Paper Review
SURGICAL ROBOTICS BEYOND ENHANCED DEXTERITY INSTRUMENTATION

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Selected Paper: Kassahun, Yohannes, et al. "Surgical robotics beyond enhanced dexterity instrumentation: a survey of machine learning techniques and their role in intelligent and autonomous surgical actions." *International journal of computer assisted radiology and surgery* (2015): 1-16.

1. Introduction

1.1 Motivation for Machine Learning in Surgical Robotics

Although the numbers of evidences that justify the cost of robotic surgery remain sparse and even discouraging at present, future system will possess a certain degree of intelligence that shows the clinical advantage people are looking for. This cognitive ability will allow robot to take over simpler parts of the surgery, and let the surgeon focus on more crucial and complicated parts of the procedure.

Another reason of the development of robotic surgery is the increasing workload on the expert surgeon. This condition has pushed the development of several computerized assistants and automations of certain surgical intervention. However, majority of the system can only works under assumption that the environment remains invariant with respect to robotic action, which severely limit the range of procedures that can be done by such system.

This condition could only be recovered with the modeling of robot-environment interaction. One of the approaches for robot-environment interaction modeling is explicit modeling, such as tissue modeling. However, depending on the choice of model and parameter, the applicability of such models can be rather limited. Furthermore, the derivation of valid model and the identification of its parameter can be time-consuming and tedious task. Given the large variability between people, organs, and tissues, explicit modeling approaches have practical limitation

On the other hand, machine learning approach could learns from implicit models directly from real sensory data, which makes it appealing for the following reasons:

- General applicability to wider range of problems and sub-tasks;
- Avoidance of complex modeling of the underlying physics and biomechanics;
- Based on data from real case scenarios.

1.2 Introduction to Machine Learning

Machine learning is a multidisciplinary field that provides the computer a way to learn without being explicitly programmed to perform specific task. Although machine learning techniques has been used extensively in wide spectrum of robotic application, it is only recently considered for surgical robotics. This following figure shows a schematic of a machine learning enabled intelligent surgical robotics system for the case of catheter-based intervention:

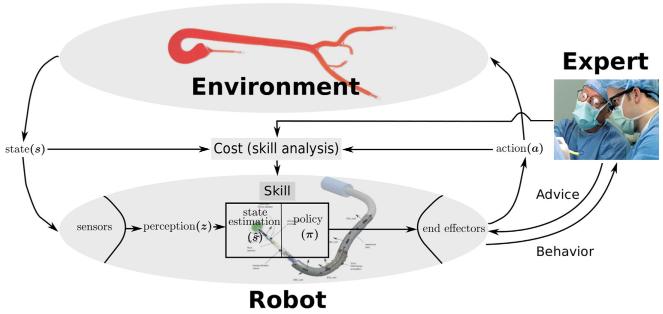

Figure 1. Schematic of machine learning enabled surgical robot [1]

In surgical robotics, robot uses its sensors to approximate its environment and do some action that will minimize some sort of cost function. This mapping between perceptions from sensor data to action can be considered as surgical skill. There are multiple ways for a robot to learn a surgical skill. First, it could learn from its interaction with environment and guess the appropriateness of its action to reach particular target states. Another way to learn surgical skill is by observing experiment conducted by expert surgeon. Alternatively, the surgeon could also intervene and guide the robot action through observation.

In the following, there are three important areas in machine learning are covered:

- Structured learning: Training data are provided externally, and consists of a set of known input vectors along with a set of known corresponding output vectors. Example: Support Vector Machine (SVM)
- Reinforcement Learning: deals with learning policy, i.e. mapping from states to action, that tries to maximize numerical reward. Example: Neural Network
- Unsupervised Learning: the training data consists of a set of input vectors without a corresponding set of target vectors. The purpose of unsupervised learning is to learn the structure and correlation of the data. Example: k-means clustering

2. Machine learning empowered instrumentation for assisted surgery

2.1 Surgical skill learning from expert knowledge

For surgical skill learning, experienced surgeon supplies prior knowledge used for machine learning data. Skill learning process usually employs implicit imitation learning technique, which is a form of structured learning that accelerates reinforcement learning by observation of expert mentor. In this technique, the robot (agent) observes the state transitions of surgeon's (mentor) action, and used these observations to update its own states and action. The surgeon and agent might have identical or different action capability, and identical or different reward structure.

There are three categories in implicit learning group. First group tries to learn mentor's policy; the second group learns the reward function of the mentor's behaviors and optimizes its own behavior using learned reward function. The third group employs a Bayesian framework for combining prior (explicit) knowledge and implicit imitation learning.

2.2 Skill analysis in robotics surgery

There are several ways to measure surgical skills:

- Explicit skill assessment: uses form of cost function defined by expert surgeon.
- Checklist and rating scales: uses rating scale graded by expert, such as video observation. This technique needs a lot of expert time.
- Structured assessment: uses rated checklist on phantom bench-top model. This assessment technique aims to quantifying medical skill evaluation without relying on expert evaluator. This technique currently suffers from subjectivity, added cost, time, and the need of clinical experts assessment.
- Outcome-based analysis: uses metric such as number of complication, morbidity, and mortality rates. This technique suffers from the fact that the patient outcomes are also strongly dependent on patient characteristic, which makes the result not directly correlated with the surgeon skill level.
- Motion analysis: surgeon's hand or tool motion are recorded and analyzed. This technique provides good assessment of dexterity and technical skill level.
- Time action analysis: surgical procedure broken down into several steps, and the time to complete each one is measured. This technique is time consuming, because manual labeling of activity is required, and it also do not report how well the particular surgical action is performed
- Virtual reality: potentially offers a vast amount of valuable information for assessment and analysis of surgical technique that may not be available from the real world. However, this technique performance depends on how well the model corresponds to the real environment.
- Error analysis: number of error made during certain part of the procedure is scored.
- Implicit skill analysis: uses metric, which is learned by a machine learning approach from a surgeon or group of surgeon, to rate other surgeons relative to the skill of surgeons from which the metric is learned.
- Classification of surgical skill levels: By recording various data, such as tool velocity, from surgeons with various skill levels, it is possible to use unstructured learning to cluster and classify skill level.

2.3 Surgical workflow analysis and episode segmentation

Surgical procedure is a combination of surgical acts, which when pertaining to the same specific surgical goal can be grouped into surgical subtasks. Workflow analysis can be conducted to identify surgical subtasks that belong to a surgical intervention, the order of which subtasks can follow each other and possible termination conditions that mark transients between distinct subtasks. The analysis of the surgical workflow is essential to assist surgical navigation and enable design of cognitive surgical system that can adapt and operate in highly dynamic environments.

So far, the analysis of surgical workflow has been extensively studied for minimally intensive surgery. The approaches proposed in the literatures can be classified into methods for segmentation of high—level surgical tasks, method to recognize low-level task, and into offline and online approach.

3. Toward autonomous robotic surgery

3.1 The role of machine learning in autonomous robotic surgery

This following table summarizes different aspect that could be constructed and learned directly from data with machine learning approach:

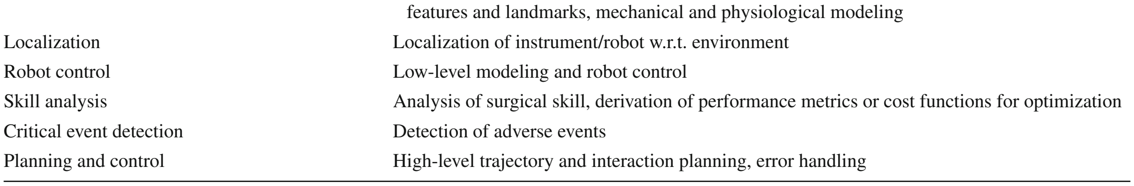

Table 1 Aspects of autonomous robotic surgery (ARS) where ML could play an enabling role

Workflow analysis episode segmentation	Surgical procedure broken down into logical subtasks or episodes
Environment modeling	Rigid and flexible registration, reconstruction of environment, recognition of anatomical features and landmarks, mechanical and physiological modeling
Localization	Localization of instrument/robot w.r.t. environment
Robot control	Low-level modeling and robot control
Skill analysis	Analysis of surgical skill, derivation of performance metrics or cost functions for optimization
Critical event detection	Detection of adverse events
Planning and control	High-level trajectory and interaction planning, error handling

Table1. Aspects of autonomous robotic surgery [1]

3.2 Example of machine learning used in surgical robotic research

- Intelligent autonomous endoscopic guidance system: Development of endoscope that have automatic steering system that could visualize patient's organs alongside instruments for grasping, cutting, ablating, and so on.
- Autonomous knot tying: Development of autonomous suturing and knot tying for minimally invasive surgery that helps surgeon to achieve faster surgery.
- Knot tying with neural network: Using recurrent neural network to tie knots autonomously, which reported to speed up the knot tying process and reduces the overall time of the surgical intervention.
- Knot tying via trajectory transferring: A system that could tie knots in ropes by training the robot by human demonstration
- Superhuman performance of surgical tasks: the robot could execute tasks with super human performance, such as smoother and faster movement.
- Skill transfer from surgeon teleoperator to flexible robot: development of a method based on inverse reinforcement learning to transfer skill from surgeon teleoperator to flexible robot.
- GMM-/GMR-based learning from demonstration:: development of a method to learn the model of the interaction between catheter and aorta using GMM algorithm.

3.3 Potential applications of machine learning in surgical robots

- Automation of the surgical operation: Machine learning technique can be employed to steer surgical robots to safely, accurately, and faster speed execution of specific surgical tasks.
- Training surgeons: Machine learning approaches can be used to learn statistical model of surgical skills of experienced model to quantify the surgical skills of trainees.
- Classification and standardization of medical practice: Machine learning techniques are able to develop statistical model, splitting the surgical techniques into several steps, and per step learning the best medical practice from all of the surgeons for a given situation.
- Saving best strategies of an experienced surgeon: Machine learning can be used to learn the skill of experienced surgeon and save it for later operating room used or training young surgeon
- Safe interaction between environment and surgical robots: Machine learning could be further used to model the environment in greater details, which is essential to the control and decision making process to figure out how to safely interact with fragile dynamic environment.
- Safe interaction between surgeons and surgical robots: Machine learning could help guaranteeing the safety of the surgeon in human-robot interaction.

3.4 Challenges for further work:

- High-quality medical/surgical data: the need of large quantities of high-quality medical data to train machine learning technique;
- Modeling challenge: Dynamic and deforming nature of living body restrict the use of preoperatively estimated 3D maps and requires analysis of intraoperative data;
- Learning and defining skill analysis metric: finding metrics that adequately capture the characteristic of best practice;
- Adaptation to unknown or yet observed situations: system need to be able to cope with unpredictable situations and guarantees the safety of the patient.

4. Conclusion

- There are various machine learning techniques that can be employed to surgical robotics.
- It is possible to extract the needed mapping from perception to action for various surgical tasks and quantitatively analyze learned skills
- Subdividing surgical procedure into individual surgical task through episode segmentation helps management of the learning process.
- By embedding surgical robot with appropriate decision-making mechanism to choose appropriate skill at appropriate time, robot could gain autonomy overtime.

References

1. Kassahun, Yohannes, et al. "Surgical robotics beyond enhanced dexterity instrumentation: a survey of machine learning techniques and their role in intelligent and autonomous surgical actions." *International journal of computer assisted radiology and surgery* (2015): 1-16.