Artificial Intelligence in Medicine 51 (2011) 147–161

Contents lists available at ScienceDirect

Artificial Intelligence in Medicine

journal homepage: www.elsevier.com/locate/aiim

Modeling surgical processes: A four-level translational approach

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ARTICLE INFO

Article history:
Received 24 November 2009
Received in revised form 14 October 2010
Accepted 7 December 2010

Keywords:
Theoretical models
Linguistics
Concept formation
Practice guideline
Operative surgical procedures
Workflow
Process model

ABSTRACT

Motivation: The precise and formal specification of surgical interventions is a necessary requirement for many applications in surgery, including teaching and learning, quality assessment and evaluation, and computer-assisted surgery. Currently, surgical processes are modeled by following various approaches. This diversity lacks a commonly agreed-upon conceptual foundation and thus impedes the comparability, the interoperability, and the uniform interpretation of process data.
Objective: However, it would be beneficial if scientific models, in the same context, shared a coherent conceptual and formal mathematical basis. Such a uniform foundation would simplify the acquisition and exchange of data, the transition and interpretation of study results, and the transfer and adaptation of methods and tools. Therefore, we propose a generic, formal framework for specifying surgical processes, which is presented together with its design methodology.
Methods: The methodology follows a four-level translational approach and comprises an ontological foundation for the formal level that orients itself by linguistic theories.
Results: A unifying framework for modeling surgical processes that is ontologically founded and formally and mathematically precise was developed. The expressive power and the unifying capacity of the presented framework are demonstrated by applying it to four contemporary approaches for surgical process modeling by using the common underlying formalization.
Conclusions: The presented four-level approach allows for capturing the knowledge of the surgical intervention formally. Natural language terms are consistently translated to an implementation level to support research fields where users express their expert knowledge about processes in natural language, but, in contrast to this, statistical analysis or data mining need to be performed based on mathematically formalized data sets. The availability of such a translational approach is a valuable extension for research regarding the operating room of the future.

1. Introduction

In the domains of medical informatics and medical engineering, surgical workflows and time-action-analyses are gathering momentum. These broadly applicable concepts [1] have been explored from the points of view of many surgical disciplines [2] and for various reasons, including the evaluation of surgical-assist systems [3], the control of surgical robots [4], instrument assessments [5], and requirements engineering [6]. Clinical work has also focused on surgical workflows for reengineering [7], assessing human reliability [8], or comparing substitutive surgical strategies [9]. A consolidated view of all of these factors indicates that there is a stable and growing demand for these kinds of studies and analyses.

What is quite salient, however, is that all of the mentioned approaches show an inclination towards a disordered growth with regard to their basic concepts; only two use explicit models or ontologies [10,11]. Instead of a formal basis, the respective authors have used a variety of self-defined description 'languages'. This situation raises the question whether it is possible to find a common set of concepts that can be captured formally and that is applicable to every approach.

The advantages of such a formal basis would be manifold; we believe that it would enrich the research fields of medical computer-science and surgical workflow analysis. It would enhance the comparability, measurability, interoperability, and communicability of findings, statistical interpretations, and data-mining operations, as well as software applications (e.g., the construction of exchange platforms for surgical process models

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doi:10.1016/j.artmed.2010.12.003

(SPMs) and study results). These may also be of increasing interest for medical personnel, who could use them to gather knowledge, plan interventions, or teach their craft.

The goal of this paper is to present a four-level framework that is ontologically founded and can serve as a basis for a formal representation of surgical processes. This framework will make different scientific approaches comparable and a mapping onto other languages possible. These 'other languages' comprise, among others, modeling languages for business process modeling [12] and languages used for the modeling of discrete system behavior (e.g., automata, Petri nets, or execution languages for workflow schemas, such as structured Petri nets or business process execution language [13]).

There is no generic framework for process modeling and analysis available that is adjusted to the medical field of surgical workflows and which specifies and integrates all relevant levels of abstraction into one coherent system. Such a framework should close the gap between individual data and the knowledge expressing abstract patterns about the data [14]. Since the intended users are typically not familiar with logical formalisms, due to their mostly medical or engineering background, this framework should include a natural language level for communication. Then, this framework should provide means to transform natural language specifications of processes into mathematical models based on ontologically based semantics. None of the existing formalisms has this as focus.

We will present a framework and its methodological basis to represent particular process models (corresponding to 'cases' in workflow terminology, in most instances). The methodology follows a four-level translational approach. Here, the term 'translational' conveys three different meanings: it refers to a translation between different levels of description specified and founded by this methodology, it relates to a translation between models associated to the corresponding levels, and, finally, it expresses the idea of a translation between theories from different fields of research. Further, the framework is related to existing approaches to modeling surgical workflows in order to demonstrate its applicability as the lowest common denominator between different approaches.

This article provides an introduction to the background of surgical process modeling, domain-specific terminology and abbreviations, and presents related approaches. The Methods section expounds basic methodological principles and the mathematical framework. The latter focuses on modeling patient-specific surgical processes, among other purposes for their electronic recording and analysis, e.g., regarding clinical questions, and the experimentally justified derivation of surgical workflows. The Application section demonstrates the implementation of the framework. Several aspects of the framework and its application are discussed, and prospects on future developments are given, finally followed by the conclusion.

2. Background

2.1. Terms and definitions for surgical process modeling

The term *surgical process* (SP) denotes a concept whose instances are individual surgical procedure courses. An SP is specified [1], in an adaptation of the definition of a business process in [15], by a set of one or more linked procedures or activities whose instances (are intended to) collectively realize surgical objectives within the context of an organizational structure defining functions, roles, and relationships.

The surgical objective is to achieve a normal, or at least ameliorated, state of the patient's body, and a surgical process changes an abnormal condition of the human body into a normal or better state. A procedure is performed in the organizational structure of a hospital which defines the functions, roles, and relationships of the participants within the operating room (OR).

In order to handle surgical processes in information systems, they must be represented as models. According to the general limitations of models – they exhibit reductions and simplifications of the domain [16] – we define a *surgical process model* (SPM) as a simplified pattern of a surgical process that reflects a predefined aspect of interest in a formal or semi-formal representation [1]. Furthermore, we take on different types of SPMs: individual SPMs (iSPMs) and generic SPMs (gSPMs) [17]. The term iSPM refers to individual, patient-specific models of SPs, thus representing the model of a single surgical case, while the term gSPM refers to a model of several surgical cases, such as a 'mean' treatment. The methods presented herein are applicable for iSPMs.

2.2. Introduction to pertinent literature

In computer science, there is a vast number of approaches, languages, and communities regarding process specifications in general. Constraining this to the present context, a considerable amount of work remains that deals with the formalization of workflow systems [18]. However, the available methods and languages mainly share the ability to represent workflows on a formal basis. Apart from that, they are best suited to different tasks in connection with workflows: graph-based approaches (e.g., Petri nets and state-and-activity charts) are powerful tools with respect to visualizing workflows, as well as regarding the specification and verification of workflow properties [13]. There is a large number of analysis methods and implemented tools for Petri nets.

Another broad line of workflow-related research comprises logic-based approaches, e.g., employing concurrent transaction logic for workflow analysis [19] or event calculus for specifying and executing workflows [18]. Moreover, other process models have been proposed in connection with workflows, but they are more limited in scope (e.g., process algebras or event-condition-action rules [18]). Temporal aspects of workflows, if supported at all, are dealt with mainly in the form of temporal constraints. Ignoring immediate relations to the field of workflows, numerous logic-based process formalisms have been presented in artificial intelligence (AI), where we just name situation calculus [20] and event calculus [21] as well-known representatives, and the unifying action calculus [22] as a more recent, integrative approach.

There are three main problems with the mentioned approaches. Firstly, according to our knowledge, all mentioned approaches are designed for other purposes than naturally and efficiently supporting statistical analysis and data mining, for which they are not well-suited. Instead, logical approaches, for instance, obviously support reasoning as a core task and can be applied to, e.g., automated treatment planning and decision support systems. Secondly, approaches applied in the workflow area in most cases assume or employ a top-down modeling of workflows in terms of manually devised models, in order to provide precise specifications, to verify their properties and schedules, to compute workflow executions, etc. Note that this holds true for medical guidelines, also, cf. [23–28]. These approaches are directed at normative processes rather than at capturing and recording actual process information and are therefore not suitable for the retrospective analysis of individual processes. However, in the domain of surgical workflows no explicit knowledge exists that might be cast into formal models in a top-down manner. A high variability of patient properties, surgical skills and experience, as well as of available surgical technologies results in models showing high diversity [17]. Furthermore, top-down models are usually equipped with few or no temporal measurements, which are in turn needed for many applications of surgical workflows, such as quantitative requirements analyses [6].

Consequently, we require a formal model that also supports the bottom-up generation of workflows by observing iSPMs, as well as detailed time measurements within those recordings. We are not aware of any corresponding workflow-formalization approach. Thirdly, especially logical formalisms are not intelligible to and comprehensible for our intended users, as mentioned above. Logical representations cannot be easily communicated to medical staff, and they are hard to use in evaluations that are to be run by medical engineers or computer scientists without an appropriate background.

The most closely related resources [2] in computer and information science that focus explicitly on surgical processes are terminological resources, for instance, national procedure classifications. In this particular context, the European norm EN 1828 [29] provides a minimal computer-based concept system for surgical procedures in order to “support the exchange of meaningful surgical procedure information between different national classifications or coding systems (. . .)”. The resulting level of granularity is coarse because such classifications are mainly used in connection with electronic health-care records and accounting systems. Moreover, temporal relationships are not covered. Modeling the temporal structure of interventions is therefore beyond the scope of EN 1828.

There is another large branch of related work that pertains to AI, with influences from linguistics, cognitive science, and philosophy. A few corresponding approaches were named above as representatives of logic-based process representations [20–22]. Indeed, the AI subdomain of theories and reasoning about action and time has been an active field of research for several decades. Frequently drawing on linguistic and philosophical inspiration, it includes works such as the development of formalisms for reasoning about actions [30] and the deployment of temporal constraints between causes and effects of causal relations [31]. Due to the close relationship between processes and time, there is a further large intersection with the AI subfield of temporal representation and reasoning, cf. [14,32]. For our purposes, the dynamic aspects of logical representations like reasoning and its further applications (e.g., for planning) are not yet immediately applicable. Adopting logical formalisms as a declarative form of representation is appropriate for some parts of our framework, but plays a minor role for the mathematical model presented below, due to its intended application cases. Therefore, currently the main connection to these fields in AI resides in the theories of time and processes that are presented there for their adoption and extension as conceptual or ontological basis of formal models.

Indeed, processes and time form important classes of entities that have been studied in ontology research, including philosophical investigations [33], knowledge representation [34,35], and computer-science ontologies [36]. The category of processes is at the most general level of abstraction of concrete individuals and, hence, is usually included in top-level ontologies. Top-level or foundational ontologies apply to every area of the world, in contrast to the various *generic*, *domain core*, or *domain ontologies*, which are associated with more restricted fields of interest. The category of processes is contained in the top-level ontologies DOLCE [37], GFO [36], and ISO 15926-2 [38], each of which represents a different approach to processes. In DOLCE, objects (endurants) and processes (perdurants) are disjoint classes of entities that are connected by certain relations. ISO 15926-2 contains processes as the only basic category, whereas GFO provides three kinds of concrete basic entities (perpetuants, presentials, and processes), which are fully integrated into a unified system. The basic integration axiom says that for every perpetuant (presenting the notion of enduring object), there exists a corresponding process such that the snapshots of that process coincide with the presentials associated with (“exhibited by”) the perpetuant [36,39].

Process modeling in the framework of top-level ontologies is a new research field, and there are few papers or investigations related to this topic [40–42] with respect to our focus on process descriptions with detailed temporal information. The closest related effort is the ISO standard 18629 on the process specification language (PSL, [34]). PSL consists of a core that exhibits the following four kinds of entities: activities, activity occurrences, time-points, and objects. The underlying ontology of PSL pertains (to some extent) to the top-level ontology of DOLCE [37]. In particular, the notion of activity occurrence relates to the notion of perdurant in DOLCE, whereas objects in PSL correspond to endurants in DOLCE. Additionally, there are several extensions of the PSL core, treating relevant aspects of processes. PSL can be interpreted and mapped into the GFO, providing an ontological foundation of the PSL semantics. PSL is formalized in machine-readable formats covering first-order logic. Alongside the resulting descriptions themselves, the main purpose of that representation is to support automated reasoning over them. The relation between process characterizations in natural language and PSL formalizations has not been established. The purposes of declarative representation and of reasoning also differ from goals such as the statistical evaluation and data mining of surgical processes, which can be more easily supported by broader, more general mathematical machinery than by first-order logic.

In this paper, we present the first application of process ontologies in the surgical domain, where no process-related ontology has yet been developed or applied.

3. Methods

3.1. Basic methodology: a four-level approach

From the methodological point of view, we propose a modeling strategy that considers four different levels: the *natural language level*, the *conceptual* or *ontological level*, the *formal* or *mathematical level*, and the *implementation* itself. Certain relations connect these four levels. The natural language level is linked to the ontological level by ontological analyses through a process called *ontological reduction* [43,44], whereas the mathematical level results from a translation of ontological categories at the second level into mathematics (e.g., set-theoretical structures). In this section, we will introduce the single levels and describe their relations to the subsequent sections.

3.1.1. Characterization of the levels

Level one, the natural language level, is related to the user. In our case, the assumed users are mostly surgeons and medical engineers. The former, especially, are not accustomed to dealing with formal representations or using formal methods to analyze surgical concepts. For this reason, the natural language level is required in order to include the implicit knowledge and experience of the clinical users into our model. The natural language level further provides an interface for communicating the results of analyses, which are carried out in terms of the remaining levels, back to the users.

The second level, the conceptual or ontological level, deals with the ontological analysis of domain knowledge, which is significantly based on natural language expressions. Because natural language expressions usually allow for distinct interpretations depending on context, distinct ontologies may be derived from them. Linguistic patterns can be employed for ontological analysis, and existing bodies of real-world knowledge might be reused, for example, as represented in pre-existing ontologies. In particular, top-level ontologies can be used as a basis for developing domain-specific ontologies. This is the primary field of application of the method of ontological reduction.

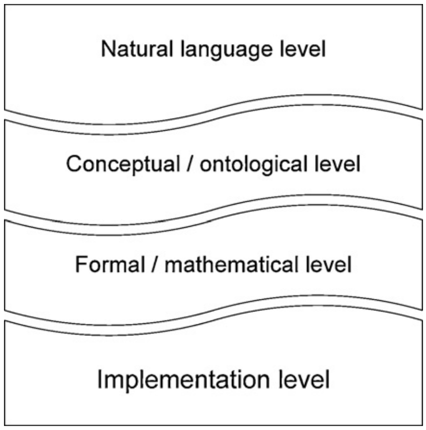

Fig. 1. The four levels of the methodology.

The third and formal level provides for mathematical formalizations of domain knowledge dedicated to determinate purposes. Such formalizations must rest on the second – the conceptual – level, where different formalizations based on a single ontology may be useful for distinct purposes. Maintaining the link to the conceptual level allows for interoperability and comparability of different models, making cross-modeling approaches possible and thus the gathering of knowledge from different sources and from different points of view.

Finally, the implementation level is concerned with the realization of formalizations from the previous level in languages with a practical orientation, primarily machine-processable languages. Here, another multiplication of representations arises due to multiple different implementations of a single formal model. Distinct implementations occur for different languages as well as for a single language. Several implementations may encode a formalization in progressively complex ways.

The four levels can be seen in Fig. 1.

3.1.2. Coverage of the levels

The goal of this article is to present a formal framework for specifying surgical processes. Accordingly, the formal level is expounded in detail in the section Mathematical Formalization. The purpose of this formalization is to share datasets of surgical processes for extended analysis, data mining, and processing. The remaining levels are only partially covered or completely elided in the case of the natural language level. For the implementation level, an example implementation is depicted in terms of the unified modeling language (UML) [45,46] and eventually defined as a dialect of the extensible markup language (XML) [47] in the section Implementation.

Regarding the ontological level, an elaborate ontological analysis of surgical processes is outside the scope of this paper and has not yet been completed. However, it is also not required at this stage of our work. One fundamental premise for the formal framework presented is the separation of concepts into those captured by representational structures and others referring to specific content. This division provides for a generic and uniform syntactic representation on an abstract, minimized conceptual basis, whereas further specificities must be encapsulated. This is desirable because of the different purposes of SPMs, on the one hand, and the high degree of dependence on natural language of detailed content on the other hand. The distinction between structure and content draws on an analogy to the relationship of top-level and domain-specific ontologies. Top-level ontologies provide a basic structure that can be refined by domain-specific concepts. Similarly, the primitives of the framework introduced below are implicitly based on an abstract ontology to which SPMs may commit by adopting the framework.

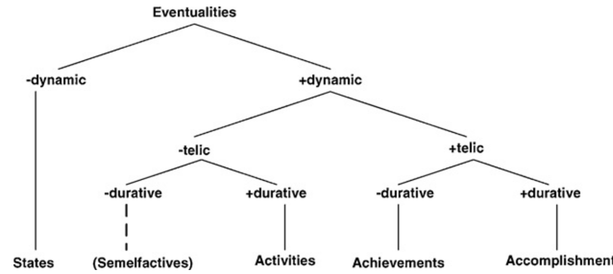

Fig. 2. Eventuality classification according to [50] and [56].

Another ontology-related aspect is to consider classifications of entities of basic types. In particular, we expect that a classification of processes will prove useful for the proposed framework. For instance, classifications can be utilized to tailor process analyses to specific kinds of processes. Therefore, we restrict the exposition regarding the ontological level herein mainly to an outline of the established theory of eventualities from the domain of linguistics, which is adopted for the classification of processes. Notably, further analyses of that theory should be conducted with respect to top-level ontologies. Initial results suggest that the classification of processual structures in GFO [36] can be used for this step, which remains for future work. The next section describes the classification system adopted in the present work. In addition, comments on the part-whole relation and granularity with respect to processes close the treatment of the ontological level herein.

3.2. Conceptual level

3.2.1. Theory of eventualities

In connection with the use of natural language in many present-day SPMs, as well as the level of abstraction in which the framework is based, we decided to rely on a basic classification of processes originating primarily from linguistics, but based on philosophical approaches (see [48]). In linguistics, and more specifically in the organization of the grammar of natural languages, eventualities have played a major role for more than 30 years. Linguists (e.g., [49,50]) rely heavily on philosophical works (e.g., [51–53]), which in turn refer to Aristotle [54]. Moreover, there is a fruitful mutual influence with process-related branches of AI, cf. [33,55].

Herein, Bach's term 'eventualities' [50] will be used to refer to the topmost category of (linguistically speaking) verbs or (from the modeling perspective) of processes and processual entities. We distinguish four 'classical' main types of eventualities that are mainly based on Vendler's theories [53]: *states* (processes without change), *activities* (unbounded processes), *accomplishments* (bounded processes), and *achievements* (point events).

The presented classification examines three semantic properties of verbs, some of which are inherent in the verb itself, while others are conveyed by the interaction of the verb and its arguments. It is important to note that the distinction between eventualities is not strict in the sense that in natural language linguistic features, such as the use of progressive or adverbials, can result in a change of eventuality [55]. The semantic properties are the following: whether or not an eventuality has a natural endpoint [±telic], whether it can be analyzed as being constructed of phases that can be different [±dynamic], and whether it continues for a period of time or is limited to a point of time [±durative]. Following [50–57] these three properties suffice to differentiate between all four eventualities, as shown in Fig. 2. Note that in this article, semelfactives [58] are excluded for simplicity.

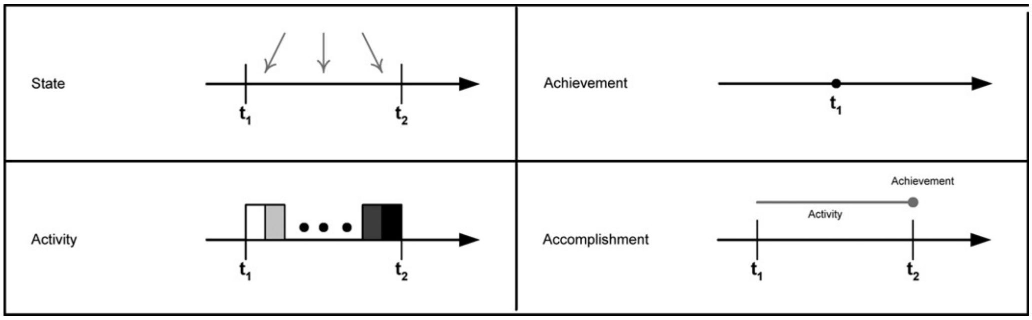

Fig. 3. Schematic representation of eventuality types.

In the remainder of this section, we further characterize the four eventuality types for better comprehension, as shown in Fig. 3. *States*, for example, 'scalpel is used', are classified as [+durative, −dynamic, −telic]. They carry on for some time, and one can ask for how long a state lasts. However, it is not reasonable to ask how long a state takes or whether it culminates because states are regarded as non-developing (there are no changes within a state with respect to its defining conditions), and, therefore, they cannot have natural endpoints. Two special characteristics of states are that they are cumulative and strongly homogenous. The former characteristic allows one to infer from the statements 'This scalpel was used from 10:00 a.m. to 10:10 a.m.' and 'This (indicating the same) scalpel was used from 10:10 a.m. to 10:15 a.m.' that 'This scalpel was used from 10:00 a.m. until 10:15 a.m.' is true. Homogeneity is concerned with parts of an eventuality. In the example above, given a state from 10:00 a.m. to 10:15 a.m., homogeneity dictates that the scalpel was used at any given point of time within this interval.

Activities share with states the properties of being extended and having no inherent endpoints [+durative, −telic], but they are [+dynamic]. An example is 'The surgeon cuts (sth.)', with the connotation that he is moving the scalpel. Although the cutting will stop at some point, the point of time *at which* the cutting will end cannot be determined from the type of eventuality given in the sentence. Activities report progress and exhibit an inner structure, for instance, by being composed of phases or by some inherent development. In terms of homogeneity, activities can be homogeneous up to a certain degree, but they need not be. Moreover, activities may be interrupted and continued later on.

The sentence 'The surgeon cuts off the thread.' reports an *accomplishment* (note again that in addition to the verb 'to cut' being of relevance for the corresponding eventuality type, the verb-argument interaction may be involved as well). Like activities, accomplishments are temporally extended and have a certain structure; in addition, they have an inherent endpoint [+durative, +dynamic, +telic]. Within accomplishments, as can be seen in Fig. 3, an activity is present, which is often referred to as a *preparation phase*. In addition, there is a natural condition characterizing the end (or the beginning) of an accomplishment, its *culmination point*, which can also be regarded as achievement. In 'cuts off the thread', the preparation phase covers all of the cutting while the thread is still attached. The transition to 'thread is severed' and 'cutting stopped' necessarily yields the culmination point. Accomplishments may be interrupted, analogously to activities. In addition, it is possible that an accomplishment remains unfinished (without culmination). In [49], this fact is called the *imperfective paradox*.

Finally, *achievements* denote eventualities that have no duration (though linguists also allow for a very limited amount of time) and no internal structure [−durative, +dynamic, +telic]. Thus, asking how long an achievement takes or lasts is irrational. What is important for achievements is the change that they incur. 'The surgeon turns off the endoscope.' is an achievement example, addressing the change of the endoscope's status from 'being on' to 'being off'. Piñon [59] argues that some achievements can be treated as the beginnings or ends of other eventualities, such as 'The surgeon starts to cut.' This view can be combined with a variation of the understanding of accomplishments reported in [60], namely that an accomplishment is composed of an activity and an achievement. This links directly with considerations of the part-whole relation (regarding processes) and different levels of granularity with respect to that relation.

3.2.2. Mereology and granularity

Existing surgical process models are often specified using different levels of part-whole granularity, which is easily visible in the approaches discussed in the Application section. For instance, there is the overall surgical procedure, which may be divided into phases. Phases might be split into work steps, and those in turn may comprise particular tasks. As indicated above, herein we cannot provide in-depth accounts of neither mereology (the theory of the part-whole relation) nor granularity, even if limiting ourselves to surgical processes.

These issues are aspects of extending the ontological analysis of surgical processes, which we will pursue in future work, cf. the Discussion section below. Moreover, this relates directly to the top-level ontological foundation of such an analysis, because the category of processes as well as the part-whole relation are commonly based on top-level ontologies. As mentioned in the Introduction, processes in general require further treatment from an ontological point of view. Nevertheless, there are numerous works that include mereological or granularity issues of processes and that are therefore expected to affect the mentioned ontological analysis. This starts from general mereology [61] in formal ontology, spans over detailed treatments in linguistics [55–57,62] and reaches into artificial intelligence in general, cf. [32] and AI in medicine in particular, see [14].

According to this situation, herein we restrict ourselves to sketching some types of constraints for processes in terms of a number of examples for which wide agreement can be expected. These are collected in natural language in this section, whereas selected formal equivalents are presented in the following subsection. Note that, based on the GFO theory of processes [36], we distinguish two basic kinds of part-whole relations for processes: *temporal part-of* (for temporal parts of processes, which may involve all participants of the process) and *layer part-of* (for parts of processes that encompass less participants or aspects than the original process, but may share its temporal extension with the original process).

1) The temporal position and extension of every temporal part of an eventuality *E* must be temporally constrained by the temporal position and extension of *E*, i.e., every temporal part of *E* must

happen during E. This entails that achievements, as eventualities without temporal extension, cannot have proper temporal parts.

2) All participants within every layer part of an eventuality E must be parts of participants in E. Analogously, aspects covered by a layer part of E must be "justified" by E, i.e., those aspects must pertain to either participants in E or to parts of E-participants.
3) For every eventuality E there is a coherent eventuality C [36] that E is a temporal or layer part of, or from which E can be derived.
4) Every temporal part and every layer part of an eventuality E is finer grained than or at maximum at the same level of granularity as that determined by E itself.

Moreover, the linguistic and philosophical literature discusses the interplay between the part-whole relation regarding eventualities and the classification of eventualities. As discussed in the previous section, accomplishments are frequently considered to be composed of an activity and an achievement [55,57,61]. Further statements of this kind are available and might be included in an elaborate mereology for surgical processes or even processes in general. Note, however, that we see this literature primarily as a starting point, whereas an integrated mereological account for processes is expected to require an extensive amount of further work.

3.3. Mathematical formalization

In this section, we present the definition and description of structural representations of surgical processes and their components, corresponding to the formal level of our methodology. This provides an abstract, general framework and terminology for the specification of surgical processes. Moreover, it serves as a basis for scientific description and usage. This framework is capable of representing, formally and mathematically, recordings of individual surgical interventions and some of their generalized patterns.

The framework is introduced in an arrangement that progresses from simple to complex. Ultimately, it is based on classical mathematical representations, mainly set theory and real-valued functions. For the specification of granularity, we introduce three functions λ, μ, and ι. λ (local granularity) is based solely on the parts/components of a process; μ (model granularity) adapts λ measures to a reference process. Whereas these two are formally captured, ι is content-oriented, referring to "global" levels of granularity. Hence, we do not assign concrete values to ι applications, but will use it merely comparatively. The domains of all three functions are the eventualities (attributive and processual) that are introduced below. The ranges of λ and μ are $\mathbf{N}$, where smaller values of $\mathbf{N}$ indicate finer granularity. To highlight that a number is to be interpreted as a granularity value, we may write λ_i or μ_i for $i \in \mathbf{N}$.

Following the theory of eventuality types as introduced above, requires a formalization adapted to the presented problems. Firstly, a formal foundation is defined in terms of attributes and values. Secondly, the eventualities are formally described at distinct levels of granularity.

3.3.1. Attributes and values

The basic data elements of the framework approximately follow the attribute-value model [63]. Measurements provide knowledge of situations that are present in a surgical process. We refer to *attributes* as representations of measurable phenomena of a surgical process in great generality. More precisely, an attribute represents a range of conditions to which a particular element may apply at a time, called a *value*. Values may refer to qualities, relations, and complex situations (each represented by a single value). From the perspective of processes, attributes characterize processes (which themselves reside at a certain level of part-whole granularity).

Formally, an attribute $A = (L_A, V_A)$ is understood as a labeled set of possible values or a value space, cf. also Gärdenfors' *conceptual spaces* [64]. Labeling is necessary because attributes are "linked" with the phenomena they measure. Therefore, two attributes may formally refer to the same set of values yet be definitely distinct and not mutually exchangeable.

The set of all attributes used for describing processes is denoted by ATT. T denotes a special attribute for temporal values, $T \in ATT$. Its values comprise time stamps, $t_i \in V_T$. For the elements of T, a strict linear order is assumed, denoted by < ($\leq$ for the reflexive variant). The elements of T are at least ordinal, if not scalable. We assume that there is no smallest and no greatest element for T.

With attributes, values, and a dedicated time attribute, the basics for recording temporal information of processes are available.

3.3.2. Attributive dynamics

The phenomena underlying attributes (apart from T) develop in the course of a surgical process, more precisely of the part that the attribute characterizes. For a single attribute A, the course of development of its values can be reflected formally in terms of a partial function $f : T \to V_A$. We require that those functions are total over an interval of T and call such fragments a *stage* of development of an attribute A over time (an A-*stage*). For reference and for flexibility in specifying temporal relations, we further add an optional identifier (S_A in the subsequent example, "_" if omitted herein) for the particular stage and the attribute label L_A for readability. Hence, an A-stage is represented as a quintuple (S_A, L_A, f, t, t') such that $[t, t']$ is the interval over which f is defined. Hence, for any stage, $t \leq t'$. Note that V_A may comprise a specific value $undefined_A$ in order to ensure f being total over $[t, t']$. For a given time stamp t'', (S_A, L_A, f, t, t') *covers* t'' iff $t \leq t'' \leq t'$.

Already at this level, three types of eventualities, as introduced in the Basic Methodology section, can be borrowed. Stages with constant functions correspond to states because they do not exhibit changes (of the phenomenon behind the attribute). S_A is a *stative stage* (or *state*) iff for every t_1 and t_2 covered by $S_A : f(t_1) = f(t_2)$. In contrast, variable functions reflect the dynamic aspect of activities and accomplishments. Grasping the further distinction between these two types according to telic aspects is harder. In some cases of accomplishments, the final value of the function may be distinguished in relation to the course of f over T. However, there are other cases that necessitate implicitly accounting for subsequent stages. Following many approaches in linguistics, we adopted the view that accomplishments are composed of "an activity and a resultant change of state, where the change of state gives the natural stopping point for the activity" [60]. Hence, we call a stage (S_A, L_A, f, t, t') an *activity* iff there are $t_1, t_2 \in [t, t']$ such that $f(t_1) \neq f(t_2)$. This entails that every stage is either a state or an activity.

For greater flexibility in modeling, we allow for several stages of the same attribute (possibly with temporal gaps) to characterize a process, instead of only a single stage. This is captured by the notion of an *admissible stage set*, which enforces an ordering of all stages in the set. Admissible means that the functions of any two stages in that collection overlap, at most, in their interval boundaries, and at most two stages overlap at every time stamp. Accordingly, a set of stages S_A^* is admissible iff the following conditions are satisfied:

- for each pair of stages (S_A, L_A, f, t_1, t_2), $(S'_A, L_A, f', t'_1, t'_2)$, it is the case that
  - $[t_1, t_2]$ and $\left[t'_1, t'_2\right]$ are disjoint *or*
  - $t_2 = t'_1$ or $t'_2 = t_1$
- for every t such that an $S_A \in S_A^*$ covers t, there is at most one further $S'_A \neq S_A$ that covers t.

The conjunction of these two conditions yields the effect that two stages can, at most, "touch" each other temporally on two of their boundaries (i.e., the stages of an admissible stage set can be completely temporally ordered). As for time stamps, the symbol < may be used to describe the temporal ordering of stages.

It remains to capture "changes of state", including achievements. An *achievement* refers to a stage (S_A, L_A, f, t_1, t_2) and its temporally closest successor $\left(S'_A, L_A, f', t'_1, t'_2\right)$. Formally, given an admissible stage set, S'_A is the *successor* of S_A iff $t_2 \leq t'_1$, and there is no stage $\left(S''_A, L_A, f'', t''_1, t''_2\right)$ with $t_2 \leq t''_1 \leq t'_1$ in the stage set. An achievement between S_A and S'_A with identifier set to E^{ach}_A is captured by any of the tuples $\left(E^{ach}_A, L_A, S_A, S'_A, t_2, t'_1\right)$ and $\left(E^{ach}_A, L_A, f, f', t_2, t'_1\right)$. The latter case allows for achievements without recording their surrounding stages. For generality, we do not establish restrictions at this point, i.e., $f = f'$ and $t_2 = t'_1$ remain possible. This would correspond to instantaneous atelic eventualities, cf. semelfactives in Fig. 2, although in our experiments we have not yet observed and thus not yet arranged to record eventualities of this type. They could be useful in connection with abstractions among attributes. Nevertheless, the default assumption for an achievement is that f and f' or t_2 and t'_1 are distinct, thus involving a "change". We can distinguish general achievements from proper ones, where the latter are temporally defined as those satisfying the condition $t_2 = t'_1$ (i.e., a proper achievement has equal time stamps). For example, a transition from a state of attribute value v to another state of v' at one moment t yields a proper achievement.

It follows immediately from the above definitions that stages and achievements are complementary to each other, which gives rise to an integrated view. An *eventuality system* E^*_A for an attribute A consists of an admissible stage set S^*_A and a set of achievements $E^{ach,*}_A$, i.e., $E^*_A = S^*_A \cup E^{ach,*}_A$. In accordance with the above remark on *accomplishments*, those can now be understood as an eventuality system $\{(\_, L_A, f, t_1, t_2), (\_, L_A, f, f', t_2, t_2)\}$ (corresponding to reaching the telic conditions at the end; a change at the beginning is analogously handled).

An eventuality system E^* can be incomplete in the sense that it need not contain an achievement for every pair of successive stages, and it need not comprise two fitting stages for an achievement. However, it must be completable. We postulate as eventuality system completion requirement that for every eventuality system $E^* = S^* \cup E^{ach,*}$ there is a corresponding completed eventuality system $E'^* = S'^* \cup E^{ach,*}$ with an admissible stage set $S'^* \supseteq S''^*$, where S'^* contains two fitting stages for every achievement in $E^{ach,*}$. Note that this prevents any two achievements from sharing a time stamp, t, because otherwise t would entail the existence of three states covering t (e.g., one for the shared later stage, plus two for both achievements, which have distinct earlier stages). This appears reasonable for a single attribute. The system E^* is said to cover an interval $[t_1, t_2]$ iff t_1 is the starting point of the first stage or achievement in E^* and t_2 is the end point of the last stage or achievement.

Regarding granularity assignments, only local granularity measures are applicable to attributes, where they do not "add" part-whole granularity. Thus, for every attribute stage or achievement E^{att} and eventuality system E^*, $\lambda(E^{att}) = 0$ and $\lambda(E^*) = 0$. Alternatively, we say that an eventuality (system) is in the local granularity level λ_0.

3.3.3. Basic and high-level dynamics

With the notions of attributes, values, and (attribute-level) eventuality systems in the previous section, we introduced basic modeling elements in order to record the temporal development of individual observables (attributes) with respect to processes. However, processes must also be represented, and most descriptions of surgical processes require a higher level of aggregation (or several levels). In general, we adopt a common representation scheme for all *processes*, which is similar to attribute stages. Tuples of the form $(P, L_P, AS, CS, t_1, t_2)$ represent processes by an identifier P, a type label L_P, a set of attribute eventuality systems AS, a set of parts/components CS (which are themselves processes), and time stamps for the beginning and end, t_1 and t_2 (examples are given in the following section). Identifier and type labels are optional, and AS and CS arguments that are singleton sets may omit set notation. Moreover, a mereological theory for processes may be adopted and should then be reflected as far as possible in terms of corresponding formal constraints, e.g., on the nesting of processes. For instance, the first sample condition in the section Mereology and Granularity would translate into the formalization presented here by requiring that, for every pair of a process $(P, L_P, AS, CS, t_1, t_2)$ and one of its components $(P', L'_P, AS', CS', t'_1, t'_2)$, where $P' \in CS$, it holds that $t_1 \leq t'_1$ and $t'_2 \leq t_2$.

Achievements between processes arise in an analogous manner to attributive achievements (i.e., as transitions between two processes referred to via their identifiers). Similar to *ATT*, *EVT* denotes the set of all corresponding tuples representing eventualities in a certain context (which are subject to further conditions introduced below).

Granularity concerning processes is modeled as follows: the local granularity of a process is determined by the (maximum of the) granularities of its components: $\lambda(P) = \max_{C \in CS}(\lambda(C)) + 1$ if $CS \neq \varnothing$, otherwise $\lambda(P) = 1$. A process is homogenous with respect to the local level if all components have the same λ value. For a fixed set of processes (closed with respect to their nested components), the model granularity μ is defined by determining the maximal local granularity $\mu_{\max}$, which is assigned to all processes not contained in any other process (called root processes). The μ value of all remaining processes is $\mu_{\max} - \mu_{path}$, where μ_{path} is the length of the shortest containment path from the process to any root process.

It remains to describe admissible compositions, starting with the basic level λ_1. This first step unites attributes describing different aspects of a single process. The latter is not subject to further 'part-whole analysis', and it is typically rather limited in temporal extent. A *basic-level process* is of the form $(P, L_P, AS, \varnothing, t_1, t_2)$, meaning that it consists only of attributive eventuality systems $AS = \{E^*_{A,1}, \ldots, E^*_{A,n}\}$ and the interval $[t_1, t_2]$ that it covers. The $E^*_{A,i}$ are defined over distinct attributes $A_1, \ldots, A_n$. All $E^*_{A,i}$ over a common attribute must form an eventuality system. All these systems must cover $[t_1, t_2]$ (the latter condition may be weakened to allow for fuzzy boundaries). Basic-level processes can again be classified as the three durative eventuality types, which yield *basic-level states, activities, and accomplishments*. In some cases, this classification can be derived from the constituents $E^*_{A,i} \in AS$. For instance, if there is only one accomplishment and the remaining attribute-level systems comprise only single states each, the resulting basic process may be considered an accomplishment. Another case is one where all attribute-level systems correspond to a single state, which most reasonably leads to a basic-level state. However, in other cases, the nature of a basic process may be hidden due to the unavailability of a corresponding observable or to not measuring it. Another observation is that basic-level activities and accomplishments are commonly aggregated from several attributes, whereas states may reasonably be lifted to the basic level as singleton sets. Accordingly, the classification of basic-level processes should be considered from case to case.

Further levels of aggregation can provide useful levels of abstraction. Given basic-level eventualities, this kind of aggregation is more focused on finding *high-level processes*, $\lambda(P) \geq 2$, whose components are temporally distinct processes. Currently, in most cases, proximate components are considered. This kind of aggregation sometimes involves further abstraction beyond temporal summarization, representable in terms of new attributes. The formal account for high-level processes is strictly analogous to basic-level processes, in terms of the common representation with attribute and component sets and time limits. Again, the four-fold classification can be considered at all levels. Because the sets of higher levels differ considerably among existing approaches, we do not introduce any particular account into the general model.

3.4. Implementation

Regarding the fourth level of our method, the implementation level, we first represent the mathematical model as a UML class diagram (unified modeling language [45,46], cf. Fig. 4), as this form of representation paves the way for software applications. Moreover, it serves as an intermediate representation for SPMs in XML [47]. For the latter purpose, we provide an XML-Schema file[1] that defines an XML dialect for exchanging SPMs according to the presented framework. The file can be used for validating models.

A few final remarks about the UML diagram may prove useful. Attributes and their dynamics are covered in the lower half, whereas processes reside in the upper half of the diagram. In both cases, the UML associations 'isFrom' and 'leadsTo' express achievements based on explicitly available stages or processes. Attributive achievements may be specified alternatively by two functions only. Time is central to both attributes and processes. Because time points must occur in a pair wise fashion (if they occur at all), the UML class 'time specification' is as appropriate as individual associations to start and stop times would be. The doubly named 'associations' link, by order, with the UML attributes 'initial' and 'final'. For example, a process starts at the 'initial' time and ends at the 'final' time. A processual achievement transitions from a process ending at an 'initial' time to another starting at a 'final' time.

4. Application of the four-level translational approach

Next, the proposed framework is compared with, applied to, and evaluated for several recent approaches to surgical workflows and SPMs. These works were chosen, because each of them established the base for clinically useful applications and explicitly published SPMs.

4.1. A model for laparoscopic Nissen fundoplications

MacKenzie et al. [65–67] have published ergonomic studies based on videotaped laparoscopic training workshops for Nissen fundoplications. Laparoscopic interventions are 'keyhole' interventions, a kind of minimally invasive surgical approach. The intention of the mentioned research was to assess the skills of surgical residents and to develop a hierarchical framework for assessment based on plans and the structure of goal-directed human behavior. Their approach was the first attempt to decompose a complete procedure to the level of simple instrument motions.

The authors identified surgical activity types and proposed a semi-formal, hierarchical decomposition of laparoscopic interventions. The modeling was performed iteratively, using both top-down and bottom-up approaches.

Fig. 5 shows a cutout of the resulting procedure model. Within this model, a surgical procedure is divided into six granularity levels: *surgical procedure*, *step*, *sub-step*, *task*, *sub-task*, and *tool motion*. Five basic motion elements were identified. This decomposition includes only one kind of relation, namely part-of relations, and attribute values as natural language expressions.

[1] Available from: http://www.onto-med.de/software/spm.xsd.

This approach, however, has some limitations. Concurrencies and iterations were disregarded by the researchers and therefore not treated. In addition, the notion *surgical event*, from which the model is derived, is not clearly defined. There are also some minor slips within the model, such as accounting for the insertion of instruments but not their removal. An ontology would seem a sensible addition to this model.

On the other hand, the approach did not aim at presenting a generic model and has some strong points: in terms of modeling, the authors tried to find basic patterns to decompose single surgical maneuvers.

In order to transform the model of MacKenzie et al. into an instance of the model presented herein, we consider only their lowest level of tool motions as attribute stages, whereas the components at all other levels amount to processes in our framework. Specifying the highlighted components in Fig. 5 in a top-down manner yields the following result, where t_{init} and t_{fin} denote postulated start and end times of the overall procedure:

- $(E_1, \text{NissenFundoplication}, \varnothing, \{E_2, \ldots, E_8\}, t_{init}, t_{fin})$
- $(E_5, \text{RepairCrura}, \varnothing, \{E_{18}, E_{19}\}, E_4, E_6)$
- $(E_{19}, \text{Join}, \varnothing, \left\{E_{54}, \ldots, E_{58}\right\}, E_{18}, \_)$
- $(E_{55}, \text{Suture}, \varnothing, \{E_{83}, \ldots, E_{89}\}, E_{54}, E_{56})$
- $(E_{86}, \text{RepositionJaws}, \{E^*_{ro}, E^*_{ghc}, E^*_{push}, E^*_{pull}, E^*_{rel}\}, \varnothing, E_{54}, E_{56})$.

Further components are merely omitted but would be specified completely analogously. Only the attributive components cannot be described because the original articles do not provide corresponding data. However, for a valid model, there must be a set of attributive eventuality systems over the five motion attributes (*reach & orient (ro)*, *grasp & hold/cut (ghc)*, *push*, *pull*, and *release (rel)*) such that each attribute-specific set yields an eventuality system over its defining attribute. For illustration purposes, Fig. 6 graphically represents the hypothetical stage set $E^*_{\text{push}} = \{(A_1, \text{push}, 1, t_1, t_2), (A_2, \text{push}, 0, t_2, t_3), (A_3, \text{push}, 1, t_3, t_4)\}$.

The attributes of E_{86} exhibit local level λ_0 and $\lambda(E_{86}) = 1$. The model level is also $\mu(E_{86}) = 1$, whereas the lowest numbered model level of all neighbors of 'Suture' (E_{55}) is μ_2, which corresponds to the task level in [65]. Regarding the conceptual levels, the model is mostly but not completely uniform compared to the model levels. For instance, $\iota(E_2) < \iota(E_5)$, where E_2 is the step "Prepare Patient", $\iota(E_5)$ as depicted above.

Altogether, this demonstrates that the formal account introduced in this work is fully applicable to the approach of MacKenzie et al.

4.2. A model for cerebral tumor surgery

Jannin et al. [10,68,69] proposed a hierarchical procedure model for cerebral tumor surgeries in the context of image-guided surgery. The objective of their work was to provide enhanced support for surgical planning with the help of a generic model of surgical procedures, which consists of a mixture of classes of different kinds. There are hierarchical classes for decomposing the procedure, limited to two granularity levels (cp. Fig. 7): *surgical procedure* and *step/action* (step and action are in one-to-one correspondence). Furthermore, informational classes were enclosed to indicate supplemental image-related data (e.g., image entities or pathological, functional, or anatomical concepts) (cf. Fig. 8). The data was acquired offline pre- and post-operatively with the help of questionnaires and assessed afterwards. The proposed procedure model represents a top-down approach and accounts for the differentiation of planned and performed work steps.

However, the model does not allow for the expression of parallel or iterative surgical work steps and does not include temporal

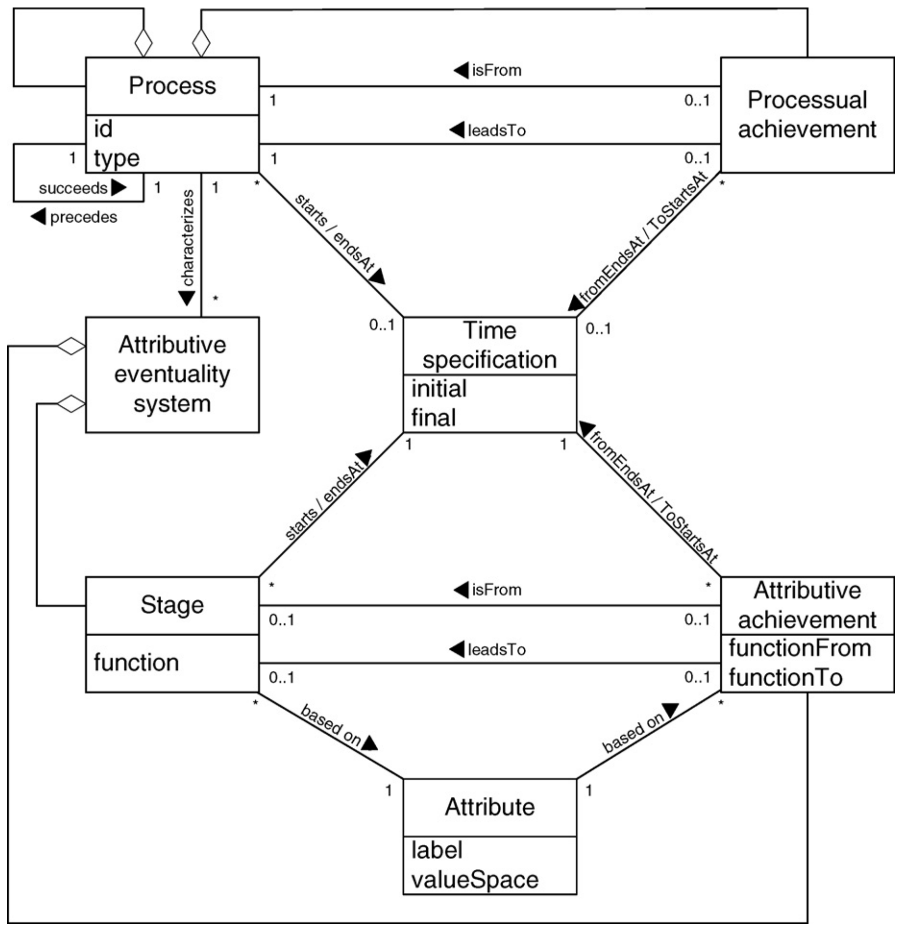

Fig. 4. UML class diagram of the presented formalization.

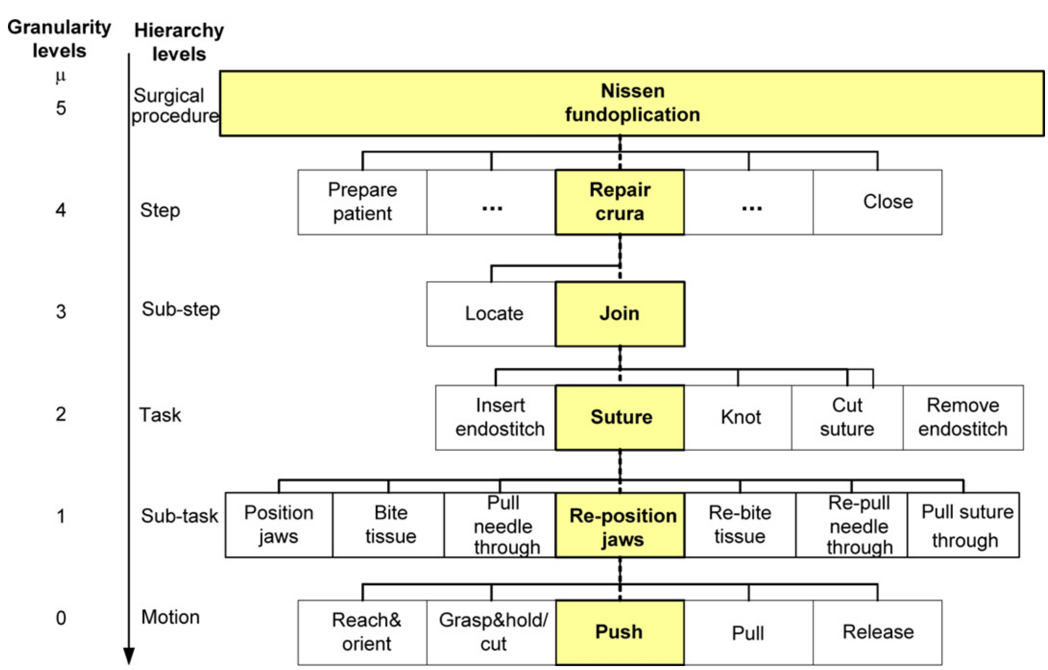

Fig. 5. Procedure model proposed for Nissen fundoplications (cutout) [65], with an example aggregation from the tool-motion level to the complete surgical procedure.

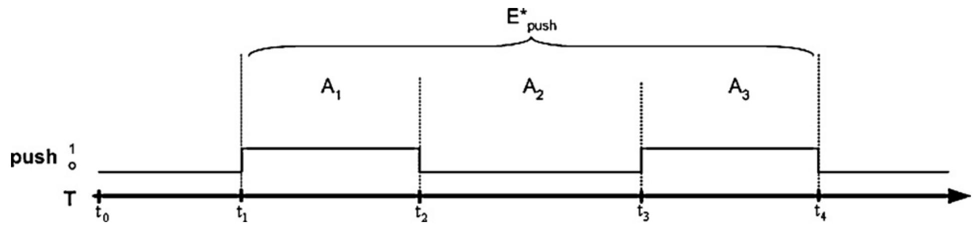

Fig. 6. Hypothetical stage set E^*_{push} (attribute level).

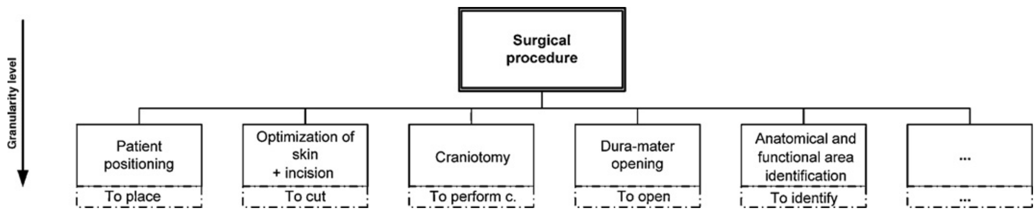

Fig. 7. The two granularity levels, ‘surgical procedure’ and ‘surgical step’, identified from the model by Jannin et al. [69].

information. Also missing are specific relation cardinalities, and mandatory and optional entities cannot be distinguished from one another. Nevertheless, this is the first approach to include surgical expertise and an ontological foundation, represented as UML model, and used as the basis for a database. This fact distinguishes this approach from the work of MacKenzie et al. (above) and Ahmadi, Padoy et al. (below).

The process-related parts of the model of Jannin et al. are easy to “translate” into the formal framework suggested in this paper, as there is no real hierarchical order. At first glance, there seem to be three levels of granularity that can be perceived: the *surgical procedure* itself (as the highest), the *step* (as the middle), and the *action* (as the lowest level). However, as mentioned above, only two hierarchical levels can be employed.

The surgical procedure is broken down into a sequential list of surgical steps. Each of these steps is then associated with a single action. Regarding the examples given by Jannin et al., it becomes clear that each *action* is actually a generalization of the corresponding *step*. For instance, the *steps* “transgyral approach” and “transsulcal approach” are both associated with the *action* “to approach”. This is a sensible solution for the authors’ specific purpose. For our purposes, however, we proceed on the assumption that this model has two granularity levels, namely *surgical procedure* and *surgical step*, including *action* into the latter by modeling it as an attribute of the step. The two granularity levels can be compared conceptually to μ_5 (surgical procedure) and μ_4 (steps) in the model by MacKenzie et al.

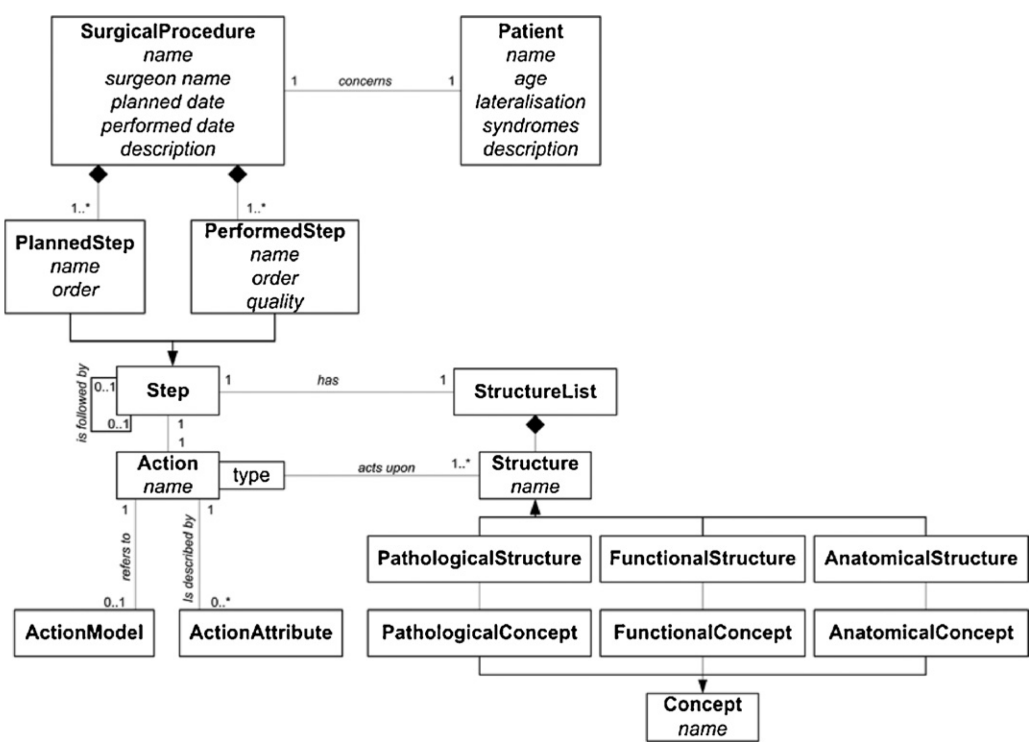

Fig. 8. Procedure model proposed for cerebral tumor surgeries (cutout) [10].

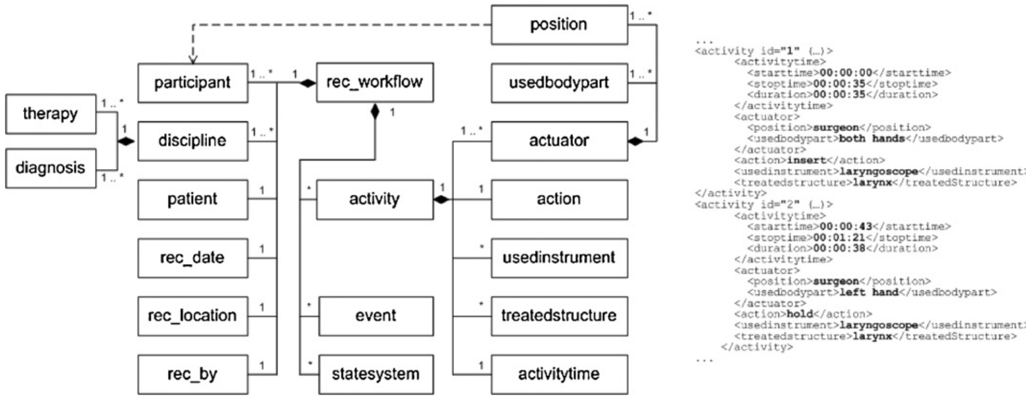

Fig. 9. Generic procedure model proposed by Neumuth et al. [73] (left, cutout) and example of activities in an SPM.

Other elements of Jannin's model can be adequately represented as attributes in our approach, in particular ActionModel, ActionAttribute, PlannedStep, PerformedStep, and Structure and its Subclasses. *Incident* is not described in detail in the available publications, but the name suggests that our achievements should be used. While some specific elements (such as ImageEntity) cannot be covered reasonably, we still conclude that the formalization developed in this paper could well be applied to this model. This should even apply to extensions with temporal information and new granularity levels.

4.3. A model applicable to multiple surgical disciplines

The approach described by Neumuth et al. [1,70–72] is aimed at developing surgical-assist systems and integrated operating-room control systems based on SPMs. Neumuth et al. describe concepts and technologies for the acquisition of surgical process models by monitoring surgical interventions. Furthermore, they subdivide surgical interventions into work steps at different levels of granularity and propose a recording scheme for the acquisition of manual surgical work steps from interventions in progress.

Trained observers record the surgical interventions live in the OR. They are supported by a software architecture, backed by dedicated ontologies, that has been devised by the authors. Live and offline recordings are possible with this method.

The drawbacks of this approach are that the attention span and the reaction time of human observers are limited in live observation settings; consequently, many rapid, consecutive, or simultaneous work steps are hard to keep track of. In addition, information that is not in the field of view cannot be recorded properly. However, this detriment is partly compensated for by the software.

The advantages of this approach are that it includes temporal information and is knowledge-based; in addition, ontologies from different domains, such as the foundational model of anatomy (FMA) [73], can be integrated into the model. Additionally, sensor signals can be included. In contrast to the other approaches presented here, the work of Neumuth et al. can be applied independent of the surgical discipline, school, or intervention type and allows for a universal adoption for observer or sensor system based data acquisition.

Processes at the lowest level of granularity, as identified in these works, are described in terms of attributes and clustered into *perspectives*. There are five possible perspectives, namely the *organizational*, *functional*, *operational*, *spatial*, and *behavioral* perspectives. The behavioral perspective captures explicit temporal information of processes in terms of start and stop times. All other attributes of the perspectives are situated at λ_0 and determine a basic process at λ_1. For instance, a partial specification of activity 1 in the XML-fragment of Fig. 9 amounts to:

- $(L_{P1}, \mathit{insert/laryngoscope/larynx}, \{A_1, A_2, A_3\}, \varnothing, 00:00, 00:35)$
- $(A_1, \mathit{action}, \mathit{insert}, 00:00, 00:35)$
- $(A_2, \mathit{instrument}, \mathit{laryngoscope}, 00:00, 00:35)$
- $(A_3, \mathit{treatedStructure}, \mathit{larynx}, 00:00, 00:35)$.

Fig. 10 shows an example of several steps of aggregation. These can also be captured in terms of the proposed framework; e.g., $(P_1, \mathit{cutting}, \{E^*_{A,1}\}, \{C_1, C_2, C_3\}, t_1, t_4)$ represents a cutting procedure composed of two cuts, with a period of not-cutting in between (C_2), to be carried out by the surgeon using his/her right hand (A_1). This indicates that the presented framework is sufficient to handle the approach of Neumuth et al.

4.4. A model for laparoscopic cholecystectomies

Ahmadi and Padoy [71,74,75] proposed a method for the determination of surgical phases based on information obtained from sensor signals. In contrast to the previously described works, this represents a bottom-up modeling approach, segmenting surgical workflows into 14 interventional phases by a temporal synchronization of multidimensional state vectors. 17 surgical instruments were used to record a binary model for instrument usage. Every instrument can acquire two states:

$$u(t) = \begin{cases} 1 \text{ \textit{if the instrument is used at time} } t, \\ 0 \text{ \textit{if the instrument is not used at time} } t. \end{cases}$$

Thus, the approach aims at the automatic detection of phases within a surgical procedure by assessing instrument usage. Until now, the work has only been applied to laparoscopic cholecystectomies, a method to remove the gallbladder. However, it requires a reference model for synchronization that yields segmentation, and the sensor signals are not obtained automatically. Information about treated structures and the detection of performed actions are not included in the approach.

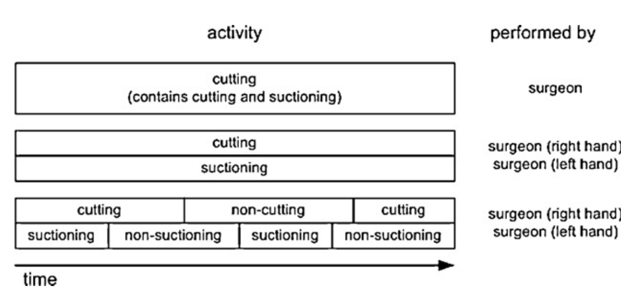

Fig. 10. Example of different granularity levels.

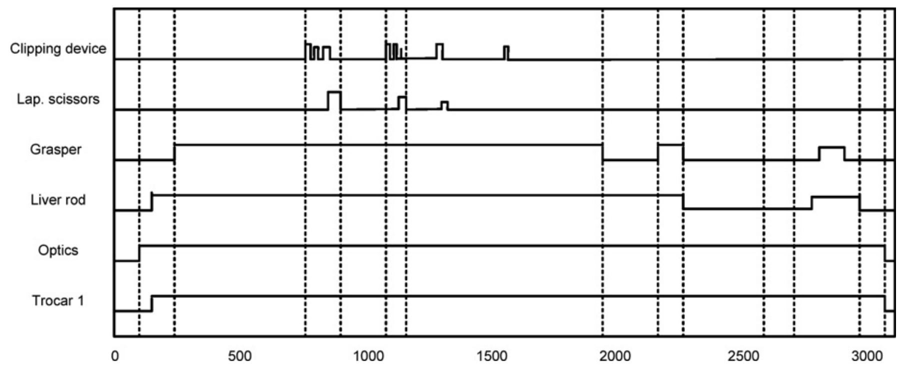

Fig. 11. Instrument usage diagram for cholecystectomies [71,76] (cutout).

This approach is the first to use live signals from the OR to detect intervention phases, later also supported by color and clip detection and an endoscopic camera signal. However, according to the authors themselves, it detects some phases according to the two previous phases and the upcoming phase [74]. The fact that a "future" phase is used speaks against live detection. In addition, the overall number of surgeries processed is not very high.

The overall approach of Ahmadi and Padoy yields three relevant model elements, namely individual signals, phases, and the surgical intervention itself, and it can be described profitably by the means presented in this paper.

The recording of the binary values of 'instrument used' or 'instrument not used' (the graph displays a baseline or a peak of variable height), as shown in Fig. 11, is understood to provide attribute stages for the overall intervention from the very beginning to the end. The course of the signal values is reflected in the function argument of an attributive stage in our framework. Subsequently, the authors calculated phase boundaries and aggregated temporal fragments of these attributes into phases. Clearly, the temporal attribute T is immediately applicable to this approach. Given the phase allocation, the surgical intervention can easily be described in our framework with those sequential phases as components, and each phase can be characterized by all instrument attribute stages. Note that these phases form basic processes at a random (ι-) level of granularity, which is mainly due to the characteristics of the recording methods. They also involve many more entities and aspects than processes described in a top-down fashion do.

5. Discussion

The goal of this paper is to present a four-level framework that is ontologically founded and can serve as a basis for the formal representation of surgical processes models for statistical analysis and data mining. The approach closes the gap between data and knowledge in the domain by using a linguistic approach.

In recent years, several different approaches to structuring and modeling surgical interventions have been proposed. Each of these attempts uses its own constructs, and the variety of different underlying conceptual systems impedes the comparability of results, the exchange of data, and their unified interpretation. We developed the approach to allow for data exchange between different groups working in the respective domain, which was not available before. The focus was not to provide a general applicable framework, but rather to provide a formalism that can be applied to the few existing approaches for modeling SPMs. The expressive power and the representational capacity of our framework were demonstrated by applying it to four recent and frequently cited approaches to surgical process modeling. Further related approaches could not be taken into account due to spatial constraints. Regardless of this, our approach is well adapted for the domain of surgical process modeling, as the evaluation has shown where all four approaches could be reconstructed within our framework.

To bridge the gap between data and knowledge, we used verbs as process categories for the selective representation of knowledge over time-distributed data of surgical processes. By using this ontological view, we can cover the entire processes. By measuring different aspects of these processes we select distinguished attributes for subsequent mathematical modeling. However, the origin of our approach is based on the ontological view, where the attributes need to have meanings that can be ontologically derived.

The reconstructions capture in detail the temporal structures of processes, offering a high degree of expressiveness. Arbitrary relationships between the temporal parts of an intervention can be represented, for instance, including concurrency and branching. This could already be achieved by requiring time stamps for all temporal entities (stages and processes), but that temporal information is not available for all approaches. For instance, Jannin et al. [10] lack time-stamped data (due to differing goals for their work). In order to cover approaches without explicit temporal data, a sequential ordering of processes was added to our framework. The expressiveness of our method suffices to cover the application cases but could be further extended to partial orders or preorders. An even greater extension would be to allow for temporal variables in the formalism, which further implies the need for a constraint language on these variables (e.g., in order to cover relationships such as the temporal ordering of time stamps ($t_1 \leq t_2$)). However, this further increases the complexity of the model. For data acquisition purposes, we would recommend restricting the dataset to explicitly time-stamped data. An extension by variables is a step towards explicitly modeling gSPMs, as well as patterns to express iterations and concurrencies, even though the latter remain implicit in the time-stamped data thus far. Alternatively and depending on the respective purpose, the adoption of other process representation formalisms is worth being reconsidered, when experimentally observed gSPMs are derivable from the data collected on the basis of the presented model.

The second consideration concerning the temporal structure of surgical processes is to assign to them different levels of granularity. Three of the four application cases define a fixed hierarchy of granularity levels. First, we believe that the notion of granularity as such, and in its particular combination with processes, requires further (ontological) analysis. One central question is whether discrete levels of granularity can be assumed or whether they should be regarded as the discretization of a continuous notion of granularity. The presented framework follows two strategies. The formal granularity functions λ and μ account for variable hierarchical levels of granularity that are oriented at the modeling primitives, which are chosen when the framework is applied. This is suitable for representing the four application cases. In contrast to λ and μ, the content-oriented granularity relation ι is intended to serve as a simple, preliminary means of comparison across different models and application cases. In future work, terminologies of surgical processes may be employed as a basis for global granularity comparison. Another future goal related to granularity is to better understand the principles of distinct methods of process modeling, in particular of (and between) the poles of top-down and bottom-up modeling.

The non-temporal aspects of surgical processes are covered uniformly in terms of attributes in the presented framework. This abstraction is fairly strong and exhibits some similarity with the process specification language [34], which also offers only one basic non-temporal modeling element. This choice promotes the uniform analysis of temporal patterns of surgical processes. On the other hand, some distinctions regarding non-temporal aspects are available in other approaches (including the norm EN 1828 [29]), e.g., between anatomical and instrumental participants in an intervention. If these distinctions are to be maintained during conversion into the mathematical framework, additional, unambiguous guidelines and conventions must be established that specify their encoding. It is reasonable to incorporate a more detailed model of non-temporal aspects in order to extend the framework. At the present stage, however, further analysis concerning which of these aspects are universally applicable to arbitrary interventions is required.

Besides the formal level, at which the proposed mathematical framework is located, our basic methodology comprises three additional levels, including the second (i.e., the ontological/conceptual) level. This requires further development and refinement. A particularly important future task is the ontological analysis and declarative formalization of the theory of eventualities. Eventualities can generally be interpreted as process categories that are related to verbs. The precise ontological foundation, also in connection with top-level ontologies, is not yet complete. We encountered some complexities that have their origins in linguistics and hence in the usage of natural language. One question remaining, for instance, is: 'How can gradual developments and the precise moment when a goal is reached (achievement) be expressed?' In the pertinent literature, there are no complete solutions to this problem, as natural language cannot be described as a clearly framed set of rules.

From the given formal representation of eventuality types, a similar situation arises as was discussed for granularity above. Many intervention models are constructed top-down and rely only on natural language labels for the phenomena that are captured (in addition to temporal aspects). These labels are reflected in the mathematical framework as stages with constant functions only. Given the built-in formalization of eventuality types, this leads to many states in intervention models. From a content perspective, such states may well be of a different nature – accomplishments or achievements, for instance – where that nature is hidden in the original natural language expression. This must be taken into account for evaluations according to eventuality types. In the context of our application cases, the distinction between different eventuality types is rare in current models. Nevertheless, we believe that the expressiveness of our framework will allow for more fine-grained statistical analyses and/or data mining of surgical procedure records.

The presented approach needs further development to meet requirements of future applications, such as a mapping onto established logical formalisms that allow for reasoning for treatment planning or decision support systems, the ontological basis of the delineated formal-mathematical elements is to be extended and can be linked with a top-level ontology, such as the general formal ontology (GFO) [36]. An explicit model of the eventualities and of the overall model in the web ontology language (OWL) [29,77,78] would be useful for the context of the semantic web. In addition, the explicit definition of semantic relations between the basic entities on a linguistic grounding is conceivable, as well as the integration into the surgical ontologies for computer assisted surgery (SOCAS) [79], which was developed in a related project. Finally, an incorporation of the framework into an interactive knowledge base will be attempted.

6. Conclusion

This work presents an attempt at developing a unifying framework for generating surgical process models (SPMs) that is ontologically founded and formally and mathematically precise. Our aim is to create a common basis for the different and varying approaches in this field. With the help of sample instantiations, it was demonstrated that the proposed framework applies to four major approaches. Thereby, we have shown that it is possible to syntactically adapt very different approaches and to render them interoperable and comparable. In effect, the value of data from surgical processes can be increased by using this framework. Its ontological foundation arises within a novel four-level methodology. The well-established theory of eventualities is initially adopted for process classification.

The growing number of recent studies based on surgical workflows and time-action analyses shows the rising interest in this subject area. That interest can be accounted for by the multitude of possible applications from both the technical and the clinical points of view. Some examples are the evaluation of surgical-assist systems or surgical skills, the design of technical support systems for the operating room, the conception of surgical knowledge bases and the generation of knowledge from them, the planning of interventions, requirements analyses, and so forth. For all of these applications, surgical process models could be more useful if they were designed according to a common basis. The formal framework and the embedding methodology presented here provide a coherent and rigorous contribution towards this end.

Acknowledgements

The Innovation Center Computer Assisted Surgery (ICCAS) at the Faculty of Medicine/Universität Leipzig is funded by the German Federal Ministry for Education and Research (BMBF) and the Saxon Ministry of Science and Fine Arts (SMWK) in the scope of the initiative Unternehmen Region with the grant numbers 03 ZIK 031 and 03 ZIK 032 and by funds of the European Regional Development Fund (ERDF) and the state of Saxony within the frame of measures to support the technology sector.

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