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An optimal motion planning method for computer-assisted surgical training

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ABSTRACT

This paper focuses on the development and validation of an optimal motion planning method for computer-assisted surgical training. The context of this work is the development of new-generation systems that combine artificial intelligence and computer vision techniques in order to adjust the learning process to specific needs of a trainee, while preventing a trainee from the memorization of particular task settings. The problem described in the paper is the generation of shortest, collision-free trajectories for laparoscopic instrument movements in the rigid block world used for hand–eye coordination tasks. Optimal trajectories are displayed on a monitor to provide continuous visual guidance for optimal navigation of instruments. The key result of the work is a framework for the transition from surgical training systems in which users are dependent on predefined task settings and lack guidance for optimal navigation of laparoscopic instruments, to the so called intelligent systems that can potentially deliver the utmost flexibility to the learning process. A preliminary empirical evaluation of the developed optimal motion planning method has demonstrated the increase of total scores measured by total time taken to complete the task, and the instrument movement economy ratio. Experimentation with different task settings and the technical enhancement of the visual guidance are subjects of future research.

1. Introduction

Over the past two decades, a variety of surgical training systems for minimally invasive surgery (MIS) have been proposed and developed [1–8]. This effort has been motivated by the fact that the traditional way of learning surgery has come under intense scrutiny; the operating room is a setting where surgical procedures take place rather than a learning environment where mistakes could occur and would be corrected [9]. Limited time and a highly stressful surgical environment complicate the training process.

Typical challenges of MIS procedures include a restricted field of vision, hand–eye coordination problems, limited flexibility of laparoscopic instruments, and the lack of tactile sensation [10]. Thus, the primary goal of surgical training systems is to bring a trainee to a higher level of proficiency without putting patients at risk in the operating room. This can potentially reduce risks, improve surgical outcomes, and mitigate trainees' stress associated with insufficient experience in practicing laparoscopic skills.

Simulation training develops proficiency in surgical procedures such as suturing, laparoscopy and angiography [11–13]. Seymour et al. report that residents trained with virtual reality (VR) methods are able to perform a laparoscopic cholecystectomy 29% faster than residents who train with just the standard box trainers [13], while trainees without VR training were five times more likely to injure the gallbladder or inadvertently burn and coagulate adjacent tissue. A large multivariate analysis has demonstrated that a surgeon's experience is the single most important factor associated with positive outcomes in laparoscopic cholecystectomy procedures [14,15]. The learning curve also proves critical: 90% of injuries occurred within the first 30 cholecystectomies performed by a surgeon [15]. Since it plays such an important role in adverse outcomes, the speed with which technical proficiency is acquired becomes an important design consideration in the creation of

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platforms to teach surgical skills. Studies have demonstrated that VR simulators employing haptic feedback quantitatively differentiate psychomotor skill acquisition between experts and novice surgeons [16,17]. Determining proficiency is an important factor in timing the transition of surgical trainees from simulation training to actual procedures in the operating room.

Sensory feedback plays a crucial role in the motor control of instruments and tissue manipulation during laparoscopic surgery [18]. Indeed, the lack of haptic feedback in most surgical robotic systems is often reported by expert surgeons to be detrimental to their surgical technique [19]. Nonetheless, the introduction of haptics in surgical simulation training seems to improve surgical skill acquisition [20,21]. Force feedback in a VR laparoscopic suturing task has been shown to shorten completion time, reduce the amount of force inadvertently applied to tissues, and improve the accuracy of suture placement [22]. More recently, haptics has also be shown to quantitatively enhance robotically assisted knot-tying with fine sutures [23].

We report on a methodology that combines an optimal motion planning system with the standardized objective assessment capabilities offered by VR trainers while still permitting trainees to use real surgical instrumentation that offers the same sensory feedback as traditional box trainers or actual surgery. VR trainers suffer from: (1) a lack of high-fidelity in the applied instrumentation (e.g., a forceps has same underlying haptic mechanisms as a scissors), (2) highly representational computer-derived depiction of anatomy, and (3) a poor approximation of the tensile and deformability characteristics of different tissues. While valuable quantitative information is obtained from haptically driven VR trainers, it is still data that are ultimately derived from a highly simplified and abstracted surgical “reality”.

Our computer assisted surgical trainer (CAST) incorporates haptic feedback for the purposes of shaping and guiding surgical movement but it also allows trainees to learn technique use, the actual surgical instrumentation and laparoscopic viewing equipment they will employ in the performance of actual procedures [10]. Harnessing this to sophisticated artificial tissue modules that offer tensile, anatomic, and vascular properties more closely approximating those of actual animal or human tissue permits CAST to offer an environment with higher fidelity and more realism in which to quantitatively collect and analyze a trainee’s acquisition of laparoscopic skills and make determinations about proficiency in those techniques.

The remainder of the paper is organized as follows: Section 2 introduces the taxonomy of surgical training systems in order to categorize existing trainers and define a group of systems that fall into the scope of our research. Section 3 provides the mathematical formulation of the optimal motion planning problem that we consider as part of surgical training procedure. Conceptual design and motivation of the problem solving method is given in Section 4. In Section 5, we implement the proposed motion planning method that generates optimal, collision-free trajectories for different task settings. Section 6 validates the developed method based on three test cases. The case study of the CAST system is provided in Section 7. Finally, Section 8 concludes the paper with a summary and discussion of further research.

2. Taxonomy of surgical training systems

The key feature that characterizes any existing surgical training system is the way in which the concept of a supervisor is represented. Based on this classification, we distinguish four different types of systems:

(a) Self-supervised training systems in which a trainee performs a self-assessment in a subjective fashion, based on analyzing the results achieved through the self-learning process.
(b) Expert knowledge-based training systems that allow performance assessment with respect to the expert-derived proficiency levels specified for laparoscopy tasks.
(c) Competitive training systems in which trainees compete with one another in a game-like setting and compare the results with those of their competitors.
(d) Intelligent training systems in which the trainee receives continuous guidance on optimal navigation of laparoscopic instruments and his or her performance is evaluated with respect to optimal solutions that are found by artificial intelligence (AI) techniques.

Nowadays, laparoscopy teaching is mainly done with the assistance of surgical training systems related to the first three categories. Typical examples of self-supervised training systems are basket trainers [2,3,24] which usually consist of a box with holes for laparoscopic instruments and a camera displaying an image from an enclosed space meant to simulate the abdominal cavity. Due to the lack of guidance toward the improvement of laparoscopic skills, basket trainers can only be used under the supervision of experts or can serve as secondary trainers.

Commercial systems such as LapSim (Surgical Science) [6,25] and LAP Mentor (Simbionix) [7] are also classified as self-supervised training systems. Although several research studies attempted to set proficiency levels for the tasks, standardized proficiency information has not yet been uploaded in these systems [26,27]. Therefore, if expert surgeons are unavailable, LapSim and LAP Mentor can only provide a subjective assessment based on analyzing preliminary results of the trainees task performance.

Expert, knowledge-based training systems are rapidly emerging in the market [1,4,5,8,28]. Such systems demonstrate a significant advance over the self-supervised training systems since the trainee is allowed to enhance his or her laparoscopic skills by reaching predefined (and usually standardized) proficiency levels for the learning tasks [17].

The most widely known expert knowledge-based training systems are as follows: McGill Inanimate System for Training and Evaluation of Laparoscopic Skills (MISTELS) [4], Computer-Enhanced Laparoscopic Training System (CELTS) [1], FLS Laparoscopic Trainer Box [28] and Minimally Invasive Surgical Trainer-Virtual Reality (MIST-VR, Mentice) [5]. In particular, MISTELS objectively grades performance of the laparoscopic tasks based on the cutoff time and penalty score in order to help the trainee target areas requiring additional attention [8]. CELTS is equipped with an expert performance baseline database to provide standardized performance scoring. In the FLS Laparoscopic Trainer Box, the trainee is allowed to begin learning the next task after the proficiency that is measured in time, number of repetitions and number of errors, is demonstrated for the current task. Finally, MIST-VR is also classified as an expert knowledge-based training system since the benchmark proficiency levels have been recently established for it by experienced physicians who are members of the Society of American Gastrointestinal Endoscopic Surgeons (SAGES) [29].

Although game-based learning has been widely applied to different fields, the competitive surgical training systems are just emerging in the research literature. One of such systems is Head2Head (Verefi Technologies) [30]. In this system, trainees are assessed on their ability to perform basic laparoscopic tasks in the virtual environment. The trainee with the most wins in a set of several rounds receives a higher score. Performance of trainees is measured with respect to the speed, accuracy, and tool movement efficiency. Although such systems benefit from engaging, focusing and motivating trainees, they are deficient in recognizing that each