Exploiting 3D Part-Based Analysis, Description and Indexing to Support Medical Applications

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Abstract. Multi-modality is crucial to handle knowledge, medical data and patient-specific information in an integrated fashion: in the course of their work, indeed, clinicians analyze a large amount of information about interrelated layers such as anatomy, kinematics, dynamics, mechanics and physiology. Much of the information related to these levels is intrinsically 3D and we believe that the adoption of 3D part-based annotation and content-based indexing will open up new ways to integrate and interact with medical information. In this paper, we will focus the attention on content-based analysis of 3D medical data and discuss related issues and trends, based on two software tools: the ShapeAnnotator and RheumaSCORE. In the illustrative scenario of the Rheumatoid Arthritis we will provide hints for even more informative Computer Aided Diagnosis systems for clinical support.

Keywords: 3D shape segmentation, 3D part-based annotation, 3D content-based description, Computer Aided Diagnosis, Rheumatoid Arthritis.

1 Introduction

With the rapid innovation in computing and electronic imaging technology, there has been increasing interest in developing Computer Aided Detection/Diagnosis (CAD) systems to improve the medical service [1,2]. CAD is emerging as an advanced interdisciplinary technology, which combines fundamental elements of different areas such as digital image processing, image analysis, pattern recognition, medical information processing and knowledge management.

CAD systems are likely to become the means of processing and interaction of the huge amount of available digital data and to incorporate new methods for comparative

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analysis and study of clinical cases. Methods of information retrieval will play a fundamental role in offering techniques to correlate and analyse such data based on qualitative and quantitative information extracted automatically. Content-based medical retrieval systems have the potential to improve the performance of clinicians [3] speeding up the diagnosis process and improving accuracy and treatment of complex diseases.

While the importance of content-based techniques is not new, this paper focuses the attention on issues related to content-based analysis of *3D* data in the medical domain. The success of CAD-supported analysis processes depends indeed on the capabilities of automated solutions to simulate and improve what physicians and radiologists do when they inspect digital data. We believe that the key challenges are:

- software applications should be able to *identify and measure* clinical parameters based on the *geometric/morphological characterization* of the shape of organs, anatomical elements or their parts;
- formal methods to assess the similarity among shapes should support the retrieval of *similar* clinical cases in order to speed up the diagnosis process and to support comparative analysis among known cases;
- gathering information about specific patients should ease the evaluation of their *follow-up* in order to highlight temporal trends of pathology markers, possibly depending on current therapy;
- performing *statistical analysis* over a significantly large population of patients would trigger the possible detection of new correlation patterns and speed up the screening of large populations for abnormal cases.

After the non-trivial segmentation and reconstruction steps, the usage of 3D models in the medical domain has mainly concerned the localization and visualization of parts. However, the highly informative content carried by 3D models can be exploited more heavily: 3D-based shape analysis, indexing, and part-based annotation can provide the novel means to integrate medical information in a truly multi-modal framework.

The contribution of this paper is the discussion about this integration, showing how 3D part-based characterization and annotation could enhance an existing CAD system. To substantiate our arguments, we will describe two existing tools, i.e. the ShapeAnnotator and RheumaSCORE, and demonstrate their complementarity and fruitful integration in the framework of Computer Assisted Diagnosis.

On the one side, the *ShapeAnnotator* is a 3D object annotation system that provides the framework for 3D part-based annotation, relying upon a multi-segmentation of 3D shapes and concepts formalized in an ontology. Along with fine-grained shape characterizations, annotated parts can be used to index relevant parts in 3D reconstructed models. On the other side, the *RheumaSCORE* software implements some prototypical tools for the automatic characterization of 3D parts, especially relying on the detection of bone erosion, and has been considered very useful to help radiologists or physicians during diagnostic processes and follow-up of rheumatic patients.

Using the diagnosis of Rheumatoid Arthritis (RA) as illustrative scenario, we will discuss how more informative content-based systems may be designed for clinical support.

The paper is organized as follows. In Section 2, the 3D multi-segmentation and annotation framework will be presented; some hints will be given on the 3D characterizations that can be automatically attached to parts in order to support their description and to be used for indexing purposes. In the medical scenario, the usage of these methodologies is still at its infancy, while we believe that coupling 3D analysis techniques with CAD systems has a high potential to innovate the field. In Section 3, the RA scenario will be described in the framework of the RheumaSCORE system and some clinical trials will be discussed. In Section 4, we will introduce an integration perspective, discussing on how these systems could be combined and improved, and briefly sketching future research directions. Section 5 concludes the paper with a short wrap-up.

2 3D Multi-segmentation, Annotation and Characterization

A variety of techniques have been developed in image processing for content analysis and segmentation: these are particularly useful in the medical domain where much of the digital content is stored as 3D images, including data from Computer Tomography (CT), Magnetic Resonance Imaging (MRI), MicroCT and other devices. The available techniques are generally based on the computation of low-level features (e.g. texture, color, edges) that are used to identify and isolate, or segment, relevant parts in the 2D or 3D image. Segmentation is primarily meant as the process to detect specific shapes in a 2D or 3D image, while content-based annotation methods allow to create correspondences between complex objects, or parts, and conceptual tags: once the content is analyzed and its relevant constituents annotated, they can easily match textual searches.

Getting accurate 3D reconstructions from raw segmented images is still very labor-intensive, but a growing number of problems in medical analysis require the manipulation of the full spatial geometry. In other words, 3D models represent the geometry of all the interesting parts (e.g. organs, bones) which can be further analyzed and possibly decomposed by dedicated computational tools [4]: in fact, 3D models, or their parts, may be characterized by morphological attributes, abstract properties (e.g. signatures for indexing and retrieval), or any other useful parameter.

With these premises, the ingredients needed to fully integrate 3D geometry into the medical processing pipeline are: 3D shape analysis tools, a rich set of tools to characterize the models and/or their parts, and a methodology to associate part-based annotations with the geometric representation. We emphasize that in the medical practice annotations need to be attached not only to the whole 3D reconstruction, but most frequently to *parts* of interest, for instance a bone or even a specific portion of it [5].

The *ShapeAnnotator* [6] was a first attempt to integrate segmentations and annotations for generic 3D models. It relies on the concurrent use of a variety of shape analysis and segmentation tools to offer a rich set of operators to detect 3D regions of interest on the 3D models. Given the complexity of shapes in the medical domain, it is widely recognized that no single algorithm can be used to provide a segmentation that yields interesting and exhaustive results for all feature types, even if the context is well-defined [7]. Hence, the ShapeAnnotator approached the problem of feature extraction via the concept of *multi-segmentation* of a 3D surface represented by a triangle mesh. The idea is to use in parallel a set of different segmentation procedures and to select and compose just the meaningful results from each of them: interesting features can be interactively selected from the resulting multi-segmented mesh.

The ShapeAnnotator allows loading an ontology to enrich the segmented model with concepts. To annotate the features of the 3D model, the user can choose the appropriate conceptual tags within the domain of expertise formalized by the ontology, expressed in OWL [8]. The result of the annotation process is a set of instances that, together with the domain ontology, form a knowledge base. Each instance is defined by its URI, its type (i.e. the class it belongs to) and by attribute values and relations that have been specified/computed. In its current version, the ShapeAnnotator saves the multi-segmented mesh along with the selected features as a single PLY file. The instances are saved as a separate OWL file that imports the domain ontology. Additionally, the OWL file contains the definition of two extra properties:

- `ShannGeoContextURI`, whose value is the URI of the multi-segmented mesh (typically the path to the PLY file saved by the ShapeAnnotator);
- `ShannSegmentID`, whose value is an index that specifies a segment in the multi-segmented mesh.

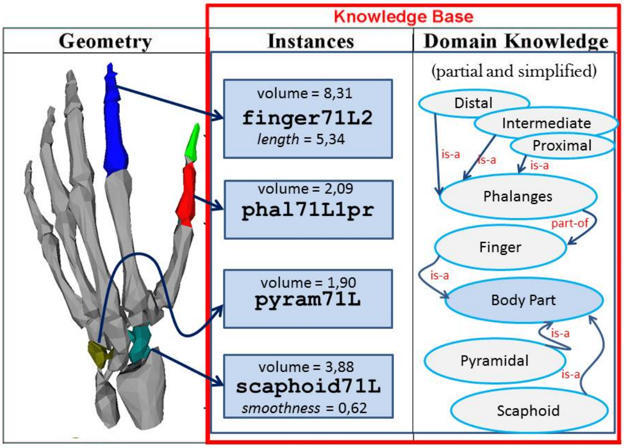

Fig. 1. An example of coupling geometric and semantic information on a human hand

All the instances produced during the annotation pipeline are automatically assigned values for the above two properties, so that the link between semantics and geometry is maintained within the resulting knowledge base (see Fig. 1). In this way, every component of the 3D model has its unique reference to its geometry and its descriptive tag, which constitute a first step towards an intelligent 3D indexing in a multi-modal knowledge based system.

Currently, the system requires the user to select manually the concepts to instantiate; for some attributes and relations, however, there is the possibility to calculate them automatically without the user intervention. Concepts of the input ontology may be equipped with descriptive attributes; for instance, a part annotated as *bone* may be described by its *volume*, *area*, and *length* as well as by other more complex attributes like *compactness*, *roundness*, or *smoothness*. How to compute the values of these attributes?

The ShapeAnnotator comes with a set of tools able to compute a number of geometric measures of shape parts (e.g. bounding box length, radius of best-fitting cylinder). These measures can be connected by the user to the attributes of the ontology in order to assign them a geometric interpretation. This allows the system to compute and fill in the values to be associated to the attributes automatically. For instance, the attribute "`length`" can be connected to, i.e. interpreted as, the *length of the first principal component* and its values computed automatically. The same kind of connections may be established to give specific interpretations to relationships. For instance, the conceptual relation "`is_connected_to`" can be connected to *topological adjacency* between the part boundaries.

Users are free to set up their "interpretation" within each specific domain of annotation by establishing an appropriate set of *connections*. Connections create a bridge between the geometrical world and the conceptual world.

Part-based annotations are important also to support comparative analysis of clinical cases: indeed, descriptions attached to parts can be used as actual *signatures*. Signatures are abstract descriptions of the content of the original resource and allow comparisons and similarity assessment [9,10]; in the medical domain they are helpful to automate part classification, to ease 3D part-based retrieval, and to monitor the changes of a specific part over time. Vast surveys on retrieval issues can be found in [11,12].

Just to name some properties that can be extracted from 3D models and used as signatures, *Shape Distributions* by Osada et al. [13] measure the distribution of properties based on distance, angle, area, and volume measurements between random surface points; Zhang and Chen [14] propose methods to compute efficiently global measures such as volume, area, statistical moments. Finally, the *configuration* of the shape features may be also detected to perform some kind of structural similarity assessment: various techniques exist to produce such signature, which range from the use of *skeletonization* to topological approaches [15,16].

3 A Medical Scenario: The Case of Rheumatoid Arthritis

The potential of part-based annotation is well demonstrated in applied cases, among which we have selected the early diagnosis and the follow-up of Rheumatoid Arthritis (RA). In the following, we will discuss the issues that motivate the adoption of 3D characterizations of parts, contextualizing the discussion to the functionalities and purpose of the *RheumaSCORE* software.

RA is a systemic, inflammatory disease that affects the synovial joints and leads to joint pain, stiffness and limited motion. It is a chronic disease that affects about 2,9 million people in Europe [17,18]. An early diagnosis, the continuous monitoring of disease activity and the constant evaluation of therapy effects can improve patients' quality of life and may reduce related social costs.

In order to evaluate RA progression and joint damage, a lot of laboratory tests are available, such as Rheumatoid Factor, C-Reactive Protein and instrumental exams, such as Magnetic Resonance Imaging. MRI has been demonstrated to be from two to ten times more sensitive than conventional radiography in detecting wrist erosions in RA (Fig. 2), especially in its early phases [19]. In general, erosions detectable on MRI may become visible on plain x-rays only 2-6 years later [20-22]. This increased sensitivity is explained by the fact that MRI is a multi-planar technique. Moreover, it can image the soft tissues, including synovial membrane, synovial fluid and tendons, in addition to bones and cartilage. The quantification of synovial volume can be used to monitor the response to therapy and to predict which patients are more likely to develop erosions within one year [23].

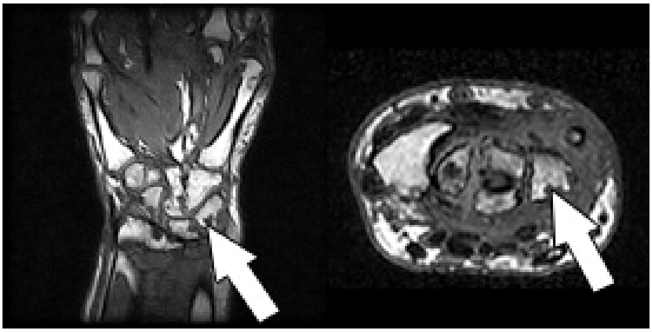

Fig. 2. MRI erosions

The wide use of MRI in the assessment of joints of patients with RA in the last years emphasized the need for an objective and reproducible scoring system of RA lesions. An international Outcome Measures in Rheumatology Clinical Trials (OMERACT) MRI in RA working group developed a MRI scoring system to assess both inflammation (activity) and bone lesions (damage) [24].

The OMERACT RA-MRI Scoring system (Rheumatoid Arthritis Magnetic Resonance Image Scoring, or RAMRIS) was developed in order to measure the lesions observed in the wrist/hand of patients with RA. These lesions are the *synovitis* (inflammation of the synovial membrane of RA and other typical forms of arthritis), the *bone marrow edema* (inflammation of the bone marrow, at least in RA), and the *erosion* (the destructive bone erosion typical of RA).

The erosion score is estimated visually by the user in the traditional RAMRIS: each eroded bone is considered individually and the ratio between the volume of the erosion and the hypothetically healthy bone is evaluated, analyzing all the slices covering the bone. The global score of the erosion is evaluated considering the eroded bone volume compared to the intact bone, with 10% increments. As a result, the rating of the erosion per single bone is comprised between 0 (healthy bone) and 10. Considering all the involved bones, the total score for the wrist is between 0 and 150, and for the hand between 0 and 80.

Manual evaluation of bone erosions volume is however tedious, time consuming and not fully repeatable (especially for inexperienced users). Considering the big amount of patients suffering from RA, this is a critical task. The *RheumaSCORE* software was developed by Softeco Sismat S.r.l. to face the RA problem [25,26].

3.1 RheumaSCORE

RheumaSCORE is an easy-to-use imaging application that supports the user (e.g. radiologist or rheumatologist) during the diagnostic process and the management of RA progression, through the analysis, the display, the measurement and the comparison of MRI acquisitions of different patients.

For each patient RheumaSCORE can load several DICOM files (study/series) simultaneously, which are used to evaluate the current disease status and monitor its progress over time. The physician is supported through several functional environments addressing:

- the *investigation*, through the recognition of wrist/hand bones and the automatic evaluation of the bones erosion scoring;
- the *tracking,* through the management of clinical data (like Rheumatoid Factor and C-Reactive Protein), the insertion of free annotations and the retrieval of similar RA cases on the basis of historical clinical data, RA measurements or keywords specified in the free notes;
- the *follow-up*, through the automatic comparison among the parameter measured in image pairs acquired at different times.

The software has a modular architecture, which can be easily expanded with other segmentation techniques and 3D visualizations to deal with other anatomical districts and pathologies.

3.2 Evaluation of RA Status and Progression

RheumaSCORE allows to analyze the bones of the hand and the wrist to assess the RA status through erosion scoring and progression monitoring. The system supports the user during the 3D segmentation process of the bones structure, which is a necessary step to evaluate automatically the bone erosion scoring.

In the recognition environment the system provides a custom segmentation procedure for each element of interest (carpal, metacarpal and forearm bones): a semi-automated method based on level sets technique using Geodesic Active Contour approach [27] has been applied, which does not rely on any prior knowledge of the shape of healthy bones. Segmentation results are reconstructed in 3D using the Marching Cube algorithm [28] and displayed using surface rendering algorithms.

After segmentation, the system provides automatic scoring of the bones erosion, using the same method proposed by OMERACT RAMRIS (see Fig. 3). It identifies and measures bone erosions, defined as the missing volume of substance of the segmented bone with respect to an average statistical model, which is built on bones of healthy subjects. Processing takes a few minutes for all wrist bones (or hand bones), which leads to a remarkable reduction of diagnosis time and costs.

Moreover, the framework permits the management and storage of clinical data (like C-reactive Protein), useful for measure and monitor RA activity. Physicians can also add annotations, possibly using the system ontology, in order to highlight lessons learnt or critical issues linked to specific features of the current patient.

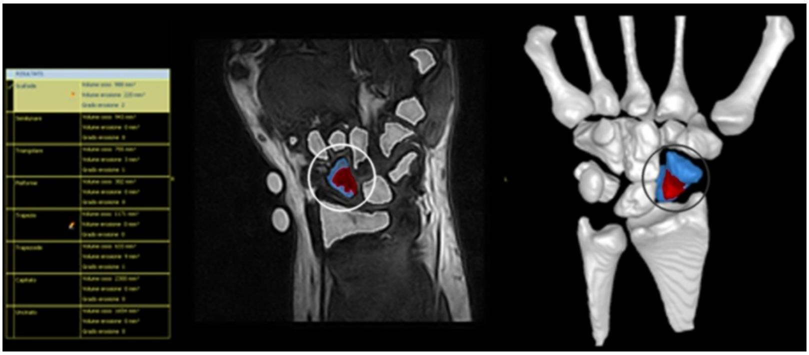

Fig. 3. Erosion Scoring

All the information related to the patient's examination (e.g. acquired DICOM images, anatomical 3D segmented elements, 3D features, user annotation) are stored in the system database and are available for retrieval.

The patient's disease follow-up is supported by storing, visualizing and comparing several sets of data acquired at different times. Differences among parameters and trends can be computed and visualized.

3.3 Clinical Trials and Results

A preliminary clinical test has been carried out at DIMI[1]. 26 patients (21 women and 5 men) diagnosed with early RA according to the 1987 ACR criteria were studied. The wrists were imaged through an extremity-dedicated MRI device (Artoscan C, Esaote, Genova Italy). A turbo T1-weighted three dimensional sequence (T3-D T1) in the coronal plane, with subsequent multiplanar reconstructions on the axial and sagittal planes, was used; slice thickness was 0,6-0,8 mm, TR 860 ms, TE 26 ms, and number of excitations (NEX) 1.

Some experts evaluated the erosion scores using the manual RAMRIS method and the RheumaSCORE software used for the segmentation of the bones of the wrist and metacarpal bases. When needed, the resulting outline was adjusted manually via a 2D editing tool. The 3D reconstruction was performed and the erosion scoring was calculated.

The median erosion scores revealed by manual application of the RAMRIS method and by automatic RheumaSCORE software were 2 (range 0-26) and 2 (range 0-21), respectively. The two scores were correlated (correlation coefficient 0.9, $p<0.0001$). The inter-rater agreement statistical measure (weighted k) was 0.706 for the entire score and was comprised between 0.264 and 0.887 for the individual bones (values greater than 0.5 are considered satisfactory). The poorest result was seen for the scaphoid due to underestimation of a relatively large erosion in a single patient (RAMRIS score 3) because of the very large size of his wrist bones. Therefore, the semi-automated segmentation software showed a good correlation with the RAMRIS erosion score, yet presenting some limitations.

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4 Integration Perspective

The functionalities implemented in the RheumaSCORE are a clear example of the directions that CAD systems are likely to take in the near future. Adding tools to select parts of interest in 3D reconstructions and automatically compute morphological parameters is of great value, and it has been shown to be effective for the early diagnosis of RA even in the initial stage of development. Currently, the systems uses the Geodesic Active Contour approach as the only technique for segmentation and the global volume of the detected parts as the only geometrical characteristic recorded.

The integration of this platform with the ShapeAnnotator tool and the experience in a finer-grained 3D analysis may produce very informative characterizations and indices to support classification and statistical analysis.

In the first place, it is necessary to adopt a multi-segmentation strategy: a rich library of tools for the segmentation of parts has to be provided to allow users to rely on various, and possibly integrated, segmentation techniques to locate better the interesting parts, possibly taking into account also uncertainty.

Moreover, by relying on the fine-grained 3D characterization techniques, each segment could be indexed not only by its volume, but also by a number of content-based descriptors, each of them highlighting diverse aspects of the considered part. For instance, spatial localization of bone erosion can be useful to evaluate more accurately the anatomical-functional damage, the possible disease progression, the pain felt by the patient and the effectiveness of the therapy. A new version of the CAD system would also provide morphological analysis to evaluate the bone roughness (i.e. lack of smoothness, which can be computed from the distribution of curvature on the bone surface) or the presence of interruptions of the bone cortex, which are typical of erosions. In fact, normal areas of tendon and ligament attachment could be rough because of traction forces and a very small cortical interruption can be seen where nutritional arteries enter the bone. In addition, a family of arthritis called seronegative spondyloarthritides, which enter the differential diagnosis of RA, is characterized by periostitis or inflammation of the periosteum and bone cortex. This lesion is reflected by a rough appearance of the bone surface. The new system would evaluate an increased percentage of rough bone surface and contribute to both differential diagnosis and damage follow-up in psoriatic arthritis patients.

In Fig. 4 we show some preliminary tests run on the semilunar bone, comparing the curvature plots between a healthy bone and a highly eroded one. Curvature has been computed with the algorithm developed in [29] and shows concave, convex and saddle areas. Numerical curvature values could be additionally gathered for a quantitative data analysis.

Finally, it is necessary to connect the annotation mechanism to the system in order to link each of the selected parts with concepts and attributes expressed in a given domain ontology, thus easing the documentation accuracy and the retrieval performance.

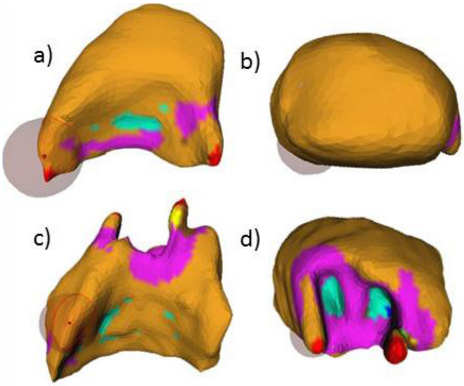

Fig. 4. Top: a) and b) are two views of a healthy semilunar bone of the wrist, which is characterized by large smooth areas. Bottom: c) and d) are two views of a RA-affected semilunar, which is well characterized by the massive presence of tips (red areas), saddles (magenta areas) and concavities (cyan areas) in the eroded zone

5 Conclusions

In this paper, we showed the high potential of including full 3D content among the heterogeneous digital data available in medicine. In fact, advanced shape analysis and similarity techniques can be exploited to improve CAD systems and content-based retrieval systems. We discussed such issues in the frame of RA, starting from the ShapeAnnotator and the RheumaSCORE tools. In particular, we mainly highlighted the promising perspectives of coupling geometric information with semantic characterization.

As a final remark, an important research challenge on the side of knowledge representation is worth to be mentioned: at the state of the art, geometric representations are not consistently linked with part-based annotations. On the contrary, it would be fundamental to define a stable markup: annotations attached to parts of 3D models should survive changes in the geometric representation (e.g. change of representation, change of resolution, shape editing). In this respect, the ShapeAnnotator provides just a partial solution and the problem of defining a stable 3D markup still remains.

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