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Paper:

Fuzzy Visual Hull Algorithm for Three-Dimensional Shape Reconstruction of TKA Implants from X-Ray Cone-Beam Images

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Three-Dimensional (3-D) shape reconstruction of total knee arthroplasty (TKA) implants *in vivo* plays a key role to investigate implanted knee kinematics. TKA implants typically consist of metal femoral and tibial components and a polyethylene tibial insert. X-ray computed tomography (CT) causes severe metal artifacts, making the 3-D shape in reconstructed images extremely difficult to understand. This article proposes a new method of 3-D reconstruction from X-ray cone-beam images. Called a fuzzy visual hull, it introduces fuzzy logic in recognizing X-ray images. X-ray cone-beam images are fuzzified and back-projected into a fuzzy voxel space. Defuzzifying the fuzzy voxel space enables the 3-D TKA implant shape to be reconstructed. The results of evaluation using TKA implants *in vitro* and computer-synthesized images demonstrated that the fuzzy visual hull provides high robustness against noise added to X-ray cone-beam images. The new approach also reconstructed the 3-D polyethylene insert despite the difficulty of recognizing the region in conventional X-ray CT.

Keywords: 3-D reconstruction, fuzzy logic, visual hull algorithm, total knee arthroplasty

1. Introduction

Total knee arthroplasty (TKA) is a surgical procedure replacing a damaged knee joint with artificial knee implants consisting mainly of a metal femoral component, a metal tibial component, and a polyethylene tibial insert. To diagnose and evaluate the implanted knee *in vivo*, researchers have studied 3-dimensional (3-D) post-TKA knee kinematics.

To evaluate these kinematics *in vivo*, some studies have used image registration using 2-dimensional (2-D) X-ray radiography [1–4]. They estimate the 3-D TKA implant positioning using 2-D/3-D image registration between 2-D X-ray images taking the implanted knee and a 3-D geometric model of the implant. The main limitation of image registration based methods is 3-D geometrical model use, because such models are available to only a very limited number of users, which is in part why few studies have discussed the clinical diagnosis of TKA cases.

3-D TKA implant positioning is also calculated by reconstructing the 3-D TKA implant shape *in vivo* from 3-D sectional X-ray images using tomographic reconstruction (TR) [5]. Medical imaging modality using TR is called X-ray computed tomography (CT). However, artifacts in X-rays are caused by the reflection of metal implant components corrupt CT images, and makes it difficult to recognize 3-D implant shapes from reconstructed 3-D images.

An alternative approach reconstructs the 3-D shape using the visual hull (VH) algorithm [6, 7]. VH has the advantages of correspondence between silhouette images unnecessary, implementing the algorithm easily, and minimizing calculation complexity. Reconstruction accuracy depends, however, on the segmentation accuracy from silhouettes. For TKA implant X-ray images, the implant contour is often unclear, making precise tibial insert contours, for example, difficult to determine. The VH algorithm alone thus cannot completely reconstruct the 3-D shape.

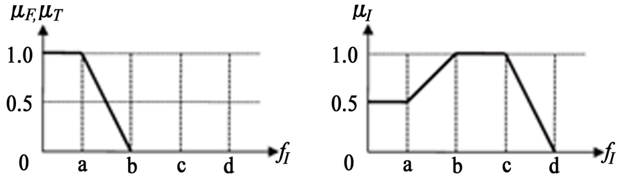
This article proposes a new 3-D TKA implant reconstruction method from X-ray cone-beam images. To reconstruct the 3-D shape from low-contrast and unclear-contour 2-D projection images, fuzzy logic [8] is introduced into conventional VH, called fuzzy visual hull (FVH).

2. Materials

X-ray images were acquired from a 3-D digital radiograph scanner, which acquires X-ray images rotating an X-ray source and an X-ray image intensifier around the

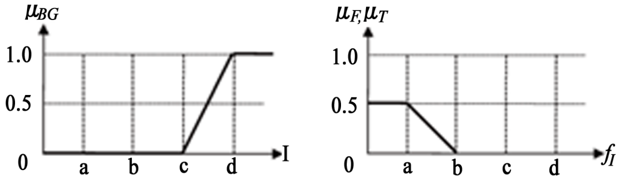
(a) #1/100 (b) #48/100 (c) #96/100

Fig. 1. X-ray images of TKA implants.



(a) Femoral and tibial components when case 1.

(b) Tibial insert.



(c) Background.

(d) Femoral and tibial components when case 2.

Fig. 2. Fuzzy membership functions.

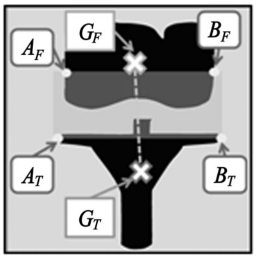


Fig. 3. Location Knowledge of TKA implant alignment.

object to be imaged. Acquisition parameters were a Field of View (FOV) of 512 mm, a matrix of 1024^2 pixels, an intensity stored in 16 bits, 100 images, a rotation angle of 100°, and a 1,000 mm distance between the X-ray source and image intensifier. Femoral and tibial components in X-ray images showed high contrast, although the tibial insert showed low contrast. **Fig. 1** shows an X-ray image of a TKA implant *in vitro*. Objects with poor X-ray transmission appear as low-intensity areas.

3. 3-D Reconstruction of TKA Implants Using FVH

3.1. Overview

VH [6, 7] reconstructs 3-D objects from multiple 2-D silhouettes by segmenting target regions from 2-D silhouettes and back-projecting segments onto a voxel space, such as a cone, with camera viewing parameters. The intersection of all back-projected cones is then extracted as a 3-D object. Reconstruction accuracy depends on the accuracy with which objects are segmented from individual silhouettes, because insufficient segmentation results in a lack of reconstructed 3-D volume. Unclear boundaries and low contrast, for example, may make it difficult to segment TKA implant contours from X-ray images accurately.

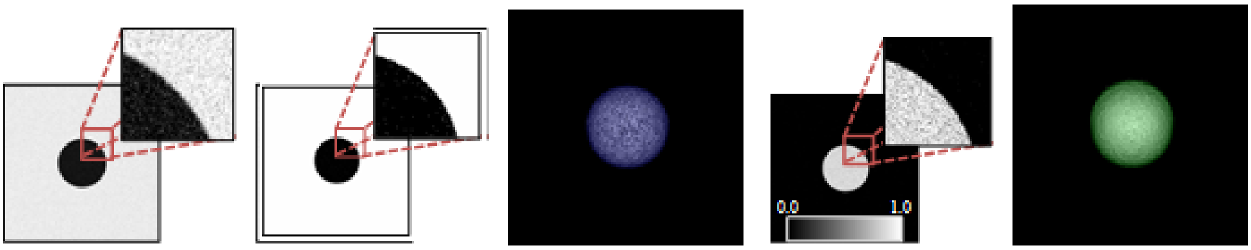
To reduce 3-D reconstruction dependence on segmentation accuracy, this article proposes FVH, based on conventional VH, and back-projecting fuzzy degrees onto a voxel space. The fuzzy degree represents the degree to which an object belongs to a pixel of interest. Introducing fuzzy logic into the VH decreases the work needed to segment accurate object contours and improves reconstruction accuracy robustness. The FVH algorithm consists of three steps;

1. Fuzzification of X-ray images.
2. Back-projection of fuzzy degrees onto a voxel space.
3. Fuzzy calculus in the voxel space and defuzzification.

3.2. Fuzzification of X-Ray Images

Fuzzification consists of calculating the fuzzy degree of objects for individual pixels in individual X-ray images, where objects are the femoral component, tibial component, tibial insert, and background. X-ray images are classified into two cases – case 1, femoral component separated from the tibial component, as in **Figs. 1(a)** and **(c)**, and case 2, femoral and tibial components overlapping, as in **Fig. 1(b)**. Regions of femoral and tibial components in case 1 are easily recognized, so we propose two methods of fuzzification. Fuzzification assigns individual pixels in X-ray images four fuzzy degrees for belonging to objects – as degrees of belonging to the femoral component, tibial component, tibial insert, or background. Fuzzy degree means the degree of object belonging, assigned a value between 1 and 0, with 1 meaning the pixel belongs completely to the object and 0 meaning the pixel does not belong in any way whatsoever to the object.

The tibial insert should be located between femoral and tibial components (location knowledge). The intensity of the tibial insert is assigned a value between the intensity of components and the intensity of the background (intensity knowledge). The fuzzy degree belonging to the tibial insert is thus calculated using location knowledge and intensity knowledge. Location knowledge is calculated using a tetragon as shown in **Fig. 3**. The four vertices – A_F, B_F, A_T, and B_T – are defined as the points furthest in the femoral or tibial component regions from a line connecting the center of gravity of the femoral component (G_F) and the center of gravity of the tibial component (G_T). The fuzzy degree belonging to the tibial insert as it relates



(a) (b) (c) (d) (e)

Fig. 4. Computer simulation results. (a) Synthesized X-ray image with a noise level of 2.0%. (b) Segmented region and (c) SSD image of the reconstructed 3-D object with conventional VH. (d) Calculated fuzzy degree and (e) SSD of the reconstructed 3-D object with the proposed FVH.

to location knowledge is calculated by:

$$\mu_{LOC}(P) = \begin{cases} 1.0 & \text{if } P \in \mathbf{T} \\ \max(1.0 - \delta(P) \times \varepsilon, 0.0) & \text{otherwise} \end{cases} \quad (1)$$

P is the pixel of interest, **T** is the set of points in the tetragon, and $\delta(P)$ is the function giving the Euclidean distance from pixel P to the nearest point of **T**. Intensity knowledge is utilized using the fuzzy membership function shown in **Fig. 2(b)**. f_I is the intensity of pixel P. The fuzzy degree belonging to the tibial insert as it relates to location intensity, $\mu_{INT}(P)$, is obtained. The fuzzy degree belonging to the tibial insert as it relates to location knowledge and intensity knowledge, $\mu_I(P)$, is calculated by:

$$\mu_I(P) = MIN(\mu_{LOC}(P), \mu_{INT}(P)). \quad . \quad . \quad . \quad . \quad (2)$$

The fuzzy degree belonging to the background, μ_{BG}, is calculated using the fuzzy membership function shown in **Fig. 2(c)** because low pixel intensity indicates a low amount of X-ray transmission between the X-ray source and pixel.

a. Case 1: Separated components

The fuzzy degree belonging to the femoral or tibial component at the pixel of interest is calculated by evaluating the intensity, because the pixel intensity corresponds to the amount of X-ray transmission between the X-ray source and pixel. For individual pixels in the segmented femoral component, the fuzzy degree belonging to the femoral component, μ_F, is calculated using the fuzzy membership function shown in **Fig. 2(a)**, where f_I is the intensity of the pixel of interest. In the fuzzy membership functions shown in **Figs. 2(a)**, **(b)**, **(c)** and **(d)** are defined using common parameters given manually by the user. For other pixels outside of the femoral component region, the fuzzy degree belonging to the femoral component is 0. The fuzzy degree belonging to the tibial component, μ_T, is calculated in the same way. Femoral and tibial component regions are segmented and labeled using a Region-Growing (RG) algorithm [9]. To discriminate among components, the user assigns labels manually in a silhouette image, and in subsequent silhouette images, discrimination is implemented automatically by tracking the center of gravity of segmented regions.

b. Case 2: Occluded components

Assigning a high fuzzy degree of belonging to components is difficult if femoral and tibial components occlude each other. Fuzzy degrees are calculated using the membership function shown in **Fig. 2(d)**. Other fuzzy degrees belonging to the tibial insert and background are calculated the same as in case 1.

3.3. Back-Projection, Fuzzy Calculus, and Defuzzification

To back-project calculated fuzzy degrees onto a voxel space with imaging parameters, the calculated fuzzy degree of belonging to the object is assigned to all voxels forming a cone space for each pixel in each X-ray image, defined by connecting an X-ray source and pixel contours. This is applied to all pixels in all X-ray images and for each target region, ensuring that for each voxel in the voxel space, fuzzy degrees are assigned in a number equal to the number of X-ray images.

Fuzzy calculus is used to calculate the fuzzy degree of a voxel as the degree of belonging to the object using multiple fuzzy degrees back-projected from multiple X-ray images. For each target object, the fuzzy degree is calculated by:

$$\mu_A(v) = \frac{1}{N}\sum_{i=1}^{N} \mu_A(v,i), \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

$\mu_A(v)$ is the fuzzy degree of belonging to object O_A $\in$ {femoral component, tibial component, tibial insert, background}. $\mu_A(v,i)$ is the fuzzy degree of belonging to object O_A back-projected from 2-D i-th X-ray image. Each voxel is then classified into an object with the highest fuzzy degree among the four fuzzy degrees.

4. Experimental Results and Discussion

4.1. Numerical Evaluation of FVH Algorithm

Performance in reconstructing 3-D objects using the FVH algorithm was validated using X-ray images synthesizing a ball with a radius of 40 mm. For each synthesized image, a Gaussian filter with a Full-Width Half-Maximum

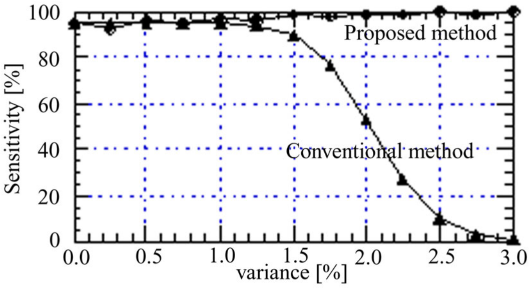


Fig. 5. Transition of segmentation accuracy of proposed and conventional methods with changing white Gaussian noise.

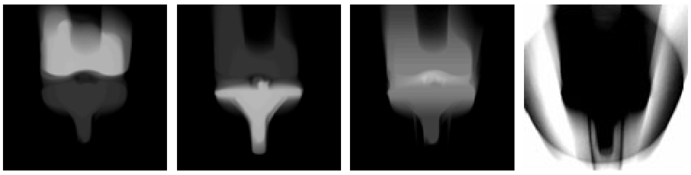


Fig. 6. Sectional images of fuzzy degrees. Left to right: femoral component, tibial component, tibial insert, and background at slice 225/440 in voxel space.

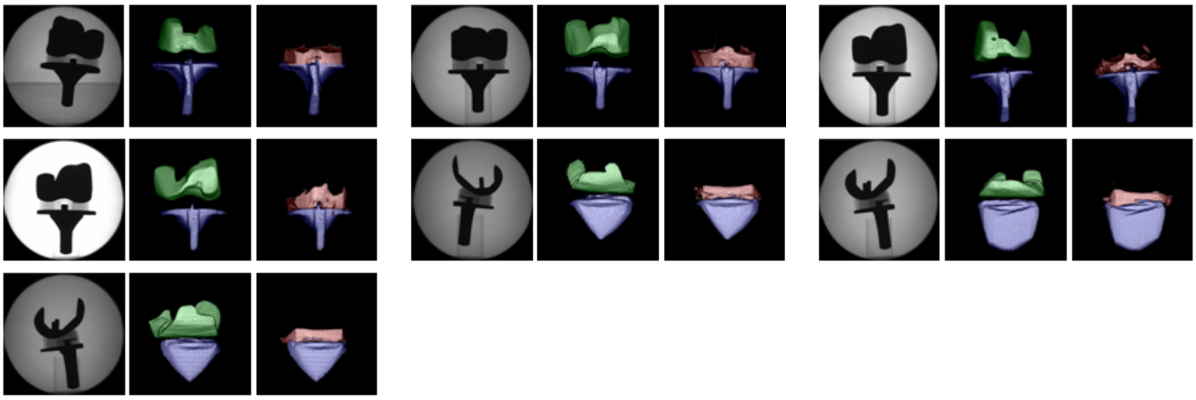


Fig. 7. 3-D reconstructed TKA implant with FVH. Left: Raw X-ray image. Center: Femoral and tibial components. Right: Tibial insert and component. Top left to bottom right: #1 to #7.

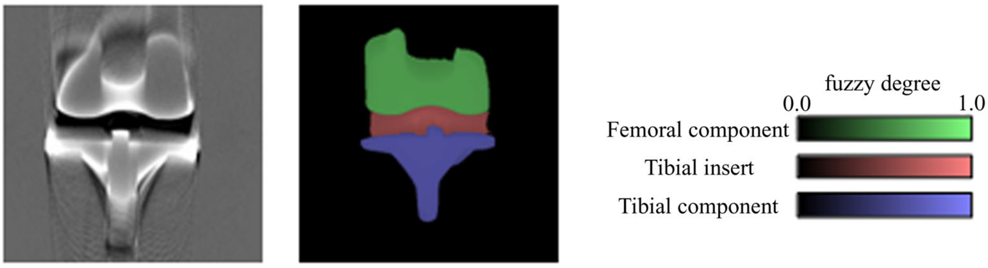


Fig. 8. Comparison with TR of dataset 2. Left: reconstructed sectional image with TR. Right: The same sectional image with FVH.

(FWHM) of 5 pixels was convoluted, and white Gaussian noise with a variance of $p\%$ added.

Figure 4 shows simulation results for a noise level of 2.0%. **Fig. 5** shows the transition of sensitivity using the FVH algorithm and conventional VH while changing the noise level. These results show that FVH provides high robustness against noise, which is added to X-ray images, compared to conventional VH. This is because the FVH algorithm calculates the fuzzy degree by integrating multiple X-ray images.

5. Performance of TKA Implant Reconstruction

The FVH algorithm was applied to 7 datasets of X-ray images using TKA implants *in vitro*. The TKA implant was fixed at a femoral rotation angle of $-10°$ (#1), 0° (#2, #5), 10° (#3, #6) or 15° (#4, #7) from normal positioning. **Fig. 6** shows sectional images of fuzzy degrees in the voxel space, and appropriate fuzzy degrees were assigned together with the shape of each component. **Fig. 7** shows surface-shaded display (SSD) images of the segmented TKA implant, which show femoral components rotated at the defined rotation angle. The FVH algorithm reconstructed the 3-D shape of the tibial insert despite the insert's occlusion by femoral and tibial components and appearing with low contrast in X-ray images.

FVH performance was then compared to TR, a type of reconstruction generally used for CT. **Fig. 8** shows a sectional image of the reconstructed 3-D voxel space with FVH and TR. Note that TR causes large artifacts on the right side of the implant due to the metal component, whereas FVH reduced artifacts dramatically and reconstructed the approximate 3-D shape well.

6. Conclusions

This study has proposed a new 3-D reconstruction method applicable to X-ray images of metal and polyethylene implants. This fuzzy visual hull (FVH) approach introduces fuzzy logic into the conventional VH algorithm. Computer simulation results show that FVH provides high robustness against noise added to X-ray images. FVH also reconstructs the 3-D shape of both the metal implants and the polyethylene insert. The main limitation of FVH is that convex 3-D shapes cannot be reconstructed, as with conventional VH. We thus intend to study the performance of reconstructing TKA implants *in vivo*. Using the FVH algorithm in clinical studies, we will also consider how to calculate numerical data such as flexion and rotation angles.

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