RESEARCH ARTICLE

Three-dimensional CBCT images registration method for TMJ based on reconstructed condyle and skull base

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Objectives: A method was introduced for three-dimensional (3D) cone-beamCT (CBCT) images registration of temporomandibular joint (TMJ). This study aimed to provide quantitative and qualitative analysis of TMJ bone changes in two-dimensional (2D) and 3D and to provide the technique for computer-aided diagnosis of temporomandibular joint disorders in the future.

Methods: 10 TMJ samples of six patients were obtained from Peking University Hospital of Stomatology. Four of the six patients imaged bilateral TMJs and the other two patients only imaged unilateral TMJ. Each sample consisted of two images from the same TMJ taken at different times. First, condyle and skull base were segmented semi-automatically for 3D model reconstruction. Then the segmented condyle and skull base were registered separately. Registration process can be divided into two processes of rough registration and fine registration. Rough registration step was achieved by selecting corresponding points manually and initialized fine registration. Condyle and skull base were fine registered by minimizing mean square error of condyle ($MSE_{condyle}$) and skull base (MSE_{skull}) respectively. Qualitative assessment of osseous component changes utilized 2D color-fused model and 3D surface-fused model and quantitative analyses the convergence of this method used the mean square error of the model (MSE_{model}). Independent repeated experiments were carried out to test the stability of our 3D registration method.

Results: Sufficiently alignment was achieved. Osseous abnormality and morphology changes were displayed using fusion model. MSE_{model} of condylar registration and skull base registration declined 51.80% and 64.58% compared with that before registration. Quantitative analysis verified the stability of the method.

Conclusions: The proposed method completed 3D TMJ registration for different physiological structure. The result of this method was accurate, reproducible and not relied on the experience of operators.

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Introduction

Temporomandibular joint (TMJ) is one of the most complex joint in human anatomic structures. TMJ osteoarthritis (OA) is a TMJ degenerative disease

virtually and belongs to TMD, and the osseous defects of condyles are the most important pathological changes. Generally, a clinical examination alone is insufficient to fully assess the osseous component changes of the TMJ.^{1,2} The defects of hard tissues of the TMJ were often diagnosed with CT and CBCT. However, CBCT

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has some advantages in detecting the bone defects of the condyles, such as the low radiation dose and high spatial resolution images for bone tissue structures when compared with CT and the conventional image modalities.^{3–7} Investigators had concluded that CBCT had a relatively high diagnostic accuracy for the detection of TMJ bone changes.⁸ Erosions are the radiographic performance of the early stage of TMJ degenerative disease,⁵ *e.g.* the bone defects will be enlarged, static or repaired. To observe such kind of bone changes, the researchers proposed that the registration of longitudinal scans of TMJ CBCT images could offer the information of the bone lesion progression and could also be applied for the assessment of growth, treatment outcome and stability after treatment.

2D image superimposing to evaluate changes in soft tissues, skeleton and dentition has been researched for many years. However, the 2D images suffered many limitations, such as tissue overlapping, landmark obstruction, distortion, magnification and object displacement.⁹ The contribution of 3D CBCT to the field of dentistry is significant especially for diagnosis, assessment of the hard tissues of the TMJ joint and quantitative analysis of tissue changes in angle and distance. For the diagnosis of TMJ degenerative disease, fused 3D CBCT images can offer the information of the bone lesion progression, increase the diagnostic accuracy by assessing trabecular architecture of the bony structures and observe the progression of osseous changes, which is superior to that of panoramic radiography and MRI.¹⁰

Image registration is a tool to realize the best match between two or more images by optimizing the image alignment criterion which is usually a cost function or a similarity measurement.¹¹ The existing registration methods can be divided into two major categories, which are marker-based methods and marker-free methods.¹² The main difference between the two methods is whether there are external markers fixed on patients before imaging. More accurate results can be obtained when the marks located on the skeleton not on the skin.^{13,14} The marker-based methods with many uncertainties are not precise enough and artificial markers attached on patients increase discomfort. In recent studies, more and more marker-free methods, such as point-based methods, surface-based methods, voxel-based methods and methods based on image statistical information.^{15–18} Image statistical information, such as mutual information (MI), is often involved in multimodal registration.^{19,20} Rigid registration often calculated moment, center of gravity and other characteristics as reference. These methods are more precise than marker-based registration methods, while computational difficulty is increased. Numerous methods based on histogram of the images have been proposed.^{21,22} This method register the histograms of the images to correct the uneven brightness, which make fused images more clearly.

The purpose of this study was to observe condyle changes in the progression of disease development and

treatment by registering 3D CBCT of TMJ. Comprehensive consideration of cost, matching transformation and accuracy, this paper introduced a method by manually selecting corresponding points to complete fast rough registration. Then fine registration is implemented by 3D rigid transformation for condyle and skull base which were divided and reconstructed before registration. The results showed condyle in different dimension and provided more comprehensive information.

Methods and materials

Data acquisition

10 TMJ samples of six patients were obtained using 3D Accuitomo 170 (J. Morita MFG. Corp., Kyoto, Japan). Four of the six patients imaged bilateral TMJs and the other two patients only imaged unilateral TMJ. Each sample consisted of two images from the same TMJ taken at different times. The image obtained earlier than the other was defined as fixed image. The datasets mentioned in this paper were agreed by patients. The exposure parameters were 90 kVp, 5 mAs. All of the images were acquired at the cusp dislocation with the field of view of $60 \times 60 \times 60 \text{ mm}^2$ in 3D. The interslice gap of samples is different. Three of them have an interslice gap of 0.125 mm ($481 \times 481 \times 481$ voxels) and others have an interslice gap of 0.375 mm ($481 \times 481 \times 161$ voxels). All available data sets were formatted in the digital imaging and communications in medicine (DICOM) standard as a series of 16-bit gray scale. In this paper, images scanned earlier were set as fixed image in the registration process.

The flow chart in [Figure 1](#) describes an overview of the image registration process, including segmentation, rough registration and registration. Registration process will be executed two times based on condyle and skull base. 2D color-fused model and 3D surface-fused model were created to express the results.

Segmentation and 3D reconstruction for condyle and skull base

Because of the existence of atomic scattering and other reasons, there is a lot of noise in the CBCT image which reduces the contrast of the organization and have influence on condylar segmentation. Separating skeletal structures from noise can eliminate interference for registration. First, an intensity threshold $I_0 = 500$ was defined which separated skeleton structure slice-by-slice. This threshold was chosen manually according to the different X-ray absorption coefficients of bone and muscle. Because the brightness of trabecular part is lower, some of the internal bone structure was treated as muscle tissue in the condyle, while this method is easy and can preserve bone edges. The raw image and processed image are shown in [Figure 2](#).

Image segmentation is the premise of the reconstruction of surface models to perform the regional

Figure 1 The flow chart of the whole registration process. It can be divided into three parts including image pre-processing, rough registration and fine registration. In 2D color-fused model (the picture in the lower left corner), bone changes can be analyzed by colour overlay. In 3D surface-fused model (the picture in the lower right corner) which aims to observe surface changes of bone, the green model is fixed condyle and the blue model is moving condyle.

registration, which used a deformable parametric curve to simulated contour boundary.²³ A rectangle was set as initial condylar contour on the first slice manually and then condyle and skull base can be separated automatically. The number of iterations I_{num} is set as $I_{num} = 1000$ and ideal segmentation effect can be obtained at each layer as shown in Figure 3. Enlarging iterations will add computing time and reducing iterations will make the result inaccurate. The results were saved as two DICOM data sets contained condyle and the skull base separately. The models with small interslice gap which means make up the mold with more slices will be segmented costing more time than the models with large interslice gap. Though interslice gap of the samples are different, the view of samples is same. After

3D surface reconstruction, the resolution in 2D has no effect on the result of segmentation. The reconstruction of surface models was performed using the VTK software (VTK-7.1.0, <https://www.vtk.org/>) to realize the 3D visualization and select the initial corresponding points. 3D reconstruction models of condyle and skull base were shown in Figure 4.

Rough registration

$$I'(x, y, z) = T(I_f(x, y, z)) \quad (1)$$

where $I'_f(x, y, z)$ is the transformed floating image and T is transform matrix.

Figure 2 Raw image data and extracted bone tissue is displayed in 2D and 3D. (a, b) Raw data cannot be investigated clearly. (c, d) Extracted bone tissue can preserve bone edges.

In order to implement fast rough registration, four pairs of corresponding points were selected manually on the reference condylar surface $P_{fn(n=1,2,3,4)}(x, y, z)$

Figure 3 The process of image segmentation based on active contour model. (a) The initial contour was represented by a red rectangle. (b, c) Correct segmentation in different slices. (d) False segmentation due to reducing iterations.

Figure 4 Reconstruction of the condyle in (a) and reconstruction of the skull base in (b).

and the floating condylar surface $P_{fn(n=1,2,3,4)}(x, y, z)$. Corresponding points also can be selected on the skull base models, while the condylar surface is simpler and easy to operate. By minimizing the average distance between the two-point sets, 3D rigid transformation matrix can be obtained. Floating image after transformation can be expressed as:

$$T_{point} = \begin{bmatrix} t_1 & t_2 & t_3 & d_x \\ t_4 & t_5 & t_6 & d_y \\ t_7 & t_8 & t_9 & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = T_{point} \begin{bmatrix} t_1x + t_2y + t_3z + d_x \\ t_4x + t_5y + t_6z + d_y \\ t_7x + t_8y + t_9z + d_z \\ 1 \end{bmatrix} \quad (3)$$

In the matrix T_{point} , $t_{1...9}$ are the rotation parameters, d_x, d_y, d_z are translation parameters. A total of 12 parameters are required to define the 3D rigid transformation. Point set $P_{fn(n=1,2,3,4)}(x, y, z)$ after transformation can be expressed as $P'_{fn(n=1,2,3,4)}(x', y', z')$.

The three pairs of reference points can be distributed randomly, which reduced operation difficulty and increased the repeatability of the method. Stable results can be achieved even if different point sets are selected. 3D surface reconstruction and the selected corresponding points are shown in Figure 5. Floating and reference points sets $\{P_{f1}...P_{f4}\}$ and $\{P_{r1}...P_{r4}\}$ were selected on the floating and reference images.

Figure 5 Four pairs of corresponding points were selected manually on the condyle surface. Even if one pair of corresponding points has deviation, it has no effect on the final result.

These points were corresponded as numbering in the figure. Rough registration can correct greater rotation and translation, whereas in applications more accurate results need to be achieved.

Fine registration

The fine registration procedure is divided into two parts. one of the parts consists of condyle only expressed as $I'_{fcondyle}$ and $I_{rcondyle}$ to show bone lesion. The other part consists of skull base only expressed as I'_{fskull} and I_{rskull} to show condylar displacement. Transformation parameter T_{point} of rough registration initialize fine registration. The final transform matrixes $T_{condyle}$ and T_{skull} were obtained using gradient descent method to minimum similarity measure. Mean square error of condyle and skull base ($MSE_{condyle}$ and MSE_{skull}) are set as similarity measure which can be calculated as:

$$MSE_{condyle} = 1/N \sum [T_{condyle} (I'_{fcondyle}(x, y, z)) - I_{rcondyle}(x, y, z)]^2 \quad (4)$$

$$MSE_{skull} = 1/N \sum [T_{skull} (I'_{fskull}(x, y, z)) - I_{rskull}(x, y, z)]^2 \quad (5)$$

where $T_{condyle}$ and T_{skull} are 3D transform matrix, $I'_{fcondyle}(x, y, z)$ and $I'_{fskull}(x, y, z)$ are transformed floating images and is image size.

Science the same tissue's absorption coefficient of X-ray is invariable. In theory, the $MSE_{condyle}$ and MSE_{skull} will be the 0, when the same images are fully aligned. In fact, radiation dose and the development of disease make there is no uniform minimum $MSE_{condyle}$ or MSE_{skull} and each case has its own minimum value.

The method in this paper used the gradient descent to find the optimal value. The gradient descent method holds that the fastest downward direction is the reverse direction of the gradient, so each time a variable moves a certain distance in the opposite direction of the gradient. The objective function is gradually reduced and eventually minimized. The iteration will stop until the extreme value was gotten or a fixed number of iteration (100) was reached this value was set by experiences. Using strict convergence conditions will increase convergence time does not help much to improve the results, which

are not worthy. Science the structure of the skull base is complex and transformation matrix $T_{condyle}$ is more accurate than T_{point} , if skull base registration is initialed by $T_{condyle}$, the computing time will be greatly shortened.

Image fusion in 2D and 3D

In order to analyze and verify the degree of registration, two fusion models were proposed. Comparing with the method of image difference, using color for image fusion is more intuitive.

Internal structure change of condyle can be analyzed in 2D images. First, the gray value of the floating image was adjusted to 0 to 255 and added to the red channel. Then, the same method was used for reference images which gray value was added to the green channel. Finally, the red and the green channel were put together and the aligned part displayed yellow. In 2D color-fusion model, the yellow part means there is no bone change.

The change and displacement of the surface of the condyle were better expressed in 3D model than 2D images. The 3D surface-fusion model was reconstructed using VTK software (VTK-7.1.0, <https://www.vtk.org/>). 3D surface reconstruction was used for both floating and reference models. Floating model was rendered as blue and reference model was rendered as green. These models were displayed in the same window in same coordinate system and the 3D surface-fusion model was obtained.

Results

In this section, the accuracy of the image registration method will be analyzed from two aspects of quantitative and qualitative analysis. According to transform matrix T_{point} and $T_{condyle}$ and T_{skull} , floating image after transformed can be used to get 2D color-fused model which express internal erosion of bone and 3D surface-fused model which can express bone surface displacement. The performance of the 3D registration method was quantitative evaluated by measuring MSE_{model} of I'_f and I_r in each phase.

Qualitative evaluation

The main effect of rough registration is to correct large deviations, which can be regarded as manual registration. Rough registration usually shortened the time of fine registration and avoid getting into local minima. The result of rough registration is shown in Figure 6 using 3D surface-fused model and 2D color-fused model simultaneously. Figure 6a shows the fused volume before registration in 3D surface-fused model. Figure 6b shows the fused volume before registration in 2D color-fused model. There is an obvious misalignment, which was corrected by rough registration as shown in Figure 6c,d in 3D surface-fused model and 2D color-fused model. Coincident area is obviously larger than Figure 6. These

Figure 6 The results of rough registration. Image difference before registration is shown in 3D surface-fused model (a) and in 2D color-fused model (b). The result of rough registration is shown in 3D surface-fused model (c) and in 2D color-fused model (d).

two models complement each other and can comprehensively analyze the result.

2D color-fused model neglects displacement and surface changes of the bones and can observe condylar trabecula structure clearly, which is more convenient to display condylar registration. Color superposition in 2D space is more intuitive as shown in Figure 7. Figure 7a shows results of

Figure 7 The results of condylar registration are shown in (a) and the results of skull base registration are shown in (b).

condylar registration and Figure 7b shows results of skull base registration. The brighter parts correspond to high brightness part in original image. The parts of arrows display the difference results between condylar registration and skull base registration which can also be observed in 3D surface-fused model.

3D surface-fused model hides internal bone information and highlights change of bone position, which is the best choice to express the result of skull base registration. The floating image after 3D rigid transformation and the fixed image were shown using VTK software. Figure 8 displays the results of skull base registration in 3D surface-fused model. The part of the arrow shows the same changes with 2D color-fused model in Figure 7b. In 3D surface-fused model it can be seen that this change is global and consecutive. Figure 8b displays the result of condylar registration in the 3D surface-fused model and there is no surface variation.

Quantitative evaluation

Quantitative analysis of the results was performed using a well-defined similarity metric, which can be calculated as:

$$MSE_{model} = 1/N \sum \left[T \left(I_f'(x, y, z) \right) - I_r(x, y, z) \right]^2 \quad (6)$$

where $I_f'(x, y, z)$ and $I_r(x, y, z)$ are images after noise removal.

MSE_{model} was obtained in the process of prior to registration, rough registration, condylar registration and skull

Figure 8 The registration results of skull base are shown in (a) and the registration results of condyle are shown in (b). The part of the arrow corresponds to the difference in Figure 7b. There is no displacement information in the result of condylar registration.

base registration. The results of all the test data in each phase are shown in Table 1. After rough registration, MSE_{model} value declined 20.01% on average from 181.72 to 145.81 comparing with original difference. In fine registration, MSE_{model} value of condyle and skull base decline 51.80 and 64.58% on average separately. Because structure of the skull base tissue is more complex, aligning skull base will get smaller MSE_{model} value than aligning condyle. In cases numbered 2 to 4, the percent reduction of rough registration declined 5.95, 7.81 and 4.31% which were smaller than other cases. This means although the results of the rough registration in these cases were not ideal, images can still be aligned after fine registration.

In order to verify the repeatability of the method, five independent repeated experiments were carried out for different data sets. Figure 9 is one of the results of repeated experiments. Figure 9a is iterative procedure for condylar registration and the ordinate is $MSE_{condyle}$. The starting position of each line depended on the accuracy of rough registration. Due to human factors, the starting point is different, while fine registration corrected this error effectively and converged to a stable value. If the initial position is not accurate, the iteration will increase, whereas it does not affect the accuracy of the experimental results. Figure 9b is iterative procedure for skull base registration and the ordinate is MSE_{skull} . The starting positions of each line depend on the results of condylar registration. Hence, there are stable initial points and less iteration number for skull base registration. In this experiment, Iterative number of condylar registration is from 20 to 70 and iterative number of skull base is from 23 to 27.

Table 1 The accuracy of registration is measured by MSE_{model} and the reduction of MSE_{model} in each registration stage

Sample number	Before registration	Rough registration	Condylar registration	Skull base registration	Rough registration	Condylar registration	Skull base registration	Percent reduction/%
1	114.11	87.95	41.35	32.23	22.92	63.76	71.76	
2	108.46	102.00	44.96	48.85	5.95	58.54	54.96	
3	121.60	112.11	68.34	48.74	7.80	43.80	59.92	
4	120.30	115.12	62.70	52.53	4.31	47.88	56.34	
5	112.65	82.68	62.94	46.34	26.60	44.13	58.87	
6	96.56	79.59	48.80	27.65	17.57	49.46	71.37	
7	115.93	53.66	49.57	40.68	53.72	57.24	64.92	
8	81.31	63.21	35.04	24.31	22.26	56.90	70.10	
9	424.86	342.49	282.90	135.94	19.39	33.41	68.00	
10	521.46	419.30	193.77	158.57	19.59	62.84	69.59	
Mean value	181.72	145.81	89.04	61.58	20.01	51.80	64.58

b **Figure 9** Results of five independent repeated experiments. The results of condylar registration are shown in (a). The results of skull base registration are shown in (b). Lines of different colors represent each experiment.

Precision of the method

In order to verify the accuracy of the registration method proposed in this paper, the same data set was used as floating and reference model. The output $MSE_{condyle}$ value is 0.0114763, which means this method can converge to the optimal value. Convergent curve as shown in Figure 10. Patients with different circumstances can be registered correctly, the results of registration can be presented differently. For example, in Figure 11, the first patient has internal bone change can be observed in 2D color-fused model and the second patient has bone displacement can be shown in 3D surface-fused model.

Figure 10 Convergent curve of the same test data. Initial rotation and translation were determined by artificial selection randomly. The X axis is the number of iterations and the Y axis is $MSE_{condyle}$. The final convergence value is close to 0.

Discussion

The present diagnosis of OA and other TMJ diseases are based on subjective analysis of images by doctors. An automatic diagnosis system for temporomandibular OA is hoped to design and realize in the future. In this process, the key technology need to be solved is the registration and fusion of TMJ images. The aim of the present paper is to provide a 3D rigid registration method, which is the basic research of automated

Figure 11 (a, b) The erosion of condyle was shown. The part means no change. (c, d) After reconstructing the surface of the condyle, the displacement of the surface can be observed.

diagnosis TMJ OA and will be adopted in the whole automatic diagnosis system in the future research.

Compared with existing methods, this method is repeatable, stable and easy operated, but calculation time still needs to be improved. The result of this paper provides essential information to design and realize automatic diagnosis system in the future. Raw images were used to make 2D color-fused model, which ensure the accuracy of skeletal structure. All the experimental results were saved as DICOM files and can be viewed online and offline.

3D medical image processing is the focus of current researches. 3D CBCT is more and more widely used in diagnosis of TMJ diseases.^{24,25} Reconstructed condyle models are helpful to quantify the displacement and rotation of the condyle. In this paper, the reconstructed surface model is an empty shell containing the surface information only and can be rotated at any angle and zoom in and out, which greatly simplifies the doctor's operation. So far, most of the point-based registration methods are based on external marker points, *e.g.* insert screws into the bone or mark physical titanium spheres on the skin. While using imaging information to select corresponding points with structural significance can be more accurate. In rough registration phase using 3D reconstruction, this method reduces the requirement for operators with extensive clinical experience when selected initial corresponding points and improves the method speed. Moreover, visual human-computer interaction is more convenient for doctors.

3D data sets are more intuitive and accurate, but increase the difficulty of calculation. Computation time must be taken into account during registration especially in navigation surgery and some treatments required high real-time.²⁶ High resolution images have a great impact on computation time. In the experiments, using high resolution images will increase the computation time by two to three times. Reducing redundant data has a very good effect on speeding up. The TMJ is a 3D rigid structure, getting parameters using parts of the skeleton information does not affect the global transform parameters, which is simpler than affine transform and projection transformation.²⁷ Simpler bone structure was removed and complex bone structure with geometric meaning was retained to prevent space-rotation error. In this method, the removed part located at the bottom of the joint like a cylinder geometrically. Using this part alone will get wrong rotation parameter, so this part can be regarded as redundant part.

Medical image segmentation plays an important role in medical image processing. The active contour model can accurately divide the condyle and skull base region semi-automatically. The accuracy of 3D condylar reconstruction models has an effect on the result of the point selection and transformation matrix T_{point} . But the biggest difficulty is to automatically get an optimal threshold value to remove image noises before segmentation and reconstruction. Because the radiation doses injected at each

time may be different and CT images have wide range of pixel gray levels, it is hard to determine a unified threshold for each data set. In this paper, an intensity threshold $I_0 = 500$ was set as threshold which caused some skeletal tissue to be mistaken for background and reconstruction models not accurate enough. Reducing the threshold to get a complete organizational structure will retain a lot of noise. Segmentation results with noise will lead to the wrong result of registration. In order not to affect the final result, threshold $I_0 = 500$ was selected.

The accuracy of the method in this paper will be tested in more cases by assessing osseous growth, treatment outcome and stability after treatment. Current verification method is observing the fused image subjectively. The image taken before treatment was added in red channel and regarded as reference image, the image taken after treatment was added in green channel and regarded as moving image. Using color information after image fusion can analyze bone change. The bone that has no change was composed of red and green two channel images, which was yellow. The bone growth after treatment is green and bone erosion is red. So, it is possible to analyze the therapeutic effect.

This study has limitations. Computation time and segmentation accuracy have already been mentioned earlier. In order to achieve better human-computer interaction, designing a more user-friendly interface and selecting initial corresponding points more flexibly need to be considered. 3D registration of CBCT is very effective to assess 3D morphological variations and local and systemic biomarker profiles in subjects with a diagnosis of TMJ OA. The TMJ cartilaginous disc is best depicted on MRI. CBCT and MRI registration is the best choice to diagnosis TMJ internal derangement. This transformation is usually non-rigid and the choice of similarity measure is also more difficult.^{18,19} In later studies, A gold standard for quantitative evaluation of registration results need to be concerned. Wider application of registration in the field of disease diagnosis, disease analysis and practical teaching needs to be explored.

Conclusion

This paper studied 3D CBCT images registration for condyle and skull base. After qualitative and quantitative assessment, the final registration results are stable and reproducible. This method can realize the registration of 3D CBCT.

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References

- Schilling J, Gomes LC, Benavides E, Nguyen T, Paniagua B, Styner M, et al. Regional 3D superimposition to assess temporomandibular joint condylar morphology. *Dentomaxillofac Radiol* 2014; **43**: 20130273. doi: <https://doi.org/10.1259/dmfr.20130273>
- Barghan S, Tetradis S, Mallya S. Application of cone beam computed tomography for assessment of the temporomandibular joints. *Aust Dent J* 2012; **57**(Suppl 1): 109–18. doi: <https://doi.org/10.1111/j.1834-7819.2011.01663.x>
- Zain-Alabdeen EH, Alsadhan RI. A comparative study of accuracy of detection of surface osseous changes in the temporomandibular joint using multidetector CT and cone beam CT. *Dentomaxillofac Radiol* 2012; **41**: 185–91. doi: <https://doi.org/10.1259/dmfr/24985971>
- Honda K, Larheim TA, Maruhashi K, Matsumoto K, Iwai K. Osseous abnormalities of the mandibular condyle: diagnostic reliability of cone beam computed tomography compared with helical computed tomography based on an autopsy material. *Dentomaxillofac Radiol* 2006; **35**: 152–7. doi: <https://doi.org/10.1259/dmfr/15831361>
- Hussain AM, Packota G, Major PW, Flores-Mir C. Role of different imaging modalities in assessment of temporomandibular joint erosions and osteophytes: a systematic review. *Dentomaxillofac Radiol* 2008; **37**: 63–71. doi: <https://doi.org/10.1259/dmfr/16932758>
- Alkhader M, Kuribayashi A, Ohbayashi N, Nakamura S, Kurabayashi T. Usefulness of cone beam computed tomography in temporomandibular joints with soft tissue pathology. *Dentomaxillofac Radiol* 2010; **39**: 343–8. doi: <https://doi.org/10.1259/dmfr/76385066>
- Alexiou K, Stamatakis H, Tsiklakis K. Evaluation of the severity of temporomandibular joint osteoarthritic changes related to age using cone beam computed tomography. *Dentomaxillofac Radiol* 2009; **38**: 141–7. doi: <https://doi.org/10.1259/dmfr/59263880>
- Ma RH, Yin S, Li G, ShuangYin GL. The detection accuracy of cone beam CT for osseous defects of the temporomandibular joint: a systematic review and meta-analysis. *Sci Rep* 2016; **106**: 1–8. doi: <https://doi.org/10.1038/srep34714>
- Pawiro SA, Markelj P, Pernuš F, Gendrin C, Figl M, Weber C, et al. Validation for 2D/3D registration I: a new gold standard data set. *Med Phys* 2011; **38**: 1481–90. doi: <https://doi.org/10.1118/1.3553402>
- Al-Saleh MA, Alsufyani NA, Saltaji H, Jaremko JL, Major PW. MRI and CBCT image registration of temporomandibular joint: a systematic review. *J Otolaryngol Head Neck Surg* 2016; **45**: 1–7. doi: <https://doi.org/10.1186/s40463-016-0144-4>
- Guo Y, Soheli F, Bennamoun M, Wan J, Lu M. An accurate and robust range image registration algorithm for 3D object modeling. *IEEE Transactions on Multimedia* 2014; **16**: 1377–90. doi: <https://doi.org/10.1109/TMM.2014.2316145>
- Lehmann TM, Gröndahl H-G, Benn DK. Computer-based registration for digital subtraction in dental radiology. *Dentomaxillofac Radiol* 2014; **29**: 323–46. doi: <https://doi.org/10.1038/sj.dmfr.4600558>
- Cevidanes LH, Bailey LJ, Tucker GR, Styner MA, Mol A, Phillips CL, et al. Superimposition of 3D cone-beam CT models of orthognathic surgery patients. *Dentomaxillofac Radiol* 2005; **34**: 369–75. doi: <https://doi.org/10.1259/dmfr/17102411>
- Bolandzadeh N, Bischof W, Flores-Mir C, Boulanger P. Multimodal registration of three-dimensional maxillofacial cone beam CT and photogrammetry data over time. *Dentomaxillofac Radiol* 2013; **42**: 22027087–82. doi: <https://doi.org/10.1259/dmfr/22027087>
- Chen CC, Lin CC, Chen YJ, Hong SW, Lu TW, Chen S-C, Lin H-S, T-W L. A method for measuring three-dimensional mandibular kinematics in vivo using single-plane fluoroscopy. *Dentomaxillofac Radiol* 2013; **42**: 20110326. doi: <https://doi.org/10.1259/dmfr.20110326>
- Gkantidis N, Schauseil M, Pazera P, Zorkun B, Katsaros C, Ludwig B. Evaluation of 3-dimensional superimposition techniques on various skeletal structures of the head using surface models. *PLoS One* 2015; **10**: e0118810–20. doi: <https://doi.org/10.1371/journal.pone.0118810>
- Economopoulos T, Matsopoulos GK, Asvestas PA, Gröndahl K, Gröndahl HG. Automatic correspondence using the enhanced hexagonal center-based inner search algorithm for point-based dental image registration. *J Dentomaxillofac Radiology* 2008; **4**: 185–204.
- Economopoulos TL, Asvestas PA, Matsopoulos GK, Molnár B, Windisch P. Volumetric difference evaluation of registered three-dimensional pre-operative and post-operative CT dental data. *Dentomaxillofac Radiol* 2012; **41**: 328–39. doi: <https://doi.org/10.1259/dmfr/94040044>
- Al-Saleh MA, Punithakumar K, Lagravere M, Boulanger P, Jaremko JL, Major PW. Three-dimensional assessment of temporomandibular joint using MRI-CBCT image registration. *PLoS One* 2017; **12**: e0169555. doi: <https://doi.org/10.1371/journal.pone.0169555>
- Maes F, Collignon A, Vandermeulen D, Marchal G, Suetens P. Multimodality image registration by maximization of mutual information. *IEEE Trans Med Imaging* 1997; **16**: 187–98. doi: <https://doi.org/10.1109/42.563664>
- Economopoulos TL, Asvestas PA, Matsopoulos GK, Gröndahl K, Gröndahl HG. A contrast correction method for dental images based on histogram registration. *Dentomaxillofac Radiol* 2010; **39**: 300–13. doi: <https://doi.org/10.1259/dmfr/57585722>
- Zacharakis EI, Matsopoulos GK, Asvestas PA, Nikita, K Gröndahl K, Gröndahl HG. A digital subtraction radiography scheme based on automatic multiresolution registration. *J Dentomaxillofac Radiology* 2004; **33**: 379–90.
- Kass M, Witkin A, Terzopoulos D. Snakes: active contour models. *Int J Comput Vis* 1988; **1**: 321–31. doi: <https://doi.org/10.1007/BF00133570>
- Cox RW, Jesmanowicz A. Real-time 3D image registration for functional MRI. *Magn Reson Med* 1999; **42**: 1014–8. doi: [https://doi.org/10.1002/\(SICI\)1522-2594\(199912\)42:6<1014::AID-MRM4>3.0.CO;2-F](https://doi.org/10.1002/(SICI)1522-2594(199912)42:6<1014::AID-MRM4>3.0.CO;2-F)
- Al-Saleh MA, Jaremko JL, Alsufyani N, Jibri Z, Lai H, Major PW. Assessing the reliability of MRI-CBCT image registration to visualize temporomandibular joints. *Dentomaxillofac Radiol* 2015; **44**: 20140244. doi: <https://doi.org/10.1259/dmfr.20140244>
- Kang SH, Kim MK, Kim JH, Park HK, Park W. Marker-free registration for the accurate integration of CT images and the subject's anatomy during navigation surgery of the maxillary sinus. *Dentomaxillofac Radiol* 2012; **41**: 679–85. doi: <https://doi.org/10.1259/dmfr/21358271>
- Cevidanes LH, Styner MA, Proffit WR. Image analysis and superimposition of 3-dimensional cone-beam computed tomography models. *Am J Orthod Dentofacial Orthop* 2006; **129**: 611–8. doi: <https://doi.org/10.1016/j.ajodo.2005.12.008>