On semantic, rule-based reasoning in the management of functional rehabilitation processes

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Abstract. A clinical decision support system, based on rules described in the semantic web rule language and with semantic annotations from biomedical and time ontologies, is used to reason on processes modeled in the business process modeling notation. This paper, as a case study within the framework of functional rehabilitation processes, analyzes the modeling of the rehabilitation activity consisting of improving the upper limb functioning of patients. The clinical decision support system provides personalization of therapies and is powerful enough to deal with the special characteristics of a rehabilitation scenario, which includes several types of indicators, medical ontologies, and time annotations of different granularities. This paper presents the main lines of a rule-based, ontological framework to translate informal, descriptive methods about functional rehabilitation with an intuitive semantics to the formal representation needed by computational systems. A rule-based reasoning system is used for the representation of processes' semantics and the modeling categories are based on well-accepted rehabilitation notions. We believe that the solution presented for functional rehabilitation can be generalized to other rehabilitation domains such as respiratory, cognitive and cardiac rehabilitation.

Keywords: Ontologies, rule-based reasoning, rehabilitation processes, disabilities with neurological origin

1. Introduction

In medical rehabilitation there are procedures that are set up with the intent of increasing efficiency, consistency and quality. Unfortunately, the degree to which these procedures are followed often is influenced by various aspects of the procedures, and of the individuals performing the tasks or managing the procedures. Such aspects include procedures' ambiguity, human errors and inconsistency, urgency, patient anxiety. The concepts of process engineering and workflows embody the ideas of controlling and coordinating these complex procedures, activities and interactions among individuals and software components (Cichocki et al., 1998).

The objective of the research described in this paper is an improved quality and efficiency of computer-supported work, and specifically the management of rehabilitation processes and the development of a new model for interoperable healthcare, in which data from heterogeneous sources are integrated through workflows that cover the full cycle from diagnosis to treatment. On a lower level, this new model will also facilitate semantic search, discovery, quality assessment, transformation, access, aggregation, analysis of information resources, and publication of derived results for new use. Crucially, the model allows interoperability across scientific domains and user-types (from expert to non-expert) by documenting not only data but also how the data are used for different purposes through workflows, which are then composed as service chains and made reusable. Whilst some progress in this direction has been made in recent research like the one by Fry and Sottara (2011), Wieringa et al. (2011), and Smith et al. (2012), the extension to include administrative, sensor and clinical data is novel, as will be shown in the application to medical rehabilitation. The paper illustrates how to effectively involve healthcare people in the development of a model for rehabilitation processes, to contribute to the evolution from the current situation to individualized rehabilitation and to solve interoperability problems. This is achieved applying rule-based reasoning to decision support and providing a framework that allows the management of semantic enrichment of process models produced by healthcare experts. Related initiatives include: using ontologies to formalize care actions from clinical guidelines (Pruski et al., 2011; Jafarpour et al., 2011; Kashyap et al., 2006); integrating temporal and resource constraints to generate patient-tailored treatment plans (González-Ferrer et al., 2011); and using rule-based frameworks to construct complex temporal queries (O'Connor et al., 2011). However, none of these deal with several characteristics of a rehabilitation scenario: (1) multiple types of indicators: session result-indicators, treatment result-indicators and process indicators; (2) multiple granularities of indicator-behaviors in time trends; (3) multiple medical ontologies, such as the International Classification of Functioning, Disability and Health (ICF) (World Health Organization, 2011), the Systematized Nomenclature of Medicine Clinical Terms (SNOMED CT) (College of American Pathologists and National Health Service, 2011), or the International Classification of Diseases (ICD) (World Health Organization, 2008) version 10 and version 11; (4) semantic annotations from time ontologies.

2. Scenario

As an example, Minerva is the (anonymized) name of a 25-year-old girl who had a car accident while she was biking, some months ago. Now she is at Institut Guttmann, a neurorehabilitation hospital, performing rehabilitation to improve social participation, performance of activities of daily living and, in general, functionality that was impaired due to her injury. Specifically, Minerva suffers from complete *spinal cord injury* (*G95.9* and *T09.3* in the ICD-10) at the C6 spinal cord segment (Foreman and Croft, 2001), and the objective of her rehabilitation is to improve her upper limb functioning (*movement functions* (*b750-b789*) and *structure of upper extremity* (*s730*), according to the ICF) executing *activities of daily living* (ADLs).

In the rehabilitation of upper limb functioning by executing ADLs, several technologies are used: a T-shirt and a robotic orthosis with sensors, which allow therapists to assess the correct execution of an activity and assist patients' movement when needed; a virtual-reality environment, which gives the patient guidance and visual/hearing feedback during the execution of an activity (The orthosis provides the patient sensory stimuli to enable the interaction with the virtual environment.); and a *clinical decision support system* (CDSS) (Gómez et al., 2012). Using this CDSS, a *personalized therapy* for Minerva, including the *Bottle-shelf* activity (which consists of taking a bottle from a shelf, putting it on a table, and returning it to the start point; see Fig. 1 and below), is recommended. In doing so, the tool takes into account that *disease of spinal cord, unspecified (G95.9)* is a subclass of *diseases of the nervous system* (*G00-G99* in the ICD-10) and that there are no contraindications for the patient.

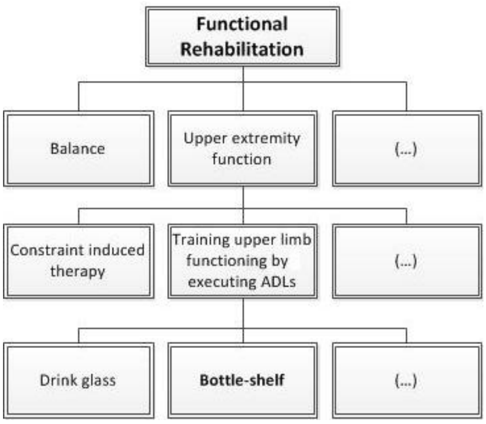

Fig. 1. *Functional-rehabilitation* processes and activities: examples of activities are on the bottom row of the tree shown and processes are the other nodes.

3. Methodology

The semantic, rule-based framework we propose uses standard annotations from biomedical and time ontologies and is validated using neurorehabilitation *processes* from clinical practice (see Fig. 2). These processes are composed of rehabilitation *activities*, such as the *Bottle-shelf* activity, which is included in the *Training upper limb functioning by executing ADLs* process, which is a subprocess of *Upper extremity function*.

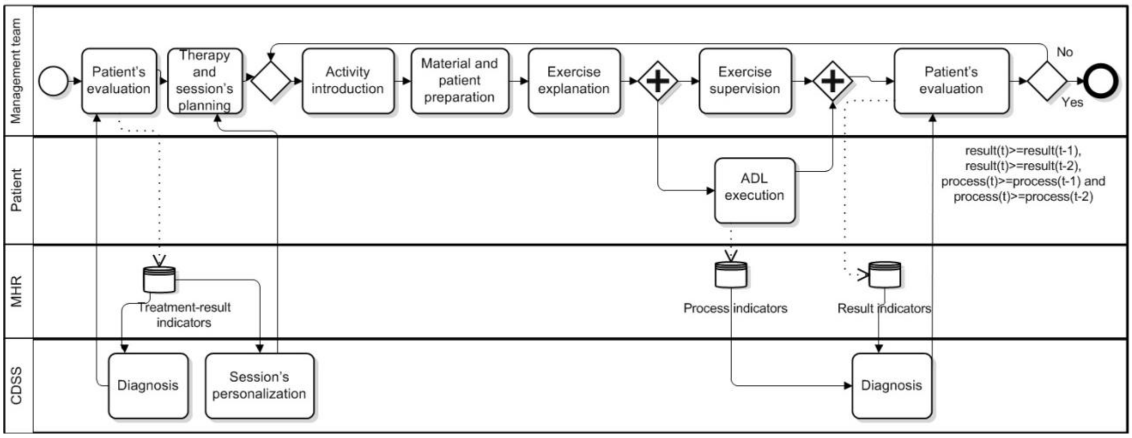

Fig. 2. General workflow of a rehabilitation process involving ADLs using the *business process modeling notation* (BPMN)

Activities of the *Training upper limb functionality by executing ADLs* process, such as *Bottle-shelf,* are modeled by Caballero et al. (2011). The tasks carried out (by different actors) are: patient's evaluation; therapy and session's planning, activity introduction, material and patient preparation, exercise explanation, ADL execution, exercise supervision, and patient's evaluation. Several indicators are monitored and stored in a *medical health record* (MHR):

(1) **Process indicators**, such as *heart rate*, are used as execution, security or end-session indicators. (A *session* is the time slot in which an activity is executed.)

(2) **Session result-indicators**, such as *maximal range of joint movement*, are used as end-criteria of an activity: the therapy continues if, at the end of a session, at least one *session result-indicator* improves with respect to the two previous sessions; otherwise the therapy ends.

(3) **Treatment result-indicators**, such as *mobility of joint functions*, *muscle power functions* or *muscle tone functions,* are periodically quantified using measures such as a measure of muscular balance, a measure of upper limb functioning, the *functional independence measure* (FIM), the *spinal cord injury measure* (SCIM) or a measure of joint balance.

The methodology used comprises the standardization of indicators, the computational management of processes initially modeled in BPMN, reasoning and querying, all of which will be described in the following sections.

3.1 Standardization of indicators and interoperability

All terminology and annotations used are based on international standards. The ICF (which standardize attributes and values; values ranging from 0 -no deficiency- to 4 -complete deficiency-), SNOMED CT, ICD-10 and ICD-11 are used for *biomedical annotations* of processes and results. The definition of interoperable indicators is done using the following steps:

(1) *Standardization* of *treatment result-indicators* found on healthcare questionnaires into ICF (together with health professionals).

(2) *Inference* of ICF core-set categories corresponding to the indicators. ICF *core sets* are subsets of ICF formed according to functioning, pathology or rehabilitation process.

Core sets are useful because, in daily practice, clinicians and other professionals need only a fraction of the categories found in the ICF.

(3) *Reduction* of the indicators (considering core sets) to no more than 10 ICF categories for each user of the CDSS's interface. The number 10 was set due to human limits in the ability of processing information (Miller, 1956).

(4) *Standardization* of *time annotations* using an ontology (O'Connor et al., 2011). This ontology provides *Web ontology language* (OWL) entities for representing propositions, valid times (both instants and intervals), granularity, and duration.

3.2 Computational management of processes initially modeled in BPMN

Rules are used to define activities and therapies, and to evaluate patients. Initially modeled in BPMN 2.0, they are then coded using the *semantic Web rule language* (SWRL) (Horrocks et al., 2004). In the following examples, a representative set of rules is described in detail. (All rules are available at [http://code.google.com/p/functionalrehabilitation/downloads/list].)

As a first example, let us consider the rule which stops a session if the value of a parameter is too high:

NextTask (?nt), ProcessIndicator (?pi), Patient (?p), hasIndicator (?p, ?pi), greaterThanOrEqual (2, ?pi) → hasNextTask(?p, ?nt)

which means that, if a patient *p* has a process indicator *pi* which is greater than or equal to *moderate deficiency* (2 in the ICF), the session is stopped and the next task is *nt*. Similar rules are applied to several process indicators of rehabilitation activities. Process indicators are used, among other things, to stop sessions because of alterations in body functions (such as a too-high heart rate) or environmental factors (such as a too-high temperature or humidity). Rules' conflicts, for example about the conditions to terminate a session, are solved by giving priorities based on: indicators' weight according to ICF *core sets*, time, and relevance of result indicators with respect to the activity.

3.3 Reasoning and querying with Pellet and SPARQL

Reasoning is used for the personalization of rehabilitation therapies, to find the most suitable activities for a patient. The following example shows how the *Bottle-shelf* activity is selected for a therapeutic plan. The Pellet reasoner is used to infer properties and relationships, while *SPARQL* (an RDF query language) is used for querying RDF ontologies.

Personalization of therapies. The following set of queries is used to personalize therapies. Firstly, the system evaluates which indicators the patient should improve through the query

(1) *Select (?i) where Patient (?p), Indicator (?i), Deficiency (?mild), hasDeficiency (?i, ?mild), has Indicator (?p, ?i)*.

Afterwards, activities which cover this objective are searched for. In the case of Minerva the objective is *power muscles of one limb,* so the query is

(2) *Select (?a) where Activity (?a), Power muscles of one limb (?i), hasObjective (?a, ?i)*.

The *Bottle-shelf* activity is among the results. Then, other activities which can be indicated for the patient based on subclasses of *neurological diseases* in the ICD-10 taxonomy are inferred through Pellet, with the query

(3) Select (?a) where Activity (?a), Patient (?p), has disease (?p, ?d), SubClassOf (?NeurologicalDiseases, ?d).

Finally, it is checked if the activity is contraindicated to the patient. In the *Bottle-shelf* activity, with the query

(4) Count (?contraindication) where Patient (?p), Moderate, severe or complete neuromusculoskeletal and movement-related functions (?mscn), hasContraindication (?p, ?mscn).

To be recommended, an activity has to appear as result in queries 2 or 3 and the result in query 4 has to be *0*.

Diagnosis. Diagnosis in order to evaluate a patient is performed using temporal reasoning. The system has to deal with two issues: different time annotations for indicators and different kinds of indicators. In order to obtain indicators of the *Upper extremity function* process the following query can be used:

Select (?p, ?resulttreatment, ?week) where Patient (?p), Upper extremity function (?process), hasProcess (?process, ?activity), hasActivity (?p, ?activity), hasIndicator (?p, ?resulttreatment), temporal:overlaps (?activity, ?interval), temporal:after(?interval,"2012-11"), temporal:before(?interval,"2013-3").

Trend granularities are used in temporal queries in order to measure the intensity of *change*, which has the following domain of values: <increase (I), decrease (D), remain stationary (S)>. Three different levels of trend granularities have been defined for the intensity of change: fine, medium and coarse (see Fig. 3). The parameters used when retrieving indicators are then: *temporal:ValidInterval*, *temporal:ValidPeriod*, *temporal:trendGranularity* and *IndicatorType*.

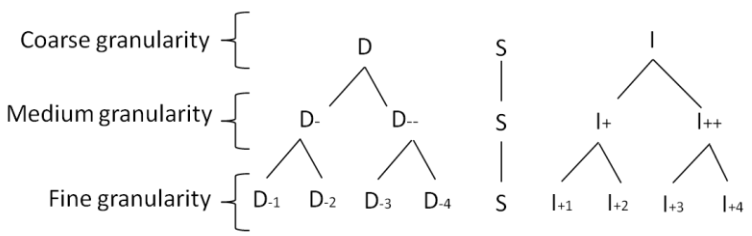

Fig. 3. Trend granularities added to the time ontology

The architecture of the proposed rule-based framework is composed of: (1) a Protégé-based knowledge editor, which uses Jena and SPARQL to interact with the OWL ontology (see Fig. 4); (2) rules implemented in SWRL; and (3) the Pellet reasoner.

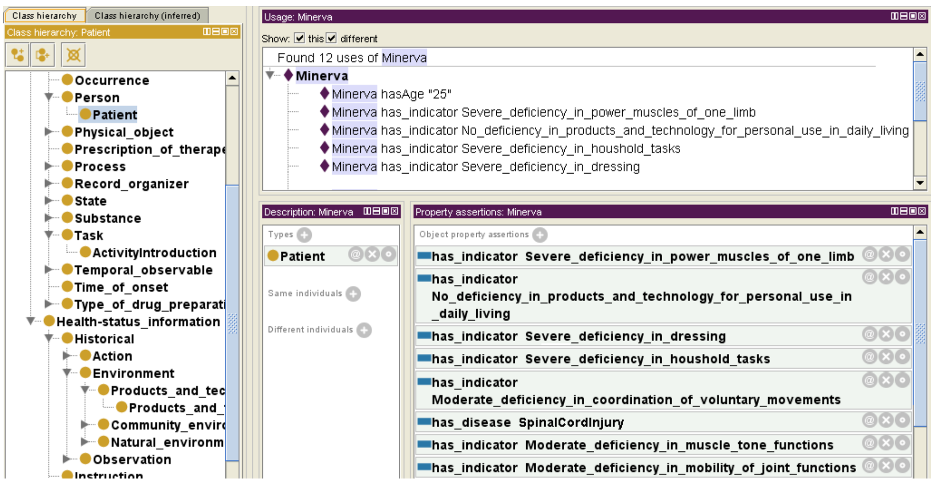

Fig. 4. The Protégé-based knowledge editor, which uses Jena and SPARQL to interact with the ontology

4. Results

Results are based on the application of the proposed framework to the previous scenario. Traceability evaluation is carried out in order to verify the completeness of the rule set. Priorities are given to each indicator and measure to gauge how much the objectives of an activity are achieved.

Let us suppose that Minerva is performing the *Bottle-shelf* activity and her heart rate is too high. As a consequence, an alarm is triggered and her session is stopped. After the alarm, her therapist wants to evaluate Minerva. She wants to diagnose her in the *upper extremity function* process with a 3-weeks granularity. From the tool, see Fig. 5, a summary of indicators of *body functions*, *body structures*, *activities and participation*, and *environmental factors* are summarized; deficiency and difficulty levels are represented as red/4 (complete), orange/3 (severe), yellow/2 (moderate), green/1 (mild) and blue/0 (no).

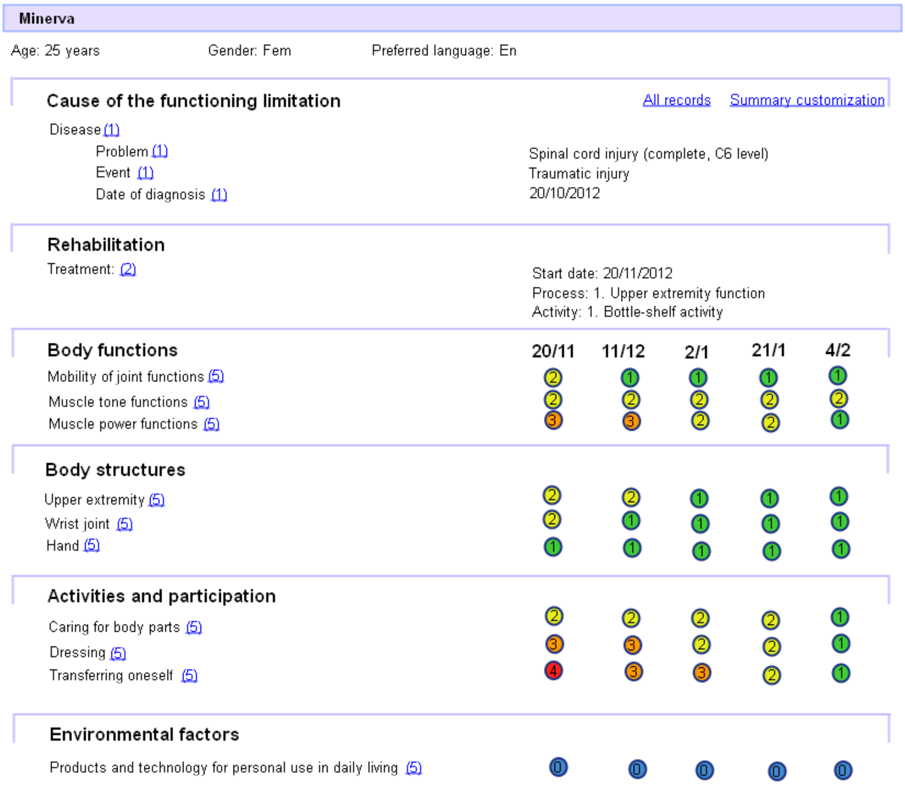

Fig. 5. CDSS's interface of Minerva's therapy and diagnosis.

5 Conclusions

Temporal and biomedical annotations can provide semantics to functional rehabilitation processes represented in BPMN 2.0. This semantics, together with rules obtained from literature and data mining, can be used to introduce automatic reasoning in decision support. We present a semantic, rule-based reasoning framework which uses existing temporal ontologies and formal processes notation to enhance interoperability and reasoning in rehabilitation: extending temporal ontologies, specifying granularities of indicator-behavior in time, working with different types of indicators and merging medical ontologies such as ICF, SNOMED CT, ICD-10 and ICD-11.

Different issues appear when there are large amount of rules in BPMN 2.0 processes which are solved generalizing rules; while problems of conflicting rules are solved by establishing priorities. Furthermore, time-trend granularities are added to temporal ontologies to construct temporal queries in order to measure the intensity of change.

The proposed CDSS is validated with a functional rehabilitation scenario and the correct execution of functional rehabilitation processes. Finally, the graphical user interface is validated by clinicians' opinions. We believe that the solution presented for functional rehabilitation, has implications in an improved quality and efficiency of management of functional rehabilitation processes, and that can be generalized to other rehabilitation domains such as respiratory, cognitive and cardiac rehabilitation.

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