Autonomous Robotic Surgical Systems

Needing Common Sense to Achieve Higher Levels of Autonomy

By Eleonora Tagliabue, Marco Bombieri, Paolo Fiorini, and Diego Dall'Alba

While executing a surgical procedure, surgeons not only rely on their specific medical knowledge but also on a set of skills that are "obvious" to them and allow for intuitively evaluating and reacting to the intervention evolution. Such skills belong to what is usually called *common sense*, which is essential to carry out an intervention. Although general common sense refers to all the basic concepts about the world and belongs to all human beings (e.g., the fact that a needle must be inserted from tip to eye), we believe that field-specific common sense is developed depending on individual experiences within a field of expertise. In surgery, field-specific common sense is the "glue" knowledge that is not explicitly described in surgical manuals, but it is acquired during lengthy surgical training. For example, a textbook does not explicitly describe how the needle should be held nor how it should be inserted in the human body, but this information is known by the domain experts. Understanding how to describe, represent, and learn this knowledge is paramount to developing robust and reliable autonomous robotic surgical systems (ARSSs). Developing ARSSs is a research trend of great interest for which taxonomies and paradigms have already been proposed. For more details, the reader is referred to [1] and [2]. The importance and challenges of common sense have been discussed in other fields [3], [4], but to the best of our knowledge, this aspect has not yet been addressed in robotic surgery.

COMMON SENSE AND SURGERY

Our research on ARSSs has shown that automatic extraction of surgical procedures from surgical textbooks is a feasible task [5], but also that the result does not include the large amount of implicit knowledge that humans use during the surgical task. In the following, we refer to the granularity classification of surgical procedures in phases, steps, actions, and motions proposed by Lalys and Jannin [6]. In this classification, a procedure (e.g., partial nephrectomy) is composed of a sequence of main events, called *phases*, occurring in the procedure (e.g., tumor excision or final suture). Each phase is then composed of a set of steps, i.e., sequences of activities to achieve a surgical objective (e.g., the main steps of the final suture phase are the removal of the trocar, extraction of the specimen, and closure of the skin). Each activity is then composed of a sequence of motions, i.e., single-hand trajectories (e.g., pulling the needle to close the suture using the right arm). Based on the aforementioned definitions and in-depth discussions with surgeons, we propose a preliminary classification of surgical knowledge into the following four levels:

1) *Procedural knowledge*: Description of the sequence of phases required to perform a procedure, as can be learned from surgical manuals. It does provide general information about the specific steps, but it does not specify the parameters of each step, i.e., the physical quantities that instantiate individual actions and motions, such as motion velocity or force to be applied.
2) *Surgical common sense*: This is a field-specific common sense that encompasses all the skills surgeons acquire while experiencing (assisting and performing) a specific procedure multiple times. It allows defining the sequence of elementary actions needed to perform the surgical task and intuitively setting their parameters. It also includes the capability to interpret surgical situations and thoroughly understand correlations, causes, and consequences of actions and thus to select the best surgical technique for each specific situation.
3) *Medical common sense*: This is another subset of field-specific common sense that is not specific to a single surgical procedure and is acquired during medical studies. For example, it includes knowledge of basic anatomical concepts (positions and functions of organs), a high-level understanding of how surgical actions impact anatomy, and evolution of the patient's prognosis after surgery and medications.
4) *General common sense*: The common sense that surgeons have as human beings. It represents the basic knowledge of the world, is acquired while experiencing everyday situations, and helps infer the meaning and behavior of things.

This classification is not always crisp because it depends on the context. The same concept can refer to one or to

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another type of common sense. For example, knowing the effects of a complex surgical action on the internal organs requires surgical knowledge and experience (and thus surgical common sense) that may not be required in simpler and standard cases, when only medical common sense may be sufficient.

To clarify the proposed classification, we introduce Figure 1, which describes the common-sense knowledge required during the suturing phase of a partial nephrectomy intervention. This classification can be adapted to other surgical phases or procedures. The sentence at the top is taken from a surgical textbook [7] and represents the procedural knowledge of the intervention. However, it does not describe how to assess the conditions of a good suture nor how to select the best surgical approach to connect the tissues, nor does it list the individual steps and actions needed to accomplish it (surgical common sense). Furthermore, it does not describe the effect that a suture generally causes on tissue nor how to pharmacologically treat the patient after the surgery (medical common sense), nor does it provide the implicit general knowledge about the objects involved in the suture, e.g., a needle is needed and it must be grasped, inserted, and extracted (general common sense). Despite these missing details, surgeons are able to perform the intervention after reading a manual. This is possible because they can leverage their broader background that glues information together. Surgical textbooks alone are not sufficient to fully describe an intervention, and an ARSS must acquire the same level of knowledge mentioned previously to perform the surgical task and properly handle the situations that occur.

MAPPING COMMON-SENSE SKILLS TO AUTONOMY LEVELS IN SURGERY

Following the taxonomy first presented for self-driving cars [8], an ARSS can be classified into five levels of autonomy, as proposed by Yang et al. [9]: at autonomy level 0, the human performs all the tasks and makes all the decisions; at autonomy level 1, the robot provides dexterity and cognitive assistance during the task, sharing controls and actions with the human; at level 2, the robot is autonomous during specific tasks, i.e., trading control of the system with the human at discrete times; at level 3, the robot generates task strategies but the human has the final decision over the proposed tasks; at level 4, the robot can make decisions on the complete surgical strategy but under the supervision of a qualified doctor; finally, level 5 introduces the full autonomy, i.e., a robotic surgeon that can perform an entire procedure without supervision. These different levels of autonomy are obviously associated with different levels of knowledge, and we propose the classification schematized in Figure 2. In particular, the sophisticated capabilities required to reach high autonomy levels are implicitly connected to the breadth of the required common-sense knowledge.

Current surgical robots are teleoperated systems with some assistive function (levels 0 and 1) and have no knowledge of the steps to be performed but simply

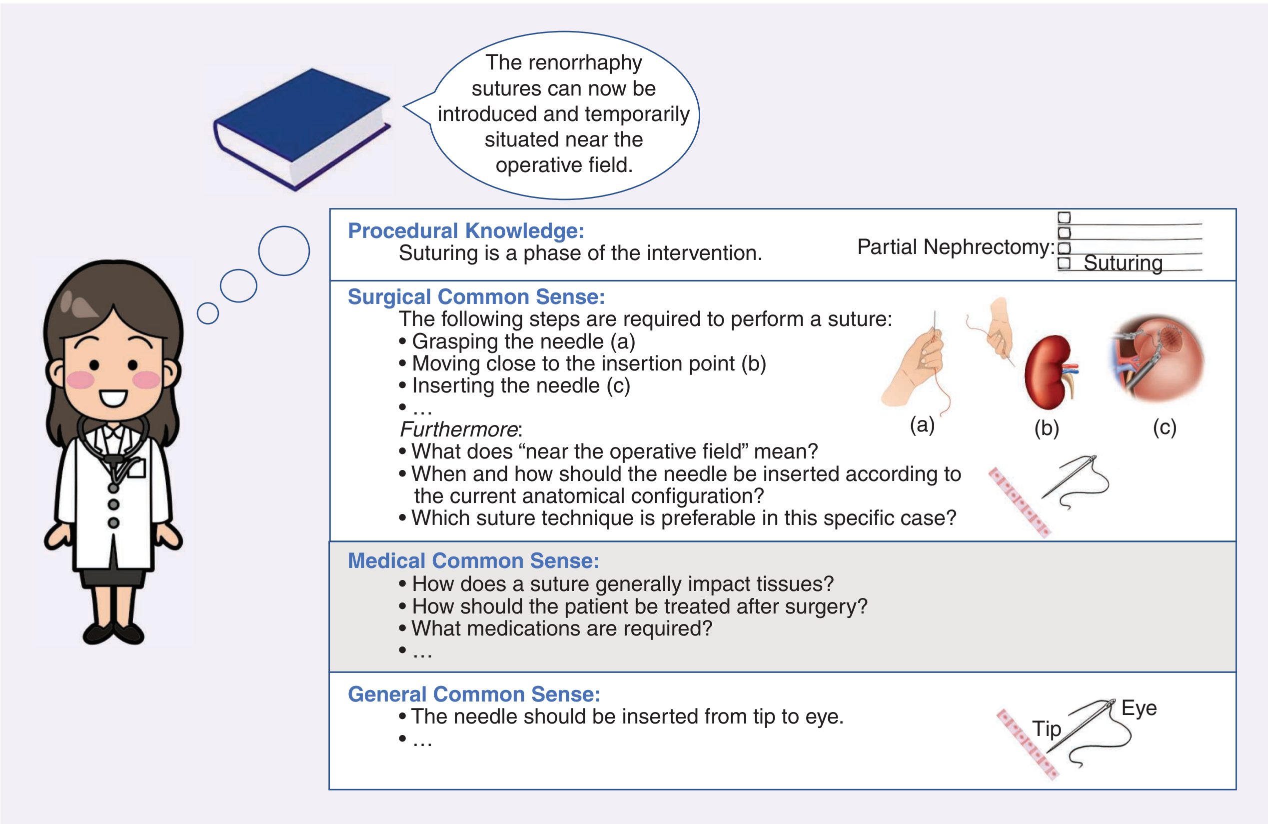

FIGURE 1. Procedural knowledge enriched with surgical, medical, and general common sense.

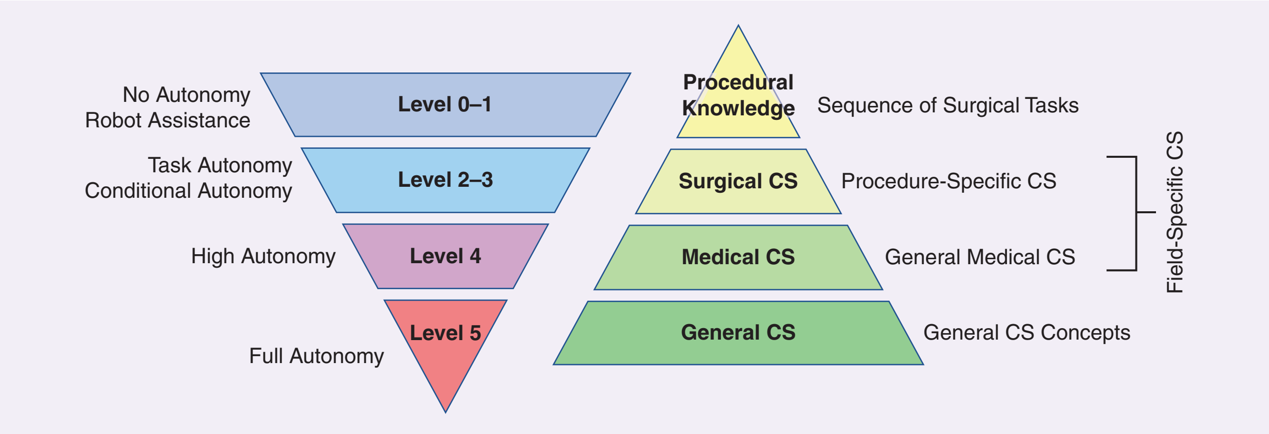

FIGURE 2. Mapping between autonomy levels and the required knowledge levels. Higher autonomy requires broader knowledge. CS: common sense.

monitor some working variables, such as current levels, maximum speed, and electrical noise. The specific phases and steps of the intervention are determined by the surgeon, who directly controls the surgical actions. However, even when autonomous functions are limited (levels 0 and 1), a certain amount of common-sense knowledge is implicitly included in the control algorithms and data analysis methods. For example, autonomy level 0 has specific actions that include, e.g., tremor suppression and maintaining orientation during clutching. At level 1, the robot provides dexterity and cognitive support to the human for specific actions or tasks but not for strategic decisions (plans) or actions, and all common-sense reasoning is provided by the surgeon.

When a surgical robot is able to execute some individual actions (levels 2 and 3, becoming an ARSS), it would require the presence of surgical common sense. In fact, the robot would need to perform some basic reasoning on the patient-specific pathology and anatomy, with the surgeon ready to intervene if needed. Referring to Figure 1, the robot would have to interpret "near the operative field" and decide where to insert the needle, given the patient's anatomy. Furthermore, in the aforementioned example, the robot would have to know that a suture needs a surgical needle, which has to be grasped with a specific orientation for optimal insertion. It has to control motion parameters (force and velocity) during the insertion, and it has to know how to close the suture. Some concepts of medical common sense would be needed to give the ARSS more autonomy and connect multiple phases of an intervention. For example, the ARSS needs to know the human anatomy and how each step impacts it. However, it is not always easy to identify a sharp division between surgical common sense and medical common sense as a combination of both is necessary to specialize a well-defined textbook procedure into the real intervention.

To achieve higher autonomy, an ARSS must be able to make autonomous decisions related to the complete procedure. It will generate, select, execute, and monitor a surgical plan; adapt it to different anatomies and react to unexpected situations. Enhanced sensing, situational awareness, and reasoning technologies are key to achieving such capabilities [1], together with a broader common sense to properly assess and react to the situation. Although medical common sense would allow reaching high autonomy (level 4), fully autonomous systems (level 5) would need the integration of general common sense because decisions would be required that go outside the medical field, such as lifting and moving objects, turning on and off devices and lights, and understanding human emotions.

> "TO ACHIEVE HIGHER AUTONOMY, AN ARSS MUST BE ABLE TO MAKE AUTONOMOUS DECISIONS RELATED TO THE COMPLETE PROCEDURE."

CONCLUSION

As long as surgical robots maintain an assistive role, they can rely on the common sense of the operating surgeons. As soon as they become aids or surgical colleagues, they must be able to perform common-sense reasoning on their own, making it crucial to understand how to deal with this kind of knowledge. The map between the common-sense types and autonomy levels proposed in this article aims at making the problem more tractable and encourages researchers to fill the scientific and technological gaps related to common-sense knowledge and reasoning. Data-driven deep learning algorithms are a promising approach to embed common sense into a process, as data implicitly encode common-sense knowledge. However, this common sense is neither explicitly formalized nor identified, thus process reasoning is not directly explainable to the user, and it also violates the upcoming regulations on using artificial intelligence methods in high-risk applications [10]. For these reasons, we feel that common sense should mostly rely on explainable reasoning, especially when used in safety-critical systems.

(continued on page 163)

robots are in the process of being better equipped to comprehend and interpret human language, enabling effective communication and interaction in diverse contexts.

These three noteworthy innovations demonstrate the evolving landscape of cognitive robotics as researchers strive to develop robots that can meaningfully engage with humans, leverage advanced learning techniques, and grasp the nuances of language in everyday scenarios. Looking ahead, the challenges in cognitive robotics involve *demonstrating the generalizability of robot skills, their adaptivity, and their ability to exhibit long-term learning in interactions*. This requires a balanced approach to exploration–exploitation, enabling prospection and internal simulation, leveraging a correct combination of language and nonverbal communication, and developing a robust memory system. An architectural view of robot cognition will be crucial in achieving continuous and adaptive collaboration. It might also support addressing the challenge of enabling robots to handle dyadic interactions and more complex group scenarios, such as autonomous driving in populated areas or collaborative robotics in industry.

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With its growing membership of 249 in 2023 (Figure 5), TC-CoRo aims to disseminate the topics of cognitive robotics further and maintain an active discussion across disciplines. The committee offers numerous resources, an active member mailing list, and support for organizing events related to cognitive robotics, contributing to the advancement and awareness of this exciting field.

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OPINION *(continued from page 151)*

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