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Validation of Osteoarthritis synthetic defect database via nonrigid registration

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Abstract

Temporomandibular joint (TMJ) disorders are a group of conditions that cause pain and dysfunction in the jaw joint and the muscles controlling jaw movement. However, diagnosis and treatment of these conditions remain controversial. To date, there is no single sign, symptom, or test that can clearly diagnose early stages of osteoarthritis (OA). Instead, the diagnosis is based on a consideration of several factors, including radiological evaluation. The current radiological diagnosis scores of TMJ pathology are subject to misdiagnosis. We believe these scores are limited by the acquisition procedures, such as oblique cuts of the CT and head positioning errors, and can lead to incorrect diagnoses of flattening of the head of the condyle, formation of osteophytes, or condylar pitting. This study consists of creating and validating a methodological framework to simulate defects in CBCT scans of known location and size, in order to create synthetic TMJ OA database. User-generated defects were created using a non-rigid deformation protocol in CBCT. All segmentation evaluation, surface distances and linear distances from the user-generated to the simulated defects showed our methodological framework to be very precise and within a voxel (0.5 mm) of magnitude. A TMJ OA synthetic database will be created next, and evaluated by expert radiologists, and this will serve to evaluate how sensitive the current radiological diagnosis tools are.

Keywords

non-rigid registration; TMJ OA; validation studies; diagnosis evaluation

1. Introduction

Temporomandibular joint (TMJ) disorders are a group of conditions that cause pain and dysfunction in the jaw joint. According to recently revised TMJ imaging criteria, 42.6% of patients with TMJ disorders presented with evidence of TMJ OA¹. However, diagnosis and

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treatment of these conditions remain controversial. To date, there is no single sign, symptom, or test that can clearly diagnose early stages of Osteoarthritis (OA). Instead, the diagnosis is based on a consideration of several factors, including radiological evaluation and the presence of clinical signs and symptoms such as pain and limited mobility.

TMJ diagnostic techniques have greatly evolved in the last few years incorporating the use of 3D imaging. Numerous imaging modalities are currently available for researchers and clinicians such as computed tomography (CT), cone beam CT (CBCT), MRI, intra-oral scanner and soft tissue 3D photography² and have the potential to improve dental diagnosis and evaluation of treatment outcomes³. Specifically, CBCT has become widely used due to the low radiation dose necessary to get good quality images (as compared with other imaging techniques).

Even with advances in imaging technology, current radiographic classification of TMJ disorders (TMD)⁴ is subject to errors. These classification scores are affected by the acquisition procedures such as oblique cuts of the CT and head positioning errors, which can incorrectly diagnose flattening of the head of the condyle, formation of osteophytes, subchondral cysts, or condylar pitting when viewed on multiplanar 2D sections. These problems are evidenced by the increasing number of studies in the research community that look into reliability of radiological diagnosis of disorders of the TMJ.

This study consists on creating a database and validating a methodological framework to simulate condylar defects of varying size and location. The simulated defects will be reoriented to mimic head positioning error to test the sensitivity of the current diagnosis tools, though this part of the research is out of the scope of this paper.

2. Materials

For this initial study, we used one CBCT dataset acquired with the iCAT CBCT at a resolution of $0.3 \times 0.3 \times 0.3 \times 0.3 \text{mm}^3$ (Imaging Sciences International, Hatfield, PA). A threedimensional virtual model of the mandibular condyle was built using ITKsnap⁵ from a set of approximately 300 axial cross-sectional slices with the voxels reformatted to $0.5 \times 0.5 \times 0.5 \text{mm}^3$. One pathological virtual model was generated, showing two defects of 1 mm (2 voxels) and 2 mm (4 voxels) in the superior surface of the condyle.

3. Methods

The process to simulate any defect on a healthy CBCT followed 5 steps:

- 1. Cropping the original segmentation of the whole head (figure 1.a) to obtain the segmentation of the healthy condyle and the segmentation of the healthy fossa (figure 1.b) with ITKSnap.
- **2.** Simulating a defect on the original segmentation of the condyle (figure 1.c) also with ITKSnap to obtain the segmentation of the condyle with a defect manually simulated (figure 1.d).
- **3.** Obtaining a deformation field from the original model to the synthetic pathologic model, via diffeomorphic non-rigid registration using ANTS⁶ (figure 2). Two

deformation fields are necessary (a) from the healthy segmentation of the condyle to the simulated pathological segmentation of condyle and (b) from the healthy segmentation of the whole head to itself.

4. Applying the deformation field, also using ANTS (specifically WarpImageMultiTransform, that is part of the ANTS suite, see figure 3), to the healthy condyle segmentation, the healthy fossa segmentation and the healthy CBCT of the whole head of the patient.

Quantitative methods were used to validate the synthetic datasets created with our simulating framework. Simulated segmentations were evaluated by measuring distances between the healthy and synthetic pathology segmentations: (a) Between the transformed condyle segmentation and the condyle segmentation with defect manually created, (b) between the healthy fossa segmentation and the transformed fossa segmentation and (c) between the healthy condyle segmentation and the transformed condyle segmentation. Average distances between two segmentations, the maximum distance between two segmentations and the Tanimoto error between two segmentations were computed.

Simulated 3D virtual models were evaluated using Closest Point (CP) surface distances, using 3DMeshMetric⁷. Color maps for qualitative assessments and Hausdorff distance between two segmentations were computed. 3DMeshMetric allows for evaluation of specific location in the color map and this will also be used for quantitative assessment of the synthetic dataset.

Finally, using linear distances in 3DSlicer⁸, we manually measured the defect depth on the deformed segmentation and the deformed grey-scale CBCT.

4. Results

Table 1 shows the results of the evaluation for the first pathological model. Measured distances indicated that the size of the defect obtained by applying the deformation field and the manually simulated defect are the same. Distances between the healthy fossa segmentation and the transformed fossa verified that the condylar fossa next to the condyle area was negligibly modified. Finally, distances between the healthy condyle segmentation and the transformed condyle segmentation showed that the size of the defect obtained by applying the deformation field is the same than the one manually simulated by the user.

Figure 4 displays color-coded surface maps quantifying distances between the 3D virtual models of (a) user manually simulated condyle and automatically simulated condyle (b) healthy condyle and the automatically simulated condyle and (c) healthy condyle and the condyle with the user manually simulated defect. Figure 4a shows that our simulation framework accurately represents user-generated pathology, since the manually generated defect and the simulated defect are the same. Furthermore, both the simulated defect and manually-generated defect have the right defect depth, which shows the accuracy of this methodological framework (figures 4b and 4c).

The linear distances measured indicated that both the deformed gray-scale and the manuallygenerated defect had similar defect depth, which further supports the accuracy and the

validity of this framework for simulating TMJ OA-like pathology as seen in figure 5. Figure 5a shows the linear distances in the transformed segmentation with the simulated condyle, having 1.94mm depth and 2.47 mm width. The same linear distances can be measured in the deformed grey-scale (figure 5b).

5. Discussion

CBCT scans have been described as the imaging modality of choice to adequately visualize osteoarthritic changes in the temporomandibular joint. However, the ability to provide clinicians with accurate information about each detail of the anatomical structures in study may be affected by both the acquisition protocol and image analysis procedures. Recent studies have compared the diagnostic accuracy of CBCT scans in detecting simulated erosion defects on dry mandibular condyles, but most of them analyzed such defects based on naked-eye inspection or 2D measurements obtained from the axial, coronal and sagittal slices^{9,10}, which do not allow for a comprehensive evaluation of the overall morphological alterations. The 3D surface modeling of the anatomical structures provides additional diagnostic information on size, shape, and exact location of the bone abnormalities on the affected joint^{11,12}.

The goal of this study is to demonstrate that a methodological framework to generate synthetic TMJ OA defects, based in non-rigid registration, can accurately reproduce user-generated defects of a known depth and width. All segmentation evaluation, surface distances and linear distances from the user-generated to the simulated defects showed our methodological framework to be very precise and within a voxel (0.5 mm) of magnitude. Automated framework generation of TMJ OA or other pathological defects can reduce systematic error for model generation when multiple operators are involved.

This work is motivated by the increasing use of imaging-based techniques to diagnose disorders of the TMJ, specifically TMJ OA. Even with advances in imaging technology, current radiographic classification of TMJ disorders (TMD)⁴ is subject to errors related to image acquisition. This is a concern for the current research community, where an increasing number of studies have reported low rates of reproducibility¹³ and a higher than acceptable rates of TMD radiological misdiagnosis and radiological incidental findings^{13–17}. By using a 2D measurement approach, Patel et al. stated that the identification and localization of simulated condylar defects were only moderately reliable when considering defects with both diameter and depth smaller than 2 mm. The authors observed that approximately 1 in 3 defects were undetected when using 0.4 mm voxel size CBCT images.

In contrast, three-dimensional (3D) imaging methodology utilized in this study allows for the evaluation and analysis of "the anatomical truth"^{15,18}. Our team has pioneered research that has focused in developing 3D imaging methodologies that can detect bone remodeling with high accuracy^{11,12,19}, as well as aid for characterizing TMJ diagnostic phenotypes in OA²⁰. Cevidanes et al. were the first to precisely diagnose the TMJ condylar morphology using a specific 3D approach for quantitative assessment of the osteoarthritic changes. Moreover, the authors reported statistically significant positive correlation between the

location and extent of condylar resorption and clinical symptoms (pain intensity and duration).

This preliminary work will lead to future studies validating the proposed framework to simulate varying physical manifestations of the progression of OA disease, including osteophytes and flattening of the condylar head. After validating the accuracy of this framework and datasets, we will also test the sensitivity of expert clinicians (radiologists and oral maxillofacial surgeons) to detect varying forms of this disease using the conventional method of multiplanar 2D views. Defects will be generated in different orientations to simulate different head errors and scanning directions.

The long-term goal of this study is to evaluate the sensitivity of the current gold standard method for detection and diagnosis of TMJ OA (2D multiplanar views) and compare it against 3D model generation. 3D model generation has the potential to increase sensitivity on detecting smaller defects while reducing diagnostic error arising for head positioning errors.

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Figure 1.

(a) Original segmentation of the whole head ; (b) Original segmentations of the condyle + fossa ; (c) Original segmentation of the condyle (d) Segmentation of the condyle with manually simulated defects (e) Original CBCT of the patient.



Figure 2.

Diffeomorphic registration workflow and parameters (in yellow).

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Figure 4.

(a) Color-coded map of the distance between the condyle segmentations with manual defect and automatically simulated defect;(b) Color-coded map of the distance between the original condyle segmentation and the segmentation with automatically simulated defect ;(c) Color-coded map of the distance between the original condyle segmentation and the segmentation with manual defect.



Figure 5.

(a) Measurement of the defect on the transformed segmentation of the condyle; (b) Measurement of the defect on the transformed CBCT scan.

Table 1				
Showing segmentation evaluation for both condyle and fossa in the data	aset			

Evaluation	Average distance	Maximum distance	Tanimoto Error
Manually simulated condyle and deformed condyle	0	0.5	0
Healthy condylar fossa and deformed condylar fossa	0	0.5	0
Healthy condyle and deformed condyle	0.006	1.8708	0.36
Manually simulated condyle and deformed condyle	0	0.5	0