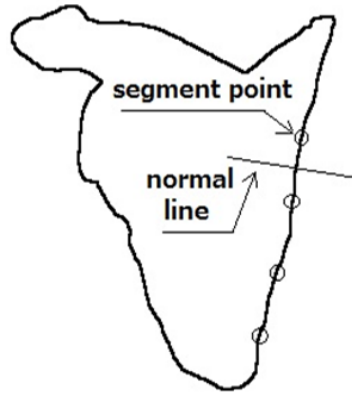


FIGURE 9. Contour of CT and normal line

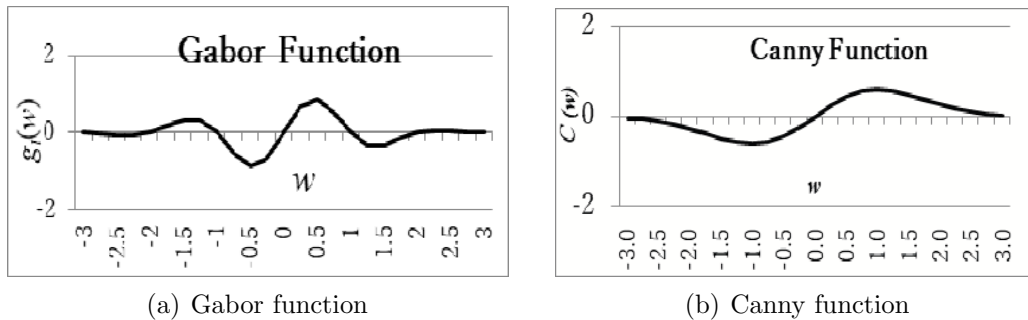


FIGURE 10. Filtering function

The contour of the CT data is projected onto the Roentgen image plane with 6 DOF as shown in Figure 9. In the calculation of the adaptation value, only the part of the outermost contour is calculated, so the presence of the middle hole does not affect the calculation. It is chain coded and divided into segments so that the number of chain codes is uniform. The segment points in Figure 9 are the division locations of this chain code. On the normal line, software calculates the convolution. The average of convolutions over the segments of the contour becomes the fitness value of the 6 DOF.

In Equation (2),  $a$  and  $\sigma$  are constants, which are determined by the state of the blur in Roentgen image. The width of  $-2.0$  point from  $2.0$  point of Gabor is similar to the blurred contour of the scapula in Roentgen. The influence of ribs is relatively small because the Gabor function direction is different from a differential direction of the ribs. There is also a Canny function used to detect boundaries, but because Gabor seems to be more suitable than Canny for the shape of blurred images. The Canny function shown in Figure 10(b) is a derivative of the Gaussian function. In the Gabor function, positive/negative inversion occurs in the sine function, and even if there is a part of a rib bone, the evaluation neglected it. The genes of the GA system are 6 DOF vectors of  $(x, y, z, \alpha, \beta, \gamma)$ , and a mutation is an addition of Gaussian random numbers to each element of 6 DOF in a manner of ES (evolutionary strategy). Crossing is mixture of two 6 DOF vectors  $o$  and

$o'$ . The software generates uniform random numbers  $r$  from 0.0 to 1.0. A new 6 DOF vector  $o''$  becomes a new individual.

$$o'' = ro + (1 - r)o' \quad (3)$$

The GA system evaluates fitness values of the new individuals of the next generation with the new 6 DOF value after mutation and crossover, etc. The order of the new individuals is re-sorted in order to fitness values by bubble sort. The fitness value is high if the lines of the segments are on the bone contour on the Roentgen image, and is low if the lines of the segments are far from the segment. GA system with several generations increases the fitness of 6 DOF of individuals. If the best fitness of a individual becomes similar to the global maximum, then the 6 DOF of the individual becomes similar to the true 6 DOF of scapula in the Roentgen image.

**3. Experiments.** We tried two experiments. One is an experiment of CG images made from CT data of a person. The other is an experiment with a Roentgen image of a person and CT data of the same person.

**3.1. 1st experiment with CG data.** Figure 11 shows CG synthesized images of CT data taken from a healthy person. Each position is between the original position  $\pm 30$  mm along 3 axes, and each direction data  $0. \pm 20^\circ$  around 3 axes, respectively, because the orthopedists and rehabilitation doctors that we know said that they are appropriate ranges for motions of scapulae in daily life.

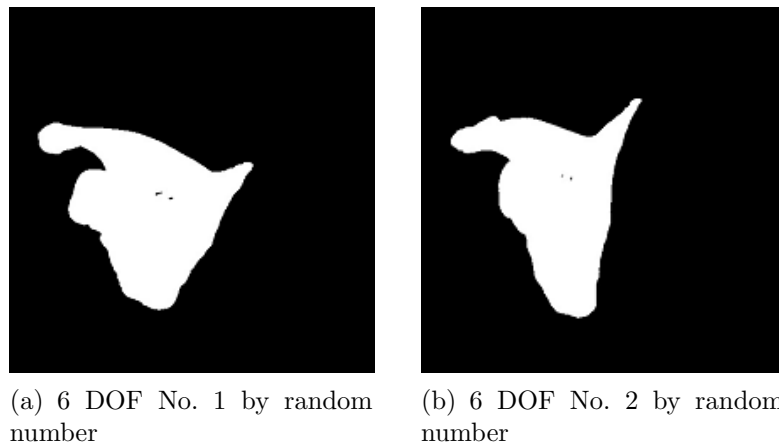


FIGURE 11. CG using real CT

We created 10 CG images, gave them to 3 operators only the image without notifying the original 6 DOF. We calculated the root mean square error (RMSE) of the difference between the original 6 DOF and their result. The RMSEs are shown in Table 1. The lateral, vertical, and AP in Table 1 are the axes ( $x, y, z$ ) of the patient at the time of radiography. The RMSEs of in-plane ( $x, y$ ) position were less than 1 mm. And the RMSE of out-plane ( $z$ ) position was less than 2 mm. The RMSEs of angles (sagittal, transversal and coronal) were less than  $2^\circ$ . The coronal plane was nearly equal to Roentgen plane because the X-ray origin was in front of a human. A scapula is like a triangle plate

TABLE 1. RMSE with CG image

position	lateral	vertical	AP
RMSE (mm)	0.218	0.420	1.87
rotation	sagittal	transversal	coronal
RMSE ( $^\circ$ )	1.09	1.27	0.758

parallel to the Roentgen plane. The shape of scapula in Roentgen image does not change by coronal rotation ( $\gamma$ ) but only rotates in image plane. However, the shape of scapula in Roentgen image changes by sagittal ( $\alpha$ ) or transversal ( $\beta$ ) rotations. Then the positions of edges of a scapula is proportional to  $\cos(\alpha)$  or  $\cos(\beta)$ . Changes of positions of edges of a scapula are proportional to  $\sin(\alpha)$  or  $\sin(\beta)$ . The changes of a shape of a scapula by  $\alpha$  and  $\beta$  are little when both  $\alpha$  and  $\beta$  are little ( $\approx 0$ ).

**3.2. 2nd experiment with Roentgen image in vivo.** Figure 1 is a Roentgen image of one of the authors. 3 persons of Osaka City University Hospital operated with an image of Figure 1 using the proposed method. Total operations were 10 trials. Image in vivo did not have a ground truth. So Table 2 shows only standard deviations (SD) around the averages.

TABLE 2. SD with in vivo Roentgen

position	lateral	vertical	AP
SD (mm)	1.52	1.74	5.48
rotation	sagittal	transversal	coronal
SD ( $^{\circ}$ )	1.12	0.662	0.930

**4. Consideration.** We [8] reported that the in-plane RMSE was 0.913 mm using an old version of GANESHA. The values of RMSE of distances along the lateral axis and the vertical axis in Table 1 are better than it. Matsuki and Wada [9] used lead beads in cadavers. The 2D-3D matching of CT was performed with the bead position as the ground truth. Matsuki's out-plane (AP) error was 4.6 mm. Matsuki's in-plane (lateral and vertical) error was 0.4 mm. Matsuki's rotation error was 3.0 degrees. Results of our first experiment are equal or more accurate than Matsuki's work. However, in-plane values of SD of positions of our 2nd experiment are three times or four times multiple of Matsuki's work. The values of SD of direction of our 2nd experiment are similar to RMSE of our 1st experiment. David Walker's targets were solid silhouettes of reverse total shoulder arthroplasties (RTSA, i.e., RSA) with sharp edges. The RMSE of position was improved compared with our previous report [8]. We do not use lead beads in bones when Matsuki and Wada [9] used them. So our method can be applied alive persons. We applied our method to pale scapula images different to artificial joints by Ikeda's method [10]. Ikeda's method needs two-view Roentgen image. However, our method needs only one-view Roentgen image.

**5. Conclusion and Future Works.** We proposed an effective method, i.e., new version of GANESHA for determining the position of the scapula in the Roentgen image with decreasing dimensions from 6D to 2D using positions of an acromion and an angulus inferior in a Roentgen image when operating manually determines initial values of 6 DOF before GA.

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