

Comparison and Integration of Erosion Evaluation Methods for Rheumatic Degenerative Diseases

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Abstract

Monitoring the development of degenerative rheumatic diseases is at the core of an efficient medical evaluation of the patient. Acquiring information on the pathology progression, indeed, helps to personalize the therapy in order to slow the pathology degeneration. Follow-up exams allow medical doctors to evaluate the situation of the patient over time. Through medical imaging scans, these exams help to identify erosion processes, which are typical indicators of a rheumatic illness. The paper presents a comparison between different methods aiming to identify erosion sites in follow-up exams. In particular, geometric-based and texture-based approaches are compared in terms of extracted information and achieved results. Finally, these two approaches are integrated in order to achieve a more complete analysis of the input anatomical district and of the underlying pathology.

CCS Concepts

• **Computing methodologies** → shape characterization; image analysis; texture mapping;

1. Introduction

In Rheumatology, as well as in most medical branches, follow-up exams are commonly used to analyze degenerative diseases. These exams consist of the analysis of the patient's situation over time. The importance of follow-up analysis resides in its support to the study of the pathology development which, in turn, leads to personalized adjustments of the therapy. In the rheumatological domain, different degenerative pathologies lead to a deformation of the bones, usually linked to an erosion process. The origin of the erosive degeneration differs according to the particular underlying pathology, but the result is an anomalous change in the tissues' composition and, as a consequence, in the bone morphology. Patients that present a similar situation suffer from severe pain and difficulties in the mobility of the interested joints, as a consequence of the anomalous changes of bones and their surrounding regions.

Since an erosion can deform the shape of a bone, an effective strategy is to analyze the morphological changes in the anatomy exploiting 3D surface models, focusing the analysis on geometric changes with respect to the normal case [BTZ*15, BCPS16]. The morphological changes are usually related to a previous degeneration of tissues, which involves a mutation in the composition of the structures around the bone that is visible in the input images. Thus, the identification of erosion sites can be studied through the analysis and quantification of image features [GPM16, LHS*06, HVvdH*15, LPBK08].

This work proposes a comparison between two approaches for follow-up analysis. In the *geometry-based* approach, the analysis

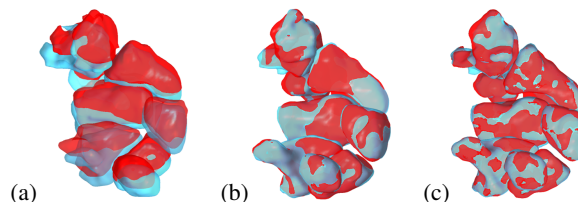


Figure 1: Registration: a) input data set, b) centroid translation. c) ICP registration.

of bone degeneration is focused on the identification of abnormal shape morphology changes. The *texture-based approach* considers the changes in tissue composition through an analysis of the image in a neighborhood of the bone surfaces. We discuss the strengths and weaknesses of these approaches, their integration and performances.

2. Geometry-based follow-up analysis

We consider the 3D surface models of the carpal district at baseline time (t_1) and the one at follow-up time (t_2). The analysis is carried out by a registration of the two carpal districts followed by an evaluation of local distances in order to localize shape changes. The registration of the district at baseline and follow-up 3D surfaces is based on the Iterative Closet Point algorithm. A centroid translation is performed prior to the ICP algorithm to coarsely superim-

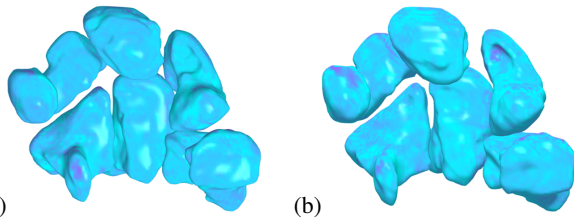


Figure 2: Comparison of the gray-levels mapping between the surface texture of the MRI baseline and (a) the MRI follow-up (b), performed on the follow-up 3D surface. Texture changes locates tissue degeneration and/or an erosion process. Light blue values are associated with darker gray-levels and pink region to brighter intensities.

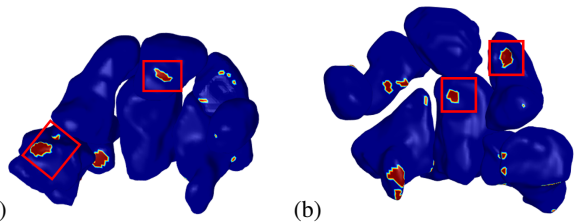


Figure 3: Erosion localization based on a geometric analysis through the thresholding of the distance distribution and on two different subjects. Blue regions indicate healthy bones and red regions locate potential erosions. The red rectangles indicate erosions identified by experts.

pose the two districts ([BM92]), since the ICP is designed to align partially overlapping meshes (Fig. 1). Then, we compute the Hausdorff distance between the two districts to identify which bones could present an erosion. Calling \mathbf{X}_1 the 3D bone surface at t_1 and \mathbf{X}_2 the registered 3D surface at t_2 , we identify eroded bones by their Hausdorff distance: $d(\mathbf{X}_1, \mathbf{X}_2) := \max\{d_{\mathbf{X}_1}(\mathbf{X}_2), d_{\mathbf{X}_2}(\mathbf{X}_1)\}$, where $d_{\mathbf{X}_1}(\mathbf{X}_2) := \max_{\mathbf{x} \in \mathbf{X}_1} \{\min_{\mathbf{y} \in \mathbf{X}_2} \{\|\mathbf{x} - \mathbf{y}\|_2\}\}$.

This general analysis is followed by a local evaluation of the distribution of the minimum distance of each vertex of the surface at t_2 from the vertices of the surface at t_1 . The results obtained in terms of distance distribution are then normalized to $[0, 1]$. The bone regions with higher morphology changes present distances close to 1, identifying possible erosion processes. To help physician in localizing the erosion on each bone, we set as threshold: $T = \bar{d}_{\mathbf{X}_1} + 3 * \sigma_{d_{\mathbf{X}_1}}$, where $\sigma_{d_{\mathbf{X}_1}}$ and $\bar{d}_{\mathbf{X}_1}$ represent the standard deviation and the mean of the distance distribution, respectively. In this way, vertices that have a distance higher than T are considered as belonging to an erosion, and the remaining vertices are classified as healthy (Fig. 3).

3. Texture-based follow-up analysis

The volume images are T1 weighted MRIs, whose voxel intensities have been normalized between 0 (black) and 1 (white), and erosion can be identified through an analysis of the changes of the voxels' intensity [PPS20].

In [PPS20], the gray-levels of the image voxels are mapped to a

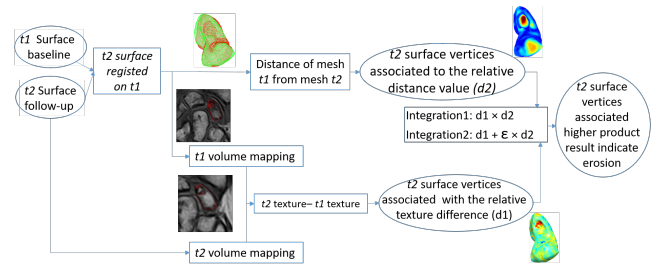


Figure 4: Pipeline of the integration method.

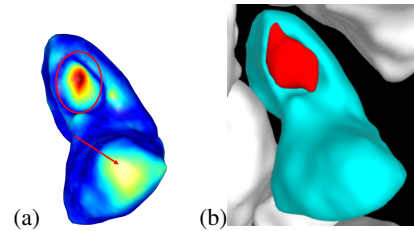


Figure 5: Scaphoid bone follow-up analysis of a patient with Rheumatoid Arthritis. Comparison of the erosion region identified by the experts (a) with the result of the geometrical analysis (b). The erosion is correctly identified (circle), but the distance distribution shows higher intensity values also in an area that does not present erosion (arrow). Blue regions in the texture are associated with values near to 0, while with yellow the values increase until the maximum (1) in red.

segmented anatomical district through a volume-surface correspondence map, which defines a gray-level texture on the segmented surface. After the coregistration of the two surfaces, the volume gray-levels at time t_1 are mapped on the surface at time t_2 and the gray-levels at time t_2 are mapped on the corresponding t_2 surface. In this way, the follow-up 3D model shows either the volume situation at time t_1 and at time t_2 . Since the erosion typically results from a degeneration of articular regions, we focus on the gray-levels immediately outside the segmented surface (Fig. 2). Then, the difference between the texture gray-levels at baseline and follow-up is computed and visualized on the follow-up models. A higher value of difference locates a region where the tissue has been substantially damaged and a color map associated with the different intensities describes the distribution of the changes in terms of tissue modification on the 3D surface.

4. Integrated geometry and texture approaches

The first approach (Sect. 2) focuses exclusively on the geometric differences that occur over time, without considering the tissue information. The second method (Sect. 3) is based on the degeneration of tissue composition. The geometrical analysis associates the distance of each vertex of the follow-up surface to the nearest vertex of the baseline. In the texture analysis, each vertex of the follow-up district is associated with the value of the difference between the gray-levels at baseline and follow-up. The texture information has intensities in the range $[-1, 1]$: a value close to 1 indicates a strong

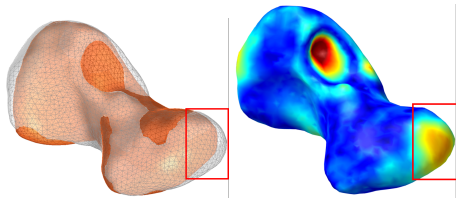


Figure 6: Inaccuracies of the registration method (a) with the relative influence on the identification of erosion regions (b) Blue region in the texture are associated with values near to 0, while with yellow the values increase until the maximum (1) in red.

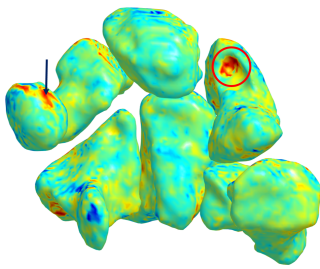


Figure 7: Erosion localization in the texture-based approach. The erosion is correctly identified (circle) but other healthy areas (arrow) are indicated as a potential erosion due to a low image resolution. Blue and light blue colors represent negative texture values (blue corresponds to -1); green areas present values near to zero. Yellow and red represent increasing values where red corresponds to 1.

change in tissue composition over time. A value of texture close to -1 could indicate a healing process, where the extension of an existing erosion has decreased due to the therapy [BTZ*15]. The value of the distance varies from 0 to 1, which indicates the entity of the geometric deformation.

Fig. 4 shows a flow-chart of the two methods used to integrate the information provided by the two approaches. The first option is to multiply the value of the geometry information to the one of the texture information for each vertex. If a variation in geometry is associated with a high variation in texture, then the result will be a higher total value. If a geometry change is not associated with a major change in texture, then the influence of the geometry variation will be diminished, thus bringing to a lower total value. In this way, the erosion site will be highlighted only if the bone has developed both a change in its morphology and tissue composition.

As a second option, we consider a linear combination of geometric and texture information. Calling d_2 the distribution of the distances obtained by the geometry analysis and with d_1 the distribution of the texture changes in the gray-levels analysis, the resulting distribution is defined as $d_1 + \epsilon * d_2$ where ϵ is a positive trade-off parameter. Varying the value of ϵ gives more emphasis to the geometric or the texture information and its value can be adjusted by the physician depending according to his/her interest. If the clinician wants to surely identify all erosions, even the smaller, ϵ will be

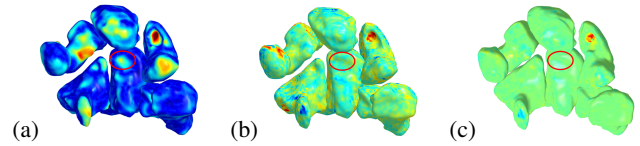


Figure 8: Comparison of the (a) geometry-based approach, (b) texture-based approach, and (c) their integration through the multiplication of the geometric and texture intensities, on the same follow-up district. The color map presents the higher intensity values of the distribution as warm colors, where red are the areas with the highest values and cold colors represent the smaller values in the distribution. The red circle indicates the small erosion identified by the geometry-based approach but not by the integration method.

increased. A low ϵ is more suitable for the identification of larger and persistent erosions. Finally, an interactive visual representation of the integrated results is achieved by changing ϵ and helps the user to better analyze the input data.

5. Results and discussion

The data set used for the analysis is composed of the 3D MRI of the carpal district associated with their segmentation performed by medical doctors. The subjects suffer from degenerative rheumatoid illnesses at different stages, and 5 subjects underwent follow-up exams. The highly complicated anatomical structure and the low-field images represent the core challenges that the various approaches have to face.

Regarding the geometry-based analysis, the erosion site is correctly identified by the geometrical analysis, which presents a particularly high value of distance distribution in the exact location indicated by the experts (Fig. 5). However, the results show also the presence of *false positives*: areas of the bone that are classified as erosion but are actually healthy regions. This misclassification is related to the inaccuracies of the registration process, since the rounded and symmetric shape of most of the bones affects the accuracy of the districts alignment. In the region where the two bones were not well aligned, the geometrical analysis shows a possible erosion site (Fig. 6).

In the image texture analysis, the difference between the texture at baseline and follow-up times shows an inhomogeneous behavior. However, the higher values of difference in texture are located in an erosion region. In fact, a major change in tissue composition implies a higher value of the difference between the texture at the two different times. Despite the correct location of the erosion, false positives are present, even if characterized by lower values of difference with respect to the real erosion locations (Fig. 7). These false positives are generally due to the low resolution of the MRI images; by increasing the resolution, we expect more precise and accurate results.

In Fig. 8, we compare the results obtained from geometric, texture-based, and integrated (multiplication option) approaches. In the integration approach, false positives are no longer present and only eroded areas show higher values. The overall result is homogeneous, indicating that geometry and texture information com-

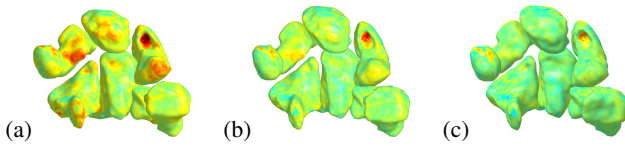


Figure 9: Results induced by the linear combination $d1 + \epsilon * d2$ of the texture distribution $d1$ and the geometry distribution $d2$ by varying ϵ : (a) $\epsilon = 1$, (b) $\epsilon = 0.5$, (c) $\epsilon = 0.2$. The color map presents the higher intensity values of the distribution as warm colors, where red are the areas with the highest value and cold colors represent the smaller values in the distribution.

pensate each other. However, the integration result could miss some newly developed and small erosions. The geometric approach identifies a small degeneration of the morphology and texture changes are not evident; indeed, the erosion could be at an initial stage, implying a minor change in geometry and a small change in the cortical bone tissue.

The linear combination of the texture-based and geometric information (Fig. 9) generally provides satisfactory results; the number of false-positive areas decreases along with the reduction of the relevance of the geometric information, but an excessive reduction brings also to a misclassification of erosion regions as healthy areas. Finally, the proposed approach is independent of any previous knowledge of the input district and the acquisition methodology.

6. Conclusions and future work

The paper presents a comparison of different approaches to support the medical follow-up analysis in Radiology, with a special focus on erosion development in rheumatic diseases. The presence of false positives presents to the physician a worsened situation and, thus, a higher level of bone degeneration, with respect to reality. Whereas, the presence of false-negatives induces an underestimation of pathology progression gravity. Indeed, the presence of false-positives or false-negative could alter the result of the therapy performance analysis, and that the identification of trade-off between the two is important.

In this context, the proposed geometry-based and texture-based approaches are meant to better localize the initial appearance or evolution of erosion sites, in particular, to provide physicians with a visual tool that could help and speed up the erosion identification process. All the methods correctly identify the major erosion that occurred over time. The analysis is able to identify even the smallest erosion but classifies as eroded areas some regions of the bone that are still healthy. The texture-based analysis shows promising results in terms of homogeneity and accuracy, which can be improved with higher resolution images. Finally, the integration of texture-based and geometric information allows us to obtain a more homogeneous result, helping the identification of which bone was actually eroded due to the pathology.

Future work will be focused on the improvement of the integration approach toward a fully automatic approach, integrated with a quantitative measure of the erosion. Moreover, testing different registration methods for the geometry-based analysis could improve

the results obtained with higher accuracy. Finally, a more complete clinical validation, with a wider data set would be useful to confirm our results.

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