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Semantic Annotation of Patient-Specific 3D Anatomical Models

Imon Banerjee*, Asan Agibetov*, Chiara Eva Catalano*, Giuseppe Patané* and Michela Spagnuolo*
*CNR-IMATI
Via De Marini 6, Genova, Italy
Email: {imon.banerjee, asan.agibetov, chiara.catalano, giuseppe.patane, michela.spagnuolo}@ge.imati.cnr.it
Telephone: (+39) 010-647-5697, Fax: (+39) 010-647-5660

***Abstract*—Nowadays, a wide range of advanced techniques provides accurate and detailed 3D data about patients anatomy, as captured by medical scans (MRI, CT, MicroCT, etc.). While medical imaging assists daily clinical practice, 3D patient-specific models (3D-PSMs) of anatomy have still a quite limited use. We consider part-based semantic annotation beneficial to bring 3D-PSMs into clinical practice. To this end, tools are needed to extract clinically relevant information from 3D models, to associate such knowledge with their corresponding parts, and to support the storage, sharing and searching of annotated 3D-PSMs in a structured manner.**

In this context, we present the SemAnatomy3D framework, which demonstrates the idea of ontology-driven annotation and indexing of 3D-PSMs and their Parts-of-Relevance, characterized by anatomical landmarks and pathological markers (e.g. articular and non-articular facets, ligament insertion sites, erosions). The key functionaity is to offer services for part-base annotation of 3D-PSMs which enables search or browse the 3D-PSM according to the annotation attached to its Parts-of-Relevance. The paper describes the results in terms of methods to support the part-based annotation of 3D-PSM, and the formalization of the data model to store and manage global and part-based annotation to improve search and analysis of 3D patient-specific anatomical models and subparts.

Finally, we specialized our framework to support the diagnosis of rheumatoid arthritis in the carpal bones, but, in principle, it can support similar tasks in other clinical applications.

I. Introduction

According to the European Commission [1], 30% of the world storage is occupied by multi-modal medical data (acquired images, 3D models, patient-records etc.). The paradox of such an expansion is that the huge amount of accessible medical data is still under-exploited. This is because 80% of the data is unstructured (IBM report April 2013 [2]). Moreover, the way medical data are searched and processed to support doctors and scientists in the field is not yet satisfactory. Such discrete pieces of medical data and knowledge are even more valuable when they are integrated, or at least interconnected, so that doctors are able to navigate and gather relevant information for analysis more easily. The performance of computer-aided diagnosis system [3] might be highly improved by coupling the retrieval services that can query distributed medical repositories for specific semantic feature of the data.

Content-Based Image Retrieval (CBIR) has achieved a high degree of maturity as clinical image retrieval technique. Traditional content-based retrieval methods depend on the definition of computational measures of visual similarities whereas a few modern applications try to incorporate the semantics in the retrieval process. This approach is known as *Semantic Content Based Image retrieval* (SCBIR), and exploits heavily knowledge related to anatomy, symptoms, and diseases in the image indexing process. In literature, a few CBIR [4] [5] and SCBIR [6] systems have been implemented for clinical images.

Advanced image segmentation and 3D reconstruction methods offer a whole spectrum of technologies to create a detailed patient-specific 3D anatomical model (3D-PSM). However, 3D-PSMs of anatomy have still quite limited use, partially due to the fact that the 3D analysis tools in clinical context are still rather limited to research and 3D models are rarely associated with the domain knowledge. In practice, clinical findings derived from the analysis of patient data are described in a separated text-report or in a data collection form. These unstructured texts are generally difficult to index, query and search for reusing and sharing. There is a demand of a framework that allows the association of features and clinical finding directly with 3D medical data to manage heterogeneous data and information together in an integrated manner [7]. One way to couple the conceptual understanding of a clinical domain with patient-specific 3D models is to use biomedical ontologies. Biomedical ontologies serve as a shared vocabulary to model the domain, including the types of entities, their properties and relations. In addition to formal representation, they also support inter-operability between various types of Semantic Web systems [8].

In this article, we propose a framework - SemAnatomy3D which allows the association of semantics formalized in a biomedical ontology directly with the whole or with the relevant parts of the patient-specific 3D model. This creates a bridge between the patient-specific geometry and the formal domain knowledge, and can be considered as a first step towards an intelligent 3D indexing for supporting semantic-based retrieval from the medical knowledge-bases. Further, SemAnatomy3D contains a rich set of 3D shape analysis tools that allows the computation of quantitative attributes included in a domain ontology to obtain a more complete insight of the patient-specific anatomy.

II. Related work

As mentioned before a few SCBIR systems have been presented, in health-care practice the isolation of the medical

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data from its semantics restricts the retrieval queries to span across the available knowledge. It is challenging to retrieve the medical data based on both its content and context using simple queries to the data management system. Mostly, acquired DICOM images are retrieved only based on header information, such as patient age, patient gender, study date. A few existing initiatives in medical research [9], [10] target to couple acquired 2D images and their ROIs with the semantic context (e.g. anatomical label, functionality, clinical findings etc.). For example, ipad [9] extends the functionality of the image viewing platform OsiriX to add semantic tags from the RadLex ontology [11] to 2D medical scans through a simple user interface. However, the process is mostly manual and can only support the annotation of 2D DICOM images. A similar semantic annotation tool for medical images is RadSem which leverages the MEDICO ontology to cover various aspects of clinical procedures [10]. The context of ipad annotation is primarily oriented towards anatomy while RadSem annotation is more focused on disease aspect. RadSem uses an ontology-driven meta-data extractor only for the medical image format DICOM and links the image with anatomical annotations and clinical findings to generate an integrated view of a patient's medical history. The Medico system [12] applies an automatic detection and localization of anatomical structures within CT scans of the human torso and maps them to the concepts that are derived from FMA [13], ICD10 [14], RadLex. However, this approach is applicable only for CT data-sets of human torso and has been verified only within a small set of sample images. 3DSlicer, a medical image visualization tool [15], attempts to annotate the 3D model of organs segmented from images by a hierarchical structure of pre-defined anatomical labels to offer a medical data analysis workflow including the flavour of a semantic annotation of patient-specific 3D data.

A discussion regarding the significance of part-based semantic annotation of 3D-PSM for supporting early diagnosis and follow-up of Musculo-skeletal diseases (e.g. osteoarthritis and rheumatoid arthritis) is introduced in [16]. The authors highlight the fact that semantic annotation of 3D subparts can be utilized as a signature to automate part classification, 3D retrieval, and monitor the change of a specific part over time in clinical analysis. In the context of annotation and management of 3D-PSMs, we believe the main challenges are: (i) automatic identification of semantically relevant sub-parts from a 3D models; (ii) integration of various medical aspects (anatomy, symptom, diagnosis) in the annotation context to support complex data retrieval queries; (iii) creation of a standard information model to code comprehensive annotation of whole 3D models and its varying dimensional subparts in the form of structured metadata for the development of effective search techniques in health-care.

III. Semantic annotation and retrieval of 3D PSMs

The requirements for a framework for annotating patient specific 3D models by relying on formalized medical background knowledge, in order to assist various clinical applications (e.g., diagnosis, documentation, browsing, retrieval) has been (partially) studied within the scope of several international and national research projects (MultiScaleHuman [17], MEDIARE [18], POLITECMED consortium [19]). Lessons learnt from those projects inspire us to pursue the research direction of coupling the computational approaches to biomedical data processing with the knowledge management techniques to bring new solutions for the next-generation CAD systems. Even though, for instance, MultiScaleHuman project addressed the knee district, the same spirit of creating digital patient models to support CAD systems is echoed in SemAnatomy3D, which primarily focuses on the carpal anatomical region.

Once the 3D-PSMs are annotated, it is possible to envision a scenario of distributed medical repositories, where querying, reasoning and discovery of 3D-PSM can be done over the Web. In this paper, we discuss the SemAnatomy3D functionalities to support the diagnosis and treatment of rheumatoid arthritis in the carpal region. However, the methodology of developing a 3D PSM semantic annotation and retrieval system is general enough to support medical applications targeting other anatomical districts.

A. SemAnatomy3D: Requirements and design

The design, development and validation of SemAnatomy3D was guided by a requirement analysis phases in which we first collected the basic requirements, opinions, perspectives, and desiderata through the distribution of questionnaires to clinical professional and external research groups.

We investigated the features that clinicians/radiologists expect from a patient-specific 3D model annotation system, and how they intend to employ them in their routine practice. Note that in the diagnosis of rheumatoid arthritis, it is crucial for a clinician to have an idea about the patient's bone morphology, as well as position and characterization of the PoRs that can help quantify diagnostic parameters, to distinguish pathological cases from normal ones, to determine the attachment areas of the ligaments etc. Besides the suggestions targeting the direct clinical relevance of the framework, we also received comments that the annotation of 3D-PSM as a whole and its subparts would be beneficial for facilitating interoperability, querying, reasoning and discovery in the 3D medical repositories.

To summarize, the requirement analysis have led us to the following conclusions: a semantically rich and interoperable annotation system should - (i) express semantics not only of the whole 3D-PSM but also of the Parts-of-Relevance (PoRs) where the PoRs can be either of anatomical significance, such as anatomical landmarks, prominent features or pathological markers, such as erosion, lesion; (ii) describe the semantics of the data (3D-PSM) by relying on formalized knowledge for both anatomy and quantitative parameters/indicators to support the documentation of patient records; (iii) provide tools to compute automatically the quantitative parameters and indicators from patient-specific 3D model. System should also leave flexibility to adjust the annotations so that the annotator can add his/her own perspective on the results obtained.

B. SemAnatomy3D: overview

To address these requirements, we propose a platform that has two main components - *SemAnantomy3D annotation tool* (cf. IV) and *SemAnatomy3D knowledge-base* (cf. V). The graphical tool SemAnatomy3D allows users to accomplish annotation of a 3D-PSM and its Parts-of-Relevance (PoRs).

The SemAnatomy3D Knowledge Base stores part-based annotations of the patient specific 3D models with the relevant medical information, and references to other media resources. To support the inter-operability with other applications over the Web we adopt an extended version of Open Annotation data model [20], promoted by the W3C community, and low-level geometric data representations of the PoRs (indices) are stored in an XML-like file format; we refer to it by its OS extension ".sem3d".

C. Domain ontologies for medical context

The domain ontologies we use in our research investigations, capture the minimal medical context, which support the use-cases mentioned in Sec. VI.

The considered medical context includes medical background knowledge on: i) patients, acquisition sessions/protocols, anatomy, as well as knowledge on ii) characterization of 3D-PSMs on geometry and structural levels which could be used in clinical practice. We represent this domain knowledge as OWL ontologies, and we follow the knowledge re-use guidelines where possible [21].

1) Knowledge formalization of carpal region: To support the part-based annotation of 3D models of the carpal region, we consider the subpart of the FMA ontology related to this anatomical district. The extracted subpart is then enriched with the part-hood and articulation relations between the facets, as depicted on Fig. 2. This additional information was needed to support the use-cases we propose for clinical practice, and it was missing in the [1]Bioportal version of the FMA ontology. We keep the same labels for our two main OWL classes of the carpal region conceptualization (*Cavitated organ* and *Zone of Short bone* (Fig. 1) as in FMA for compatibility with other applications which use FMA ontology.

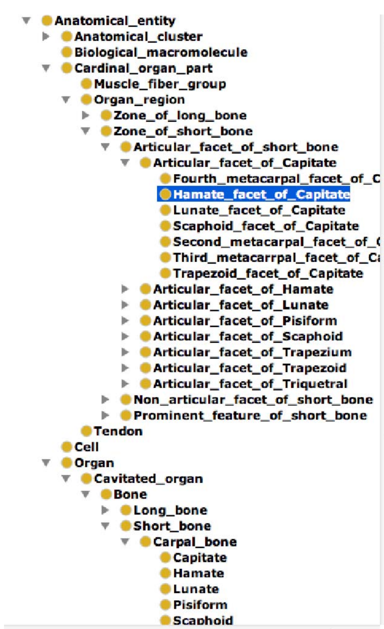

Fig. 1. Taxonomy of carpal bones and PoRs

[1]http://bioportal.bioontology.org/ontologies/FMA

2) Knowledge formalization of clinical practices: The formalization of medical background knowledge consisting of patient information, acquisition sessions, acquisition protocols, and relations between these concepts: patients undergoing acquisitions sessions, acquisition protocols performed during the acquisition sessions is captured by the *MultiScaleHuman Ontology* [22]. This ontology was developed in the EU FP7 "MultiScaleHuman" project, where the goal was to associate multi-scale biomedical data with anatomical entities, patient and acquisition session/protocol information to support CAD and visualization systems for diagnosis of musculoskeletal diseases of a human knee.

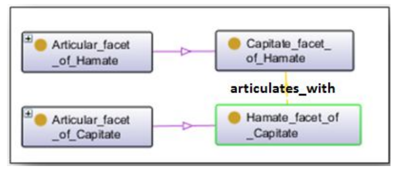

Fig. 2. Articulation relations between the facets of Hamate and Capitate bones

IV. SemAnantomy3D annotation tool

Using the SemAnantomy3D annotation tool, the annotator can identify the PoRs from individual 3D-PSM in an interactive and/or in an automatic manner (Fig. 3(b)), associate conceptual tags derived from the ontology, measure quantitative attributes and store both geometry and annotation in such a way that can support efficient part-based 3D-PSM retrieval. Besides, SemAnatomy3D also supports collective annotation of a set of 3D-PSMs in a same scene (Fig. 3(a)), since it is relevant to consider a complete setting when performing analysis of anatomical joints.

In our case-study of carpal bones (cf. Sec.III), PoRs may corresponds to (see Fig. 4), such as: *surface patch (areas)* - articular and non-articular facets of the bone, prominent features such as scaphoid tubercle, hook of hamate, ligament insertion sites; *edges (polylines)* - boundaries between anatomical landmark regions, contours indicating abnormalities/disease affected regions, e.g. eroded regions; *vertices (points)* - extremal features of the bone, such the tip of a protruded facet, extreme pressure point. Thus, the realization of 3D annotation becomes more challenging in terms of PoRs identification and management.

A. Descriptive annotation

The descriptive annotation of 3D-PSMs aims to associate the concepts that are formally defined in the domain ontology with the whole 3D reconstructions of patient's anatomy or with the PoRs. This creates an ontology-based indexing of the 3D-PSM and its relevant subparts, and can be used by the search engine to retrieve more semantically meaningful result than the keyword-based approach.

The identification of PoRs in a 3D-PSM is not trivial in terms of interaction, and therefore SemAnatomy3D provides support with two different PoR selection methods:

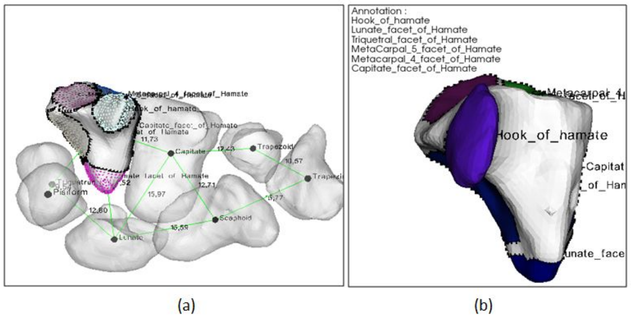

Fig. 3. SemAnatomy3D: (a)Annotation of Hamate bone in a complete "Carpal region" setting, (b)Individual annotation of Hamate bone.

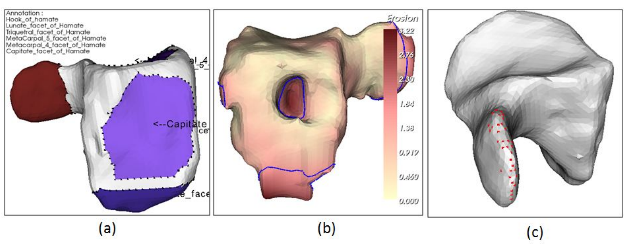

Fig. 4. SemAnatomy3D annotation of varying-dimensional anatomical landmarks (Hamate bone): (a) articular facets - surface patch; (b) contours indicating erosion - edges; (c) pressure points - vertices

1) Fully interactive annotation: SemAnatomy3D allows to select various elements (e.g. vertices, edges, surface patch) of a 3D surface mesh as user-defined PoRs by interactive 3D selection tools, such as smart-cut, draw, paint and delete strokes, picking of points. For instance, in smart-cut the user can simply select a region over a 3D-PSM, and the system automatically computes the minimal cut in the 3D surface including the region that is not visible from the user-viewpoint, and colours the selected portion of the model accordingly. Furthermore, the system allows precise modifications of the PoRs boundary by inserting/deleting elements from the selected PoRs using a simple interaction (paint/delete strokes). After the precise selection of PoRs, the user can associate corresponding conceptual tags to the selected PoRs by the interactive navigation of the reference ontologies.

2) Automatic annotation: We have developed an automatic template-based method to associate descriptive annotations to the predefined parts of 3D-PSM (see Algorithm 1). The basic idea is to automatically annotate a 3D-PSM by a parametric 3D template which contains the anatomical landmark positions as parameters [23]. We register the parametric template against the targeted model using an elastic transformation, and propagate the annotation onto the target model. Additional annotations, such as personal notes, text documents, can be added in a manual way after the automatic PoR recognition process.

In particular, we apply an non-rigid variation of the Iterative Closest Point (ICP) algorithm [24] initialized with coarse alignment using centroid matching between template and target model. We build a KD-tree [25] of the co-registered model to find the closest-point on target model for mapping the annotation. Using the nearest neighbour search method [25], the annotation is propagated from the vertices of annotated template to closest vertices of the target mesh. After the propagation, the system automatically detects the boundary of each annotated surface fragments. We apply a filtering which takes into account neighboring vertex relations to generate a continuous region annotation based on 1-ring neighbour rule. Afterwards, the system allows precise modifications of the PoRs boundary using simple user interaction tools described in Section IV-A1. Algorithm 1 summarizes the steps of the automatic annotation process in SemAnatomy3D.

Algorithm 1 Automatic annotation of PoRs

procedure PARAMETRIC METHOD
  Input: $M \leftarrow$ Target 3D-PSM
  $T \leftarrow$ Parametric template model
  Output: Sub-parts of M annotated with labels.
  $R \leftarrow$ *Coarse_alignment(T,M)* ▷ using centroid matching.
  $K \leftarrow$ *Nonrigid_ICP(R,M)* ▷ to refine the alignment locally.
  $KDTree \leftarrow$ *BuildKDTree(M)*
  $Subparts_M \leftarrow$ *Propagate_annotation(T,M,KDTree)* ▷ by nearest neighbour search method.
  Flitering_regions(Subparts_M) ▷ to generate continuous regions.
note: Adjustment of the subparts and modification of the annotation can be done interactively.

B. Quantitative annotation

In clinical investigation, specific quantitative parameters computed directly from the data, are interpreted to detect the symptoms and perform the diagnosis. As a consequence, the annotation of 3D-PSM should entail not only the association of the conceptual information to the 3D model, or to the PoRs, but also the computation of those attributes that could be used to analyse patient records.

In our case-study (cf. Sec.III), we focused on identification and measurement of the parameters/indicators that can be computed from 3D carpal bones or their PoRs to support the diagnosis and the evaluation of follow-up data related to the treatment of rheumatoid arthritis. In Table I, we present a set of parameters that could be computed automatically, and currently implemented in the system, to provide a rich characterization of the bones or its subparts. In this study, we take into account two different computational approaches:

1) Quantitative measurement: we developed a 3D shape analysis tool library within SemAnatomy3D to automatically compute some of the quantitative parameters (Table I) directly from a 3D-PSM or from its annotated PoRs based on popular geometric and shape analysis methods.

2) Dissimilarity from normality: we compute non-trivial measurements such as position of erosion/lesion based on co-registration of the healthy template [23]. As our target is to measure the difference between pathological data and the corresponding healthy template, we consider only rigid transformations.

TABLE I. LIST OF PARAMETERS FOR THE CHARACTERIZATION OF RHEUMATOID ARTHRITIS

Computation	Input	Output	Parameters
Quantitative measurement (ref. section IV-B1)	3D-PSM	Scalar value	Bone Volume (BV)
			Bone Surface (BS)
			Bone Length (BL)
			Bone Volume/ConvexHull Volume (BV/CV)
		Scalar value map	Curvature map [Gaussian] (CMap)
	3D-PSM and annotated PoRs	Scalar value	Area of articulation region
			Geodesic distance between landmarks
Dissimilarity measurement from normality (ref. section IV-B2)	Template model (Healthy) and target 3D-PSM	Scalar value map	Erosion map
		Scalar value	Erosion score/Lesion volume
		Identified PoR	Eroded region

After the co-registration of the healthy template and pathological models, SemAnatomy3D generates a vertex-wise scalar-value map on the target data representing the Euclidean distance from each vertex on registered template to the closest vertex on target data (Fig. 5). We identify the closest point on the target data based on nearest neighbour search operation on the KD tree. For further analysis, the system identifies the eroded regions based on a pre-defined rule (e.g. average scalar value greater than 1.5) and draws the contours to identify the PoR boundary. After the measurement, SemAnatomy3D offers the possibility to generate an individual PoR based on a given scalar value range. We also store the information on the average erosion value of a specific PoR which is the average scalar value of the vertices belonging to that specific region. Afterwards, we utilize it to support data retrieval queries in the knowledge-base (some examples on this in the dedicated section VI).

We present a result of our implementation on scaphoid bone in Fig. 5, where we use a healthy template scaphoid bone which belongs to the same age and gender group as the target patient, and apply the dissimilarity measurement technique to compute the scalar value map and highlight the eroded regions.

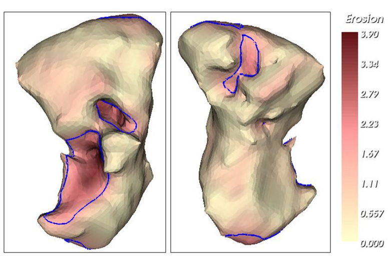

Fig. 5. Erosion analysis in SemAnatomy3D (use case-Scaphoid bone)

V. SEMANATOMY3D KNOWLEDGE-BASE

Annotations are stored as instances in the SemAnatomy3D knowledge base and serve as a bridge between the conceptual context of the medically relevant information of the PoRs (semantics) and their geometric representations (fragments of 3D models). Each instance is therefore connected to the concepts from the domain ontologies we use and contains a link to the ".sem3d" file stored in a local file system.

A. Sem3D annotation data model

The main role of the Sem3D annotation data model is to manage the annotation in a way to facilitate interoperability, querying, reasoning and discovery of 3D-PSM as a whole and its subparts. A number of semantic annotation data models have been proposed which aim to support interoperability on the Web. These include: the Annotea model [26], and the Open Annotation (OA) [27]. Unfortunately, none of these common models provides sufficient specifications for annotating 3D-PSM and their subparts.

The OA data model [20] developed by W3C Open Annotation Community Group specifies a extensible data model to support interoperable annotations for enabling discovery and sharing of annotations without using a particular set of protocols. We extended the OA model to fulfill three main requirements of SemAnatomy3D annotation framework: (i) store the annotation of varying-dimensional 3D fragment (Figure 4); (ii) support whole and part-based annotation with descriptive and quantitative attributes; (iii) multimodal annotation, i.e. annotation with textual tag/numeric value, 2D image or text file. We present our proposed schema in Figs 6, 7.

In addition to Open annotation model (OA) new concepts in Sem3D annotation data model have been defined:

- `sem3D:3DFragmentSelector` is specified as a rdfSubClassOf the oa:Selector element to model different representations of the 3D PoRs (Section III).
- `sem3D:Media` stores various types of data format, e.g., 3D triangulated models, 3D fragments (.sem3D), 2D images, textDocument, which can either have their own annotation (*source of annotation*) or can be considered as annotation of another data (*body of annotation*).
- `sem3D:Quantitativevalue` stores a single numeric value parameter or scalar value map computed from the sem3D:Media. It can be considered as form of annotation. It has two rdf:DataProperties: (i) `sem3D:paramtype` - describes the type of quantitative parameters, e.g., volume, area, curvature map; (ii) `sem3D:paramvalue` - stores the numeric value of the parameter.
- Restrictions - We put the following restrictions on `oa:SpecificResource` and `sem3d:3DModel`: `oa:SpecificResource` rdf:subClassOf `sem3D:has source` exactly 1 `sem3D:Media` that means `oa:SpecificResource` should have exactly one data file. `Sem3d:3DModel` rdf:subClassOf `sem3D:has specific resource` some `oa:SpecificResource` that means `sem3d:3DModel` can have some (one or multiple)

TABLE II. SEPECIFICATION OF SEMANATOMY3D FRAMEWORK

Type	standalone annotation client & web-based query interface
Imports	segmented surface model in .off, .ply, .vrml, .vtk format.
Exports	.sem3D file for each annotated fragment.
Annotation data model	SemAnatomy3D extension of OA.
Domain ontology	Multi-Scale Ontology in .owl.
Saves	instances in SemAnatomy3D knowledge-base
Annotation technique	automatic and interactive
Ontology-driven metadata	descriptive and quantitative
Query in KB	Jena SPARQL processor

specific resource.

The SemAnatomy3D annotation data model snapshot in Fig. 6 is related to the saving of a 3D surface fragment annotated as "Hook of hamate". Each instance of `oa:Annotation` is linked to the instance of `oa:specific_resource` and each `oa:specific_resource` instance `oa:has_source` exactly 1 `sem:3D Media` instance. The `sem3D:Media` instance describes the data by storing the actual file location of annotation source. If a `oa:specific_resource` instance corresponds to a PoR (sub-part) annotation, then it will be linked with a specific `sem3D:FragmentSelector instance`, e.g., for "Hook of Hamate" it is linked with `sem3D:SurfaceSelector`. In Fig. 7, we show how the annotation instances are related to various information, such as semanticURI, external link, quantitative values in the SemAnatomy3D knowledge-base.

B. .sem3D file

We developed a simple and effective file format .sem3D with three main goals: (i) support a faster way of reading, writing and rendering of 3D subpart annotation; (ii) to be as simple as it can, so it can be customized for various applications; (iii) avoid storing redundant information.

We came up with a index-based method of storing varying topological dimensional 3D fragments in a .sem3D file as follows: i) *Surface fragment in .sem3D* - we store only the index of the cells (triangle) belonging to the fragmen, ii) *Line fragment in .sem3D* - we store index of the points of belonging to the line fragment. We maintain adjacency of the points in the form of - $xy, yz, zk, \ldots$, iii) *Point fragment in .sem3D* - we only store the index of the points. With this approach, a .sem3D file which stores a surface fragment containing 717 cells and 379 points has a size less than 1KB.

VI. USE CASES: DISCUSSION AND EVALUATION

In the following subsections, we present some examples of retrieval where the formalized domain knowledge and the semantic annotation of 3D-PSMs can be utilized to support the diagnostic analysis related to rheumatoid arthritis in carpal bones. Our prototype implementation uses SPARQL queries [28] to retrieve relevant information through Jena semantic-web framework [29]. For better understanding we use description of SPARQL queries in natural language.

A. Identification of the affected neighbourhood in anatomical joints

A clinician, when consulting a surface fragment of a 3D-PSM annotated as an articulation facet, might be willing to consult adjacent facets of the fragment with which it articulates. In fact, in the case of RA, if one articulation facet in a joint contains erosion or lesion, there can be a certain chance of erosion in adjacent articulation regions. A sample query could be expressed as *"Where can be probable chance of erosion in "Carpal region" of patient XX, if "Capitate facet of Hamate" has average erosion value 2.5?"*.

The execution of such a query is possible, since our anatomical formalization (cf. III-C) captures adjacency relations between the articular facets of bones, together with annotated quantitative parameters, among which there is the average erosion value (cf. IV-B2). Thus, we first retrieve the adjacent facets of the selected facet, and then filter the answer set so that it contains only those whose associated average erosion value falls inside a pre-defined range. For instance, we assume that any articular facet whose average erosion value is between 1.0 and 2.0 is considered as a possibly eroded region.

B. Similar-case retrieval

In the scenario of similar case search, clinicians look for other patients having some analogies to the case in question. Assuming that the condition of patients anatomical entities evolves over time (e.g. from healthy to pathological), it is possible to express the following query: *Retrieve the cases where "Capitate facets of Hamate" are similar to that of the Patient X's one?*

One way to establish the similarity between cases is querying the knowledge-base for 3D models of patients annotated with similar quantitative parameters to those of the given patient. For example, the KB could be queried to retrieve all patients where average erosion value of "Capitate facets of Hamate" region falls into some interval. The interval should be chosen based on the erosion value of the given patient, which can be done by using built-in SPARQL algebraic operators [30], which could filter all patients whose erosion score is different from that of the given patient by at most 2.

C. Follow-up report

Analysing the difference in articular facet erosion of the same patient at different time intervals can help clinicians in the diagnosis and follow-up monitoring of the patient's health status. An advanced query may be summarized as *"Retrieve all "Articular facet" (s) of patient XX "Carpal bone" where erosion increased compared to the last acquisition session"*.

SemAnatomy3D allows its users to annotate 3D models of the same PoR (e.g., capitate facet of hamate), belonging to the same patient associated with two different acquisition sessions and ultimately store the annotations into the KB. To support follow-up monitoring of the patient, we proceed as follows: i) we query the KB for the 3D-PSM created from different acquisition sessions of patient XX, which he/she underwent at different times, ii) we then, filter the answer set to get 'Articular facet" PoR annotations of carpal bone with their quantitative measurements, iii) we compare pairs of annotations of the same PoR, distinguished by their acquisition time, and return only those annotations which exhibit a difference.

The adoption of 3D annotation systems tailored to the clinical domain, as we proposed with SemAnatomy3D, allow

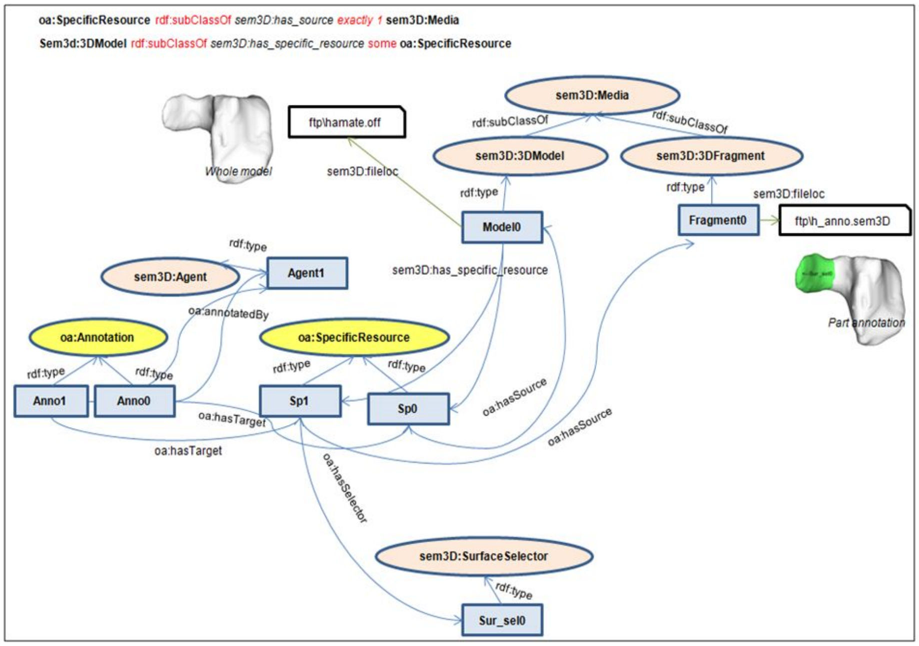

Fig. 6. SemAnatomy3D extension of OA model - saving of 3D surface fragment annotation

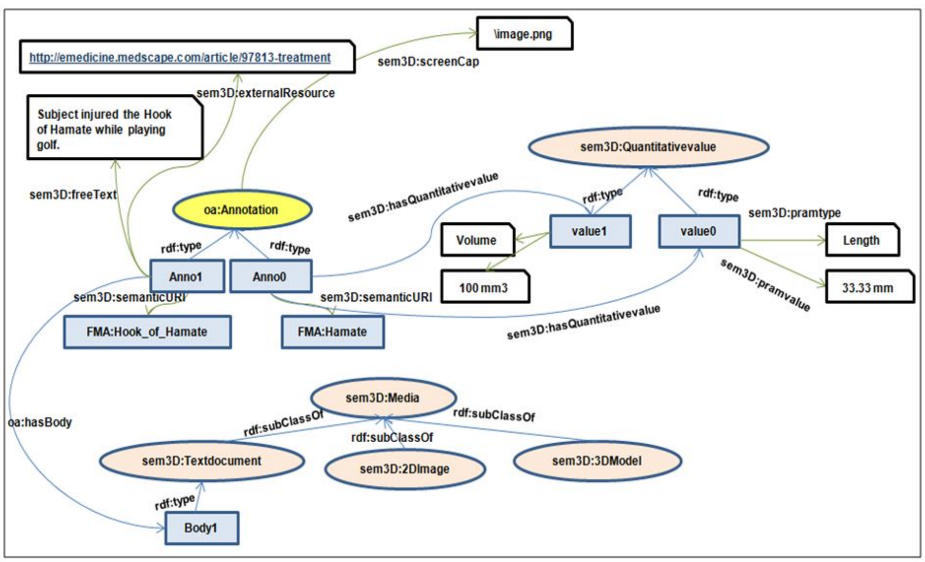

Fig. 7. SemAnatomy3D extension of OA model - formalization of annotation

us to envision distributed medical repositories where querying, reasoning and discovery of 3D-PSMs can be done over the Web. As a concluding remark, we are currently testing our system locally only and on a small dataset (≈ 98 patients). Due to the privacy issue and unavailability of a standard exchange protocol for clinical 3D data, as of now, the system cannot be tested for retrieval performances over the Web. We are now in the clinical validation phase, where we consult clinicians to asses our framework and its ability to support clinical investigations.

VII. Conclusion

In this study, we have proposed SemAnatomy3D, a framework for creating expressive 3D-PSMs, through the process of 3D annotation, which associates semantics with the whole 3D model and to its Parts-of-Relevance. Specifications of the framework is presented in Table II. Annotations and extracted quantitative parameters are stored in the knowledge-base, thus allowing storage of both data and annotation in an integrated way. Ontology-driven part-based annotations are then used to index relevant parts of the 3D-PSMs by fine-grained shape characterization for supporting efficient semantic-based retrieval from the knowledge-base. As a result, SemAnatomy3D provides an integrated view, enabling the analysis of the 3D-PSM with information related to anatomy and pathology to obtain efficient clinical reporting of patient's records. Finally, applications of SemAnatomy3D have been presented through three use-case scenarios, focusing on rheumatoid arthritis. We specialized our framework on the carpal bones, but the approach can be analogously extended to any other anatomical district.

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