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Modeling surgical processes: A four-level translational approach

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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.

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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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(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].

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