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ONTOLOGICAL FRAMEWORK FOR KNOWLEDGE MANAGEMENT IN ORTHOPEDIC SURGERY

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Milan Zdravković, Miroslav Trajanović, Dragan Pavlović

Faculty of Mechanical Engineering, University of Niš, Serbia

Abstract. *Efficiency and effectiveness of orthopedic surgery can be achieved by enabling proper decision-making in a shortest period of time, based on complete and updated information on the status, type of fracture and fixators used for a particular fracture. In this way, the risk of possible complications caused by a late intervention can be reduced. In such circumstances, there exist critical needs for an effective and efficient knowledge management approach where different domain models are combined and formally interrelated, so that the decisions are based on the consistent and complete information. In this paper, ontologies are used to propose a framework for implementing such an approach in the domain of orthopedic surgery. The framework combines formal models of the generic products and supply chains for their manufacturing and delivery, anatomical elements, e.g. bones, types of their fractures and fixators – the medical products which are used in the fracture treatments. Then the possible uses of this framework for the purpose of knowledge management in orthopedic surgery are discussed in the context of the assumptions of development of Next Generation Enterprise Information Systems.*

Key Words: *Knowledge Management, Orthopedic Surgery, Ontology, Systems Interoperability, Semantic Interoperability*

1. INTRODUCTION

One of the major challenges of modern health care organizations refers to the possible improvement of the health service quality. To achieve this goal, health care organizations are using standardized clinical protocols in many medical domains [1]. These protocols are now represented in a variety of different formats, languages and formalisms. This variety is considered as a significant obstacle for semantic reconciliation of the models as well as the interoperability of the respective systems that are using those models, thus

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Corresponding author: Milan Zdravković
Faculty of Mechanical Engineering in Niš, University of Niš, ul. Aleksandra Medvedeva 14, 18000 Niš, Serbia
E-mail: milan.zdravkovic@gmail.com

posing a strong need for unification and alignment which will significantly increase the effectiveness of the given systems.

One way of resolving this problem, namely, that of achieving the unique representation of the clinical models and protocols, is to use ontologies. According to [2] "an ontology is an explicit specification of a conceptualization." Thus, it represents an approach to formal modeling of a specific reality. Ontologies can provide a significant contribution to the design and implementation of the Enterprise Information Systems (EIS) in the medical domain. Their role in the integration and harmonization of heterogeneous knowledge sources is already considered by many research projects, especially in the field of clinical guidelines and evidence-based medicine [3]. Besides the interoperability aspect, the use of ontologies as means for formal representation of the medical concepts will enable the validation of these concepts in terms of consistency and completeness checking and thus it will contribute to more accurate decision-making at the implementation (systems) level.

The aim of the research done for this paper is to demonstrate that the ontologies can help in making the decisions regarding conceptually different notions in healthcare, i.e. medical products, management of the supply chain for their manufacturing and delivery and anatomy features. Since these notions are handled in different EISs, within or outside the clinical domain, we indirectly aim at demonstrating that these systems can be made interoperable. Namely, based on the common, inter-related models, the respective systems that are using these models may exchange the relevant information, that is by default understood by all of these systems.

In specific, this paper deals with a set of such decisions being made in the domain of orthopedic surgery. Namely, we propose an ontological framework which will facilitate a timely and accurate selection of the fixator – a device that is used in the treatment of the specific types of fractures of so-called long bones. This selection is being done based on the anatomical features of the fractured long bone and correct classification of specific fracture type. Finally, the ontological framework enables efficient establishment and management of the supply chain for the manufacturing and delivery of the selected fixator. Thus, it will facilitate a prompt response of the medical centre in case of an urgent need for non-standard, customized medical products, typically manufactured in made-to-order fashion.

2. The Ontological Framework for Knowledge Management in Orthopedic Surgery

The use of ontologies in medicine is mainly focused on data management, i.e. medical terminologies. Data collection (grouping) is becoming one of the most important issues that the researchers in the clinical domain are facing. Due to the inconsistency of the formats used for data representation, it is very difficult to develop generic computer algorithms for their interpretation. Researchers tend to represent knowledge of their domain in an independent and neutral format so that data can be shared and reused in different platforms. This problem can be solved by using ontologies. Ontologies provide a common framework for structured knowledge representation. These ontological frameworks provide common vocabularies for concepts, definitions of concepts, relations and rules, allowing a controlled flow of knowledge into the knowledge base [4].

Today, ontologies are not only used as modeling assets but also as runtime models, which continuously create and maintain the relationships between the logically related concepts in the different models or systems. Thus, they represent not only a tool for the knowledge management in a specific domain, but also act as enablers for the interoperability between the corresponding systems. In this paper, we demonstrate that the ontologies can be used as a facilitator for interoperability among the Clinical Information Systems (CIS), which are used to manage the comprehensive patient information, including different aspects of diagnosis and treatment, the Decision Making systems and even, Supply Chain Management systems.

The proposed framework has been developed by using the OWL (Web Ontology Language). The OWL, adopted by the World Wide Web Consortium (W3C), is a semantic markup language designed for publishing and sharing ontologies on the World Wide Web. It was developed by extending the Resource Description Framework (RDF) vocabulary and it is based on the experience of developing the DAML + OIL Web ontology language [5].

The framework uses and combines four different ontologies. The ontologies of anatomy and formal representations of the Electronic Health Record (EHR) are used to establish the link with CIS, namely to provide a dictionary for pulling information about the specific anatomical features of the patient with the injured bone. The ontology of fractures is used to automatically classify the type of the fracture, based on the information already instantiated in the Anatomy and EHR ontologies. The ontology of fixators is used to select the medical device that accurately fits the diagnosis of the injured patient.

2.1. Medical ontologies and electronic health records

The anatomy domain is that domain of medicine in which, so far, ontologies are most commonly used. In the medical domain, the anatomy is a fundamental discipline that represents the basis for most medical fields [6]. Formal anatomical ontologies are an important component of the informatics healthcare infrastructure [7]; also, they are informatics tools used to explore biomedical databases. Structural relationship that is primarily used in these ontologies is part of the relationship, because smaller anatomical entities are naturally seen as components of the larger ones [8].

There exist plenty of anatomical ontologies, clinical ontologies or ontologies of other domains in medicine. Based on the Bioportal statistics, the most frequently used ontology is the Foundational Model of Anatomy (FMA) [9]. The FMA is a domain ontology that represents a coherent body of explicit declarative knowledge about human anatomy.

Clinical vocabularies play a strategic role in providing an access to computerized health information because clinicians use a variety of terms for the same concept. When a clinician evaluates a patient, the resulting documentation typically captures free text and unstructured information, such as history and physical findings. The efficiency of payment (reimbursement) processing is probably the key incentive for transforming this free text into more structured data. Some of the most commonly used clinical vocabularies today are the Logical Observation Identifiers, Names, and Codes (LOINC) [28] and the Systematized Nomenclature of Medicine - Clinical Terms (SNOMED) [29]. The LOINC for ordering lab tests and the SNOMED-CT for recording test results provide well-defined meanings for specific terms that can be standardized across applications. The LOINC is used to identify individual laboratory results, clinical and diagnostic study observations. It is most widely used in laboratory systems. The SNOMED is designed to be a comprehensive, multi-axial, controlled terminology, created for the indexing of the entire medical record.

There are three main organizations that develop and maintain the standards related to EHR messages: the Health Level Seven (HL7), the Comité Européen de Normalization – Technical Committee (CEN TC) 215, and the American Society for Testing and Materials (ASTM) E31. The HL7 [10] develop the most widely used healthcare-related electronic data exchange standards in North America. The CEN TC 215 is the preeminent healthcare IT standards developing organization in Europe. Recently, the research community interest was brought to the OpenEHR [11] open standard specification in health informatics. In contrast to HL7 and CEN's EN 13606 standards [12], which are strictly concerned with data exchange between EHR systems, the OpenEHR describes management and storage, retrieval and exchange of health data from EHRs.

Unfortunately, there is no developed standard RDF/RDFS/OWL ontology that could be used to formally describe an EHR yet. This is considered as a major obstacle for semantically interoperable CIS, as EHR records often suffer from the vendor-specific realizations of patient record data sets which rarely accommodate to the controlled terminologies [6]. For the proposed framework, we use the OpenEHR OWL ontology developed by Roman [13]. Some preliminary work has been done in integrating the above ontology with SNOMED [14] and LOINC [28] OWL representations.

2.2. Ontology of fixators

For the representation of the fixators, the Product ontology [15] is selected, for the reasons of its simplicity vs. the fulfillment of requirements related to modeling fixators and their features. The product ontology is mapped to the UNSPSC product classification scheme [16], by using the UNSPSC-SKOS ontology as a mediator. The SKOS [17] is a family of formal languages, built upon RDF and RDFS for representation of thesauri, classification schemes, taxonomies or other types of structured controlled vocabulary.

The ontology of fixators was developed [18] with the objective to represent the topology of these medical products. It represents a meta-model of their Bills of Materials (BOM). It extends the Product ontology by specializing its Product, Part and Feature classes, as illustrated in Fig. 1.

Structural dimensions of the elements fixators depend on certain dimensions, i.e. features, so the feature class contains a subclass named dimension. Class dimension contains subclasses of characteristic features that may affect the structural dimensions of fixator elements. Note that some of the features above are the features of the bone and not of the fixator itself. However, these features are represented at the level of the product, in order to facilitate the selection of the proper fixators, based on the features of the bone and its fracture.

The ontology of fixators is instantiated with two specific fixators: the external fixator "Mitković" and hybrid external fixators. Hence, the former one consists of the following elements: Rod, Screw, Lateral supporting element, two clamping rings on the lateral supporting element, Screw Nut, Washer, and two clamping ring plates on the clamp ring. Each of the part individuals is assigned with the characteristic dimensional features. Thus, it becomes possible to select the specific fixator whose features correspond to the geometrical features of the fractured bone, where these features are established by using the X-Ray or CT scans of the patient.

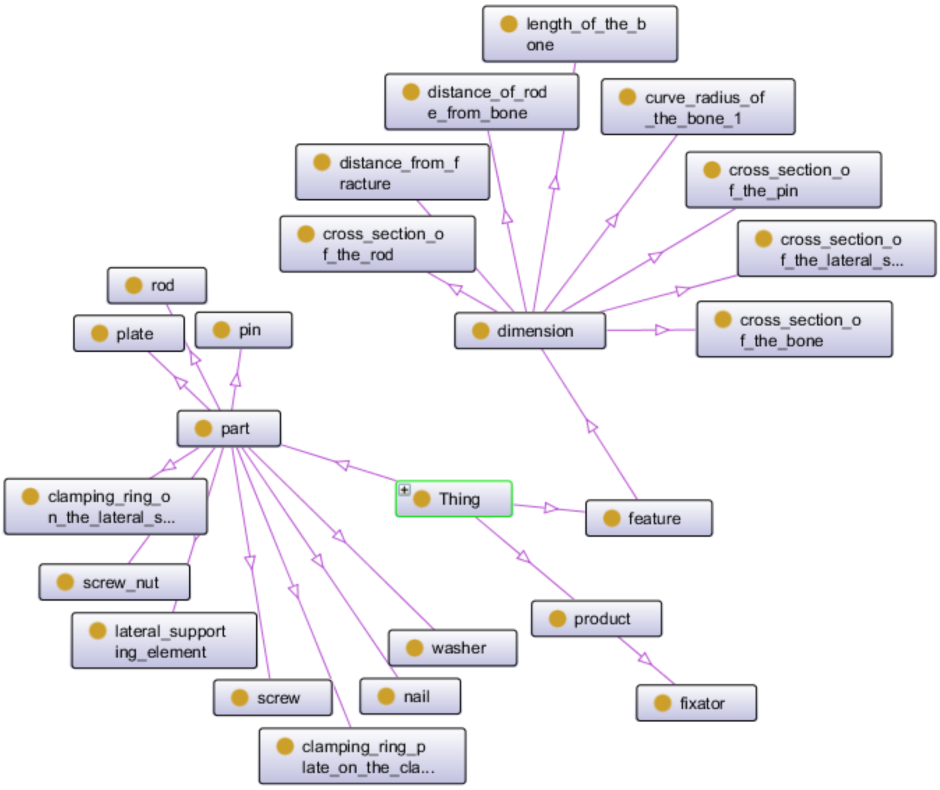

Fig. 1 Fragment of the ontology of external fixators

2.3. Ontology of fractures

Ontology of fractures formally describes different types of the bone fractures and thus, it makes possible inference of the exact type of fracture, based on its diagnosed features (such as fracture location, number of fragments and their geometry, fracture lines, etc.). This inference is considered as a trivial problem when humans are interpreting the X Ray or CT scans. However, the ontology of fractures is intended to be used by the systems, which can automatically interpret the observed specific features of the fracture, e.g. based on image processing and feature recognition. The inferred type can then be used to select the corresponding fixator for the injury treatment. The proposed ontology's scope is restricted to diaphyseal fractures because these fractures are treated by using the external fixators. The fragment of ontology, related to humerus bone is illustrated in Fig. 2.

As highlighted above, the ontology of fractures is strictly formal and it uses the relationships of the specific types of diaphyseal fractures with the observations from CT scans to define the necessary conditions for the classification of the specific type. These observations include: number of fracture planes, angle of the fracture planes to a sagittal plane, number of bone fragments and existence of contact between the bone fragments. For example, a simple humerus fracture is characterized by only one fracture and hence, two bone fragments. In the Manchester OWL syntax, this restriction is represented as follows:

```
hasBoneFragment exactly 2 bone_fragment
```

The simple humerus fracture can be further decomposed into oblique, transverse and spiral fractures, depending on the angle of the fracture plane to a sagittal plane of the bone and/or its existence. The following restrictions are used to represent the oblique and transverse fractures, respectively:

```
hasFracturePlane some (hasFractureAngle min 30)
hasFracturePlane some (hasFractureAngle max 29)
```

Spiral fractures, caused by torsion, are characterized by the fact that the fracture plane does exist at all, as the fracture line represents the spiral. Hence, the condition is:

```
hasFracturePlane exactly 0 fracture_plane
```

Furthermore, the wedge humerus fracture is characterized by the minimum of 3 bone fragments, where the one is of wedge-shaped. The second condition is that all bone fragments remain in contact with each another. Hence, the restrictions are as follows:

```
hasBoneFragment min 3 bone_fragment
hasBoneFragment only (inContactWith some bone_fragment)
```

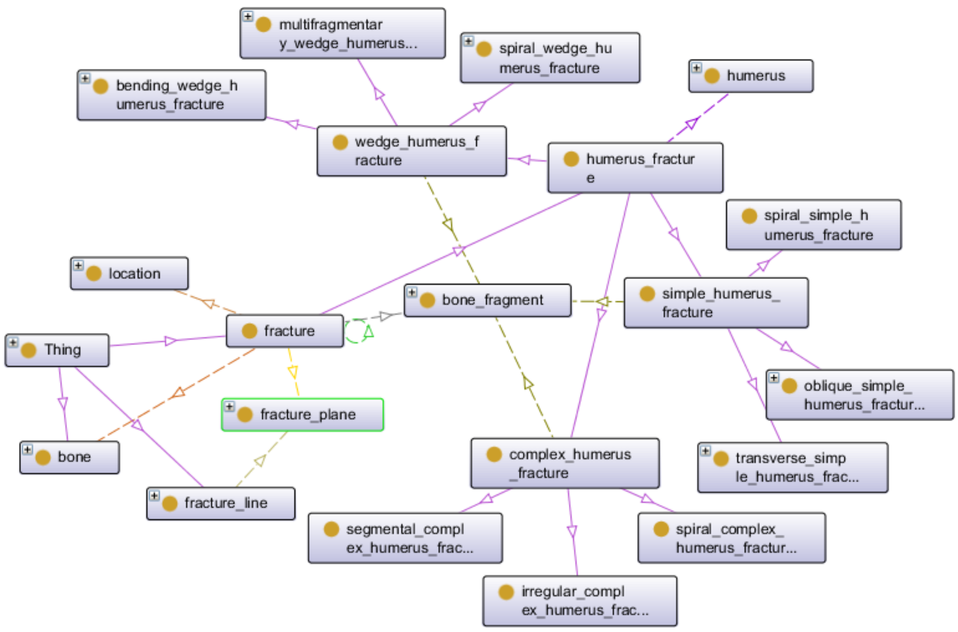

Fig. 2 Fragment of the ontology of long bones' diaphyseal fractures

The wedge humerus fracture can be further decomposed into multifragmentary, bending and spiral fractures. Each of these subtypes is described by the corresponding conditions. For example, the classification of the bending wedge humerus fractures is enabled by the following restrictions:

```
hasBoneFragment exactly 3 bone_fragment
hasFracturePlane only (oblique_fracture_plane or
transverse_fracture_plane)
```

In the presented ontological framework, the ontology of fractures is imported by the ontology of fixators, which is then used to execute semantic queries, with the objective to select the specific fixator for a given circumstances of the fracture and anatomical features (e.g. bone length).

2.4. Supply chain ontology

The response time is one of the critical factors for a successful treatment of the orthopedic disorders. The ontologies of these disorders (i.e., the bone fractures) and the medical products for their treatment (i.e., the fixators), when combined with the atomic observations from the CIS (acquired through medical ontologies), provide the framework for accurate and fast decision making and hence, reduction of this response time. However, sometimes, due to the specific anatomy features of the patient or fracture, it is not possible to effectively treat the orthopedic disorder with the medical devices on stock. Instead, a custom orthopedic fixator may be needed to facilitate an efficient treatment. Needless to say that the process of ordering, manufacturing and delivering such a fixator is extensively time-consuming and may incur the delays that could be critical for a successful treatment. However, the proper knowledge management strategy can significantly reduce this time. With such a strategy implemented, a clinical centre can overtake some of the roles of the medical devices supplier and directly implement the management of the supply chain for their manufacturing and delivery.

This approach is facilitated by the supply chain ontologies, namely the SCOR ontological framework and a semantic web application for supply chain configuration that is using that framework.

Based on the product's topology and manufacturing or delivery strategies of each product part (including the services), a sourcing (S) strategy, namely the supply chain configuration is generated by the SC-CONF-Sys application [19]. The SC-CONF-Sys is based on the SCOR reference model for supply chain operations [20], a standard approach for analysis, design and implementation of the core processes in supply chains.

The SCOR ontological framework [21] represents knowledge at three different levels of conceptualization (see Fig. 3). First, the implicit SCOR ontology is used to enable interoperation of the SC-CONF-Sys with proprietary SCOR tools. Second, the explicit SCOR-Full ontology is an expressive domain ontology which defines the meanings of the implicit SCOR entities and thus, it facilitates interoperation of the SC-CONF-Sys with other enterprise applications.

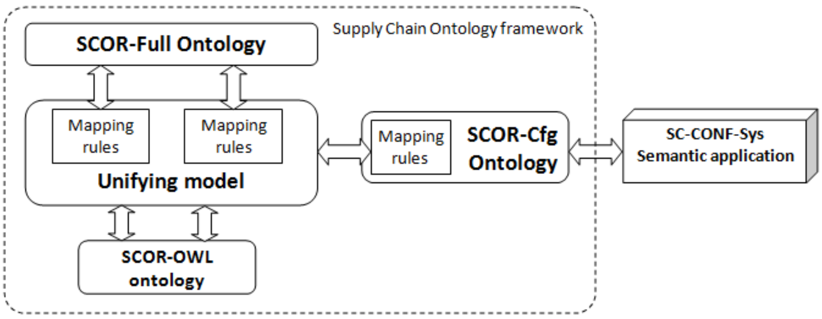

Fig. 3 Supply Chain ontology framework

Third, the SCOR-Cfg is application ontology, used to enable the formalization of the competency questions relevant for the framework, namely to enable the representation of the semantic queries. Then, the supply chain configuration can be inferred, based on the common rules related to the orderings of the SCOR source, make and delivery processes in the different cases of the manufacturing strategies: make-to-stock, make-to-order and engineer-to-order; and a capacity of the supplier to deliver the desired part.

4. DISCUSSION

The digital era in which we live and work today evolves the IT infrastructures towards the ubiquitous computing paradigm. The latter assumes an environment in which an increasing number of devices collaboratively collect, process and store an extensive amount of data, information and knowledge. The paradigm of ubiquitous computing gives a boost to development of new storage technologies, such as clouds. However, while the cloud-based systems enable storage and sharing of big data, the common and unified approach which will facilitate management of this data and its subsequent transformation to knowledge has not been developed yet.

With the advent of semantic web technologies, such as the RDF/OWL, the ontologies are being increasingly used not only as means to represent meta-data structures, but also to serve as runtime models for different applications, i.e. semantic web applications. There exists a visible trend of increasing formalization of the standards, reference models and dictionaries, as well as the developing of transformation tools which enable mapping of less-expressive modeling languages (such as UML) to formal the RDF/OWL structures.

This trend will have a significant impact on how the information systems of the future are designed and developed. In the recently submitted position paper of the IFAC TC5.3 Technical Committee for Enterprise integration and networking [22], the next-generation Enterprise Information Systems (NG EIS) are foreseen to be omnipresent, model-driven, open, dynamically reconfigurable, aware and computationally flexible.

The list of these properties implies that, in fact, the future EIS will be inherently interoperable. In the remainder of this section, we present the scenario of use of the proposed knowledge management framework for the orthopedic surgery domain, by the above-mentioned systems.

4.1. EIS Infrastructure for knowledge management in orthopedic surgery

The omnipresent property of the NG EIS means that a computing becomes ubiquitous in the sense that the communication, processing and storage capabilities are not anymore exclusive to computers or smart phones. In fact, a number of devices with these capabilities, connected to Internet, rapidly grow, forming so-called Internet-of-Things (IoT). This development has a tremendous impact on the healthcare domain.

Todays' medical devices [23] combine sensors for spatio-temporal detection of electrical, thermal, optical, chemical, genetic and other signals with physiological origin, as well as with actuators, e.g. medical dispensers or assisting tools, capable to autonomously and intelligently implement or change the therapy [24]. Their operation depends on an extensive amount of information that is continuously being pulled out and pushed back to different medical information systems.

With an increased number of medical devices with processing capability, the complexity of the overall IT infrastructure becomes extremely complex. One of the imminent consequences of this complexity is the rising difficulty to achieve seamless collaboration and exchange of information between all systems within the IT environment. This problem is dealt by the NG EIS by transferring the data models and business logic based on which these systems operate from their core runtime environment to possibly external, unifying models. Hence, the NG EIS becomes model-driven. These models are represented in a formal and explicit way – by using ontologies.

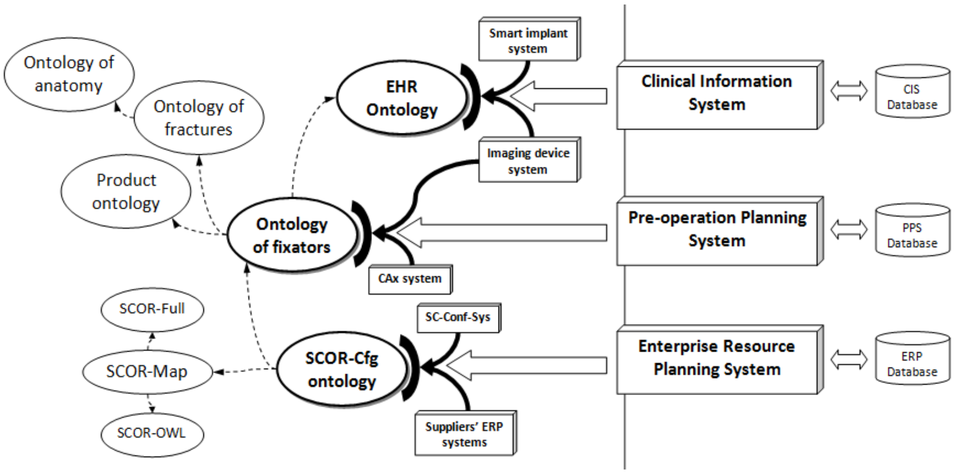

Fig. 4 Example architecture of the Next Generation Enterprise Information System for knowledge management in orthopedic surgery

Such ontology-driven approach is illustrated in Fig. 4 which describes the basic architecture of the NG EIS for knowledge management in orthopedic surgery. It also distinguishes (but also takes into account) the traditional architecture of clinical IT infrastructure (right-hand side) from the model-driven one, which also considers new, evolved systems, such as imaging device and so-called smart implant [25] (left-hand side).

In the traditional approach, the EISs are typically considered as monolithic applications, driven by static data structures, implemented by Database Management Systems. The integration of EISs is carried out by using separate infrastructures (such as Enterprise Service Buses) whose setup is costly and time-consuming because it involves the negotiation and alignment of different data structures that need to be exchanged between the systems. Hence, the scalability of one EIS, in terms of its capability to seamlessly work with Enterprise Service Bus facilities is considered as one of the most important properties. In contrast, the NG EIS will be driven by dynamic meta-data structures, modeled by far more expressive means than database schemas – the OWL ontologies. The increased expressivity implies that these structures will not store only knowledge about data, but also about business logic of EIS [26] – thus enabling a truly model-driven approach to running EIS. Instead of exchanging semi-structured formats, such as XML, the NG EIS will communicate by perceiving and reacting to the environment observations, where data about the different stimulus will be transformed into perceptions – sets of logical statements about these stimuli [22]. In other words, the NG EISs will become aware of their environment and thus, the need for interoperability mediators, such as ESBs, will no longer exist.

In such context, all the systems will remain autonomous and the only centralized role will be related to maintaining the consistency of the ontological models used by these systems. Hence, in our scenario (see Fig. 4), imaging device system and smart implant system will operate autonomously of central CIS. However, all these systems will use EHR ontology. Imaging device system will use it to validate patient information, based on the Computerized Physician Order Entries (CPOE), used to order radiology services; and to automatically assert the atomic perceptions from the scans into EHR. These perceptions will take the form of the logical statements by using the schemas described in ontologies of fractures and anatomy, as presented in the following example:

```
fracture of humerus
fracture_plane hasFractureAngle 45
fracture hasBoneFragment exactly 2 bone_fragment
```

Based on the above listed statements, the ontology of fractures can be used to automatically diagnose an oblique simple fracture of humerus. This diagnosis will be asserted to CIS, by using the formalisms present in EHR ontology. As argued before, based on the formal description of diagnosis, an automatic selection of the appropriate fixator can be carried out, by exploiting the rules that formalize the correspondences between the geometric features and topology of the fixator and type of fracture, on one hand, and formal description of diagnosis.

After the surgery, the healing process of the bone can be tracked by the smart implants, which will host the sensors to measure force, torque, load (e.g. load sharing between the bone and implant), strain, motion (e.g. implant elastic deformations), pH, temperature, and pressure [27]. These measurements will be transformed into perceptions, again, represented by using logical statements and then asserted into CIS by using EHR ontology formalisms.

Sometimes, when it is not possible to select the existing fixator design due to the specific anatomy of the patient, the new, custom design will be done by using the Computer Aided Design (CAD) system. Then, this new design will be asserted to ontology of fixators. Obviously, in this case, it will become necessary to setup and track processes related to the manufacturing of this new fixator design. SC-CONF-Sys application can be used for this purpose. Namely, it will generate a SCOR-based model of the supply chain and assert this model into the supply chain ontology framework. The sourcing, manufacturing and delivery orders will then become accessible by the suppliers' Enterprise Resource Planning (ERP) systems.

5. CONCLUSIONS

With the variety of models, standards, protocols and other formalisms for representing medical concepts and processes, the healthcare domain is one of the most diversified fields and test-beds for ontologies. Many research projects have already demonstrated the number of advantages of using ontologies in healthcare. Ontologies can help in building more interoperable information systems in healthcare. They can facilitate transferring, re-use and sharing of patient data. Finally, ontologies can support the integration of the necessary knowledge and information in healthcare. The work that this paper is based on deals with the latter aspect.

In this paper, we presented the knowledge management framework for the representation and use of the knowledge in the domain of orthopedic surgery, by using the ontologies. Such a representation combines the anatomical models, EHR data, the types of bone fractures, the models of the medical devices and models of the supply chains that can be swiftly employed for the purpose of manufacturing and delivery of custom fixator. Such a framework can enable automated decision-making in the domain, but it will also contribute to achieve the universal and unconditional interoperability between all relevant systems. Thus, it will facilitate further development of the paradigms related to so-called Next Generation Enterprise Information Systems in healthcare domain.

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