Automated Electro-Mechanical Assessment of Psychomotor Skill for High-Stakes Certification in Surgical Robotics

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1 Background

In recent years, surgical robotic systems (SRS) have been employed to great effect in a wide range of minimally invasive procedures [1]. Yet despite the increasing use of these devices in clinical practice, there exists to date no definitive, objective system of measurement of the skill level of a surgeon using an SRS. Assessments of patient outcomes, surgical speed and instrument docking time have shown that improvement in skill using an SRS requires in-depth training, with exposure to as many as 20 cases of a given procedure to attain proficiency [2].

The model employed for the certification of a surgeon in the practice of minimally invasive laparoscopic surgery has addressed a parallel problem since its inception by establishing a set of exercises comprising what is now known as the fundamentals of laparoscopic surgery (FLS) assessment [3]. This high stakes examination tests the surgeon's psychomotor skills in the crucial subtasks involved in the successful execution of laparoscopic surgery. The foundations of robotic surgery (FRS) project is an ongoing collaborative effort to create a similar, high-stakes assessment for surgical robotics undertaken by an international consortium of authoritative surgeons from multiple specialties. This consortium has conceptually identified and built consensus for the general system concept, subtasks, and objective performance metrics for robotic surgery, but does not intend to design or prototype working models [4].

We herein present an instrumented, electro-mechanical design and prototype of the overall system and two of the seven subtasks developed for eventual inclusion in the complete FRS high-stakes assessment [4]. The first subtask, the ring tower transfer, requires that the surgeon move a small ring positioned at the base of one tower to the base of another tower while avoiding contact between the ring and the tower along the way. The second subtask, knot tying, requires the test taker to use a provided silk suture to draw together two metal rings and secure them with a surgical knot. In both cases, our system provides automated, objective evaluation of the required performance metrics.

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2 Methods

We implemented a modular system design consisting of a dome-like shape, 24 cm in base diameter, analogous to the dome proposed by the FRS concept video (Fig. 1, left). Subtasks employ latching mounts that allow each subtask to be removed at a tunable break-off force and used independently of the dome. This enables the dome to serve as an evaluation platform for subtask candidate designs. Our dome also incorporates a low cost USB-enabled electronic data acquisition system based on the Arduino platform (http://arduino.cc). Electronics for each subtask are implemented on "shields" that plug directly into the Arduino, maintaining subtask modularity. Custom C++ software based on the cross-platform Qt library (http://qt.digia.com, digia Helsinki, Finland) presents a graphical user interface for the exam proctor to enter test subject information and control task selection. This software also provides a method of logging data from the Arduino to properly formatted text files that are compatible with typical analysis packages like Excel (Microsoft Corp. Redmond, WA) or MATLAB (Mathworks Inc. Natick, MA) to facilitate subsequent data analysis or validation studies. Mechanical elements were created in CAD and utilized 3D printing for rapid prototyping.

For the ring tower sub task, our design aims to automatically sense and record instances of spontaneous contact between the each tower and the ring, the start and stop of a task, and the time required to complete the task. The ring tower task was comprised of a ring and 4 'S'-shaped posts resting on conical bases. We evaluated three candidate methods for reliably sensing contact given the geometry of da Vinci surgical robotic tools (Intuitive Surgical Inc. Sunnyvale, CA). These were tethered contact based on electrical continuity through the tool shaft, non-tethered contact where the tool tip creates contact between conducting channels embedded in the "S" shape, and capacitive sensing. Four conducting channels at the base of each 'S' serve as a continuity test for determining the presence of a conducting ring. Removing an existing ring breaks continuity and starts timing and electronic data logging for the task. The task ends when the last ring comes to rest and establishes continuity on the last tower base. We tested for reliable contact detection with conducting rings of different sizes and materials (jump rings of diameters 4, 6, 8 and 10 mm) and with the robotic and laparoscopic tool tips in different configurations (da Vinci grasper model 400121 and Covidien 31 cm Endo Grasp (TM) 5 mm, model number 173030). Any approach that produced a false negative was disqualified.

The knot-tying task design implements a start/stop button, contact-sensing eyelets which accept suture material to be tied, a potentiometer track that measures knot approximation, and an internal actuator that supplies an accurate, tunable, and repeatable constant force to separate the eyelets and test knot integrity. The system logs total time and the distance the knot has slipped for use in assigning a pass/fail grade to the performance of the task.

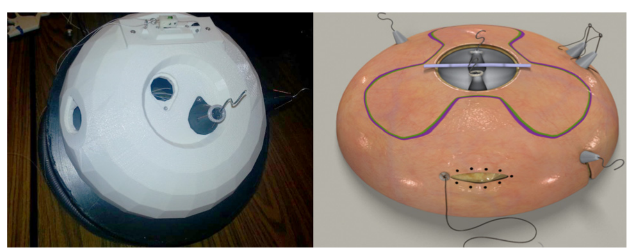

Fig. 1 The FRS dome concept proposed by the FRS Consortium (right) and our modular implementation (left)

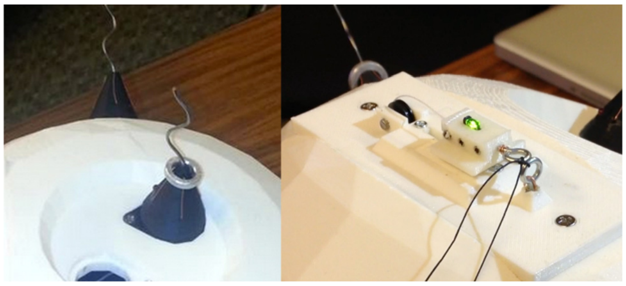

Fig. 2 Our modular implementations of the ring-tower (left) and knot-tying subtasks (right). LED's show task status.

Table 1 Ring tower contact sensing design comparison

	No tool modification required	Low cost/easy to manufacture	Reliable contact testing
Tethered Continuity	No	Yes	Yes
Non-tethered continuity	Yes	No	Yes
Capacitive	Yes	Yes	Yes

Table 2 Performance metrics desired by the FRS consortium compared to implementation

Ring tower		Knot tying	
Requested metric	Implemented	Requested metric	Implemented
Total time	Yes	Time	Yes
Ring-S contact	Yes	Eyelet approximation	Yes
Tool tip-S contact	Yes	Knot integrity at 2.5lbs force	Yes
Tool Collisions	No		
Dropped rings	No		

3 Results

The implemented prototype of the dome is shown in Fig. 1 (right), the ring tower subtask in Fig. 2 (left) and the knot-tying subtask in Fig. 2 (right). A comparison of candidate contact-sensing approaches is presented in Table 1. The recorded knot integrity values for the two knots correctly tied by a medical professional were 97.1% and 96.5% approximation of the eyelets following loading, while two sub-optimal knots showed post-loading approximation of 74.6% and 72.9%.

The targeted metrics requested by the FRS consortium along with those provided by our designs appear in Table 2.

4 Interpretation

We proposed a fully automated, electro-mechanical version of the FRS psychomotor skills exam. We implemented a modular system with two of seven subtasks incurring a total prototyping cost for the assembly of approximately 220 dollars. This price can be dramatically reduced from the prototyping cost for large-scale production. The implemented subtasks have demonstrated acceptable fidelity in assessing and recording several quantitative performance metrics proposed by the FRS committee. Specifically, the knot-tying task was shown to quantitatively discriminate knot quality. The tasks meet 6 out of 8 metrics requested by the FRS committee. We expect that tool collision may eventually not be required, and that we can infer dropped rings by implementing a start/stop switch as in the knot-tying task.

Further validation of both subtasks will assess factors such as the number of uses to failure, inter-rater reliability and overall unified system performance. The proposed system and analysis serve as an initial framework for automated mechanical assessments of psychomotor skills in the context of surgical robotics. The development of highly repeatable practices for fabricating these assessments is crucial to ensure an equal testing opportunity in the high-stakes academic testing context. Validity of the testing metrics in assessing surgical skill is another direction that will be of importance in establishing the proposed methodology as the standard for certification in the use of SRS. The system can be easily modified to reflect different physiological parameters in both the load applied to the surgical knot and the break off force of each tower, and can be practiced in the physical orientation and space limitations of a real surgery. Through the implementation of these improved accreditation procedures, surgical outcomes, efficiency, resident training, and ultimately patient quality of life can potentially benefit. Our future work will include refining system reliability, improving the manufacturability and extending our low-cost automated electro-mechanical approach to the additional subtasks.

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