Sensorized Psychomotor Skill Assessment Platform Built on a Robotic Surgery Phantom

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***Abstract*—The spread of robot-assisted minimal invasive surgery presents new challenges to surgeons and researchers alike. The novel surgical tools, methods and processes require different skills from the clinicians, thus surgical training and skill-assessment has become increasingly important. In this article, we describe the modification process of a widely used training device, the Fundamentals of Robotic Surgery (FRS) Dome, that was made capable of automatic skill-assessment too, by applying different sensors on it. The basic principles and methods of the sensorization process are shown, together with the first results obtained on the amended training platform.**

***Index Terms*—Robotic surgery, Surgical skill assessment, Automated skill assessment, Sensorized phantom**

I. INTRODUCTION

The spread of Minimally Invasive Surgery (MIS) and Robot-Assisted MIS (RAMIS) opened a new chapter in modern medicine[1]. MIS requires new kind of surgical tools that can be inserted into the patient's body through small incisions, hence the whole process of the surgery changes. Generally, this results in less pain and tissue-trauma, smaller scars and faster recovery time, however the new devices, methods and principles require a different skillset from surgeons (e.g., manoeuvring with the endoscope). Furthermore, during MIS and RAMIS, surgeons have to rely mostly on visual feedback (e.g., no real haptic feedback during RAMIS), they receive higher cognitive load and need to work even more precisely, compared to open surgeries. Although modern technologies also brought devices that assist surgeons, the outcome of a surgical procedure still depends mainly on the specialist's skills and practice. Thus – considering the new difficulties of MIS and RAMIS described above – surgical skill assessment became even more important than before [2].

II. MOTIVATION

Traditionally, the common practice in surgical education is based on peer assessment, however, in the 21st century, this method might seem to be obsolete. Similarly to most disciplines, there is a growing demand for scientific data in the field of surgical skill training too, that could be fulfilled by objective surgical skill assessment techniques [3].

The first steps towards objective skill evaluation were the manual skill assessment techniques, i.e., the combination of training devices and standardized global rating scales, like the Global Operative Assessment of Laparoscopic Skills (GOALS, [4]) or the Global Evaluative Assessment of Robotic Skills (GEARS, [5]). These methods produce numerical, analyzable and comparable results, although they require the full attention of at least one reviewing expert, and the scores will always depend on the expert's more-or-less subjective judgement.

In opposition, automatic skill assessing techniques only rely on measured and calculated data, hence the presence of an expert is not required, and the rating process becomes more objective. The most important question at automatic skill assessment is whether the scoring is based on the actually important parameters from surgical aspect. The skill assessment system presented in this paper is the modified version of a surgical skill training device, for which the manufacturer has already established the most important parameters and most common mistakes, thus most of the measured and calculated scores are already proven to be relevant.

III. BACKGROUND

A. Technical skill assessment

Technical skill training and assessment have always been cardinal parts of the surgical education, and the spread of laparoscopic techniques inspired many new platforms, devices and methods to help the surgeons learn the new techniques [6]. Nowadays the most accepted curriculum for laparoscopic training is the Fundamentals of Laparoscopic Surgery program (FLS, [7]), the so called FLS-compatibility is an important attribute of all laparoscopic training systems.

The rejection and distrust towards robots in operating rooms (even from experts and surgeons [8]) made it necessary to scientifically prove their efficiency, although the most important factor is still the surgeons' skills [9], [10]. The spread of RAMIS emphasized the importance of surgical data collection, but also made it easier. It contributed the progress of surgical data collection and made skill assessment simpler, since whole

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Fig. 1. The original FRS dome with the accessories; S and I shaped towers, rings and a rubber band [16].

processes (kinematic and kinetic data, camera-handling etc.) can be recorded by the robots directly. For the most objective skill evaluation — called automated skill assessment — software computes the results for given exercises based on these measurements [2].

B. Fundamentals of Robotic Surgery

Similarly to FLS, the Fundamentals of Robotic Surgery (FRS) program offers ”multi-specialty, proficiency-based curriculum of basic technical skills to train and assess surgeons to safely and efficiently perform robotic-assisted surgery” [11]. The FRS curriculum was compiled by 14 international surgical societies through several conferences, the project is now based at the Florida Hospital Nicholson Center. Despite the FRS curriculum is still undergoing its official validation (while Satava et al. recently statistically proved its effectiveness in [12]), FRS is already accounted as one of the most important curricula for RAMIS [13], [14], [15].

The developed online FRS program consists of 4 modules. This paper focuses on the 3rd module, the Psychomotor Skills Curriculum. The developers of this module initially identified 16 basic outcome measurements that are necessary for RAMIS skill assessment, and defined 7 principles upon which a set of training tasks for RAMIS should be designed [16], [17]. Based on these assumptions the group designed a single integrated device, the FRS dome (Fig. 1), that is claimed to be appropriate for RAMIS psychomotor skill training with its 7 tasks (”FRS tasks”) [18].

However, the online FRS curriculum naturally lacks expert mentorship, and although the tasks of the dome are properly explained, real-time performance feedback during practise would be useful [13]. In this paper, the retrofit sensorization of the FRS dome is presented, resulting in a detached device sufficient for basic RAMIS psychomotor skill assessment and training.

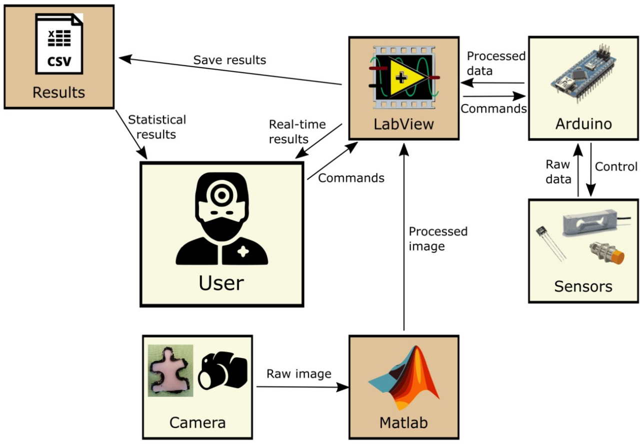

Fig. 2. Block-diagram of the sensorized system. Orange color indicates elements on the PC, yellow indicates external elements.

IV. METHODS AND MATERIALS

A. Concepts

The goal of the project was to develop a standalone device that is capable of RAMIS training and skill assessment, while it is independent of the surgical robot itself (does not use the surgical system’s internal data). Since many devices already exist for surgical training purposes, we decided to choose a commercially available, already tested and documented one, on which different sensors can be applied, thus making the device capable of objective performance-evaluation. The FRS dome became the starting point of the project; it is widely used, well-documented and structurally seemed to be easily modifiable.

Throughout the whole work, the official documents and recommendations regarding the FRS tasks were kept in mind. References [17] and [18] describe the basic goals and psychomotor skills attached to the FRS tasks, while on [19] and [20] instructional and example videos can be found for each tasks, beside basic descriptions. The psychomotor skills curriculum’s web-page [19] also offers ”Measurements and Metrics” and ”Potential errors” sections separately for each tasks.

The main goals throughout the sensorization were the followings:

- Sensors should fit on/inside the dome, they must not bother the user or change the nature of the original FRS tasks;
- As many as possible of the ”Potential errors” should be detected directly by sensors;
- As many as possible of the ”Measurements and Metrics” lists’ items should be monitored;
- The final sensorized FRS dome should be a standalone device (connected to a computer), that can be used with any kind of surgical systems (MIS or RAMIS).

Considering these goals, first the metrics and possible mistakes were identified that can not be measured effectively

TABLE I
SUMMARY OF THE FRS TASKS.

FRS task	Docking	Ring Transfer	Knot Tying	Suturing	4^{th} Arm Cutting	Puzzle Piece Dissection	Vessel Dissection
Description	Docking & Instrument insertion	Transfer the ring from one S-shaped tower onto the other	Tie a knot to approximate the eyelets of the I-shaped towers	Horizontal mattress suturing through the target points	Hold and cut the band using the 4^{th} arms	Cut the puzzle piece pattern staying inside the line	Dissect, seal and cut the vessel
Important factors	All devices and the entire dome should be in the field of view	Wire-instrument collisions, breaking the ring or wires	Appropriate knot, tower-movements	Wound approximation, accurate targeting, tissue-tearing	Accurate cutting, appropriate tension, dropping the vein	Accurate cutting, Tissue handling	Accuracy, blood loss, injury of the vessel
Measured metrics	None	- Time - Forces - Contact time - Tower movement - Tower falls	- Time - Forces - Tower movement - Tower falls - Eyelets touching	- Time - Forces - Wound approximation at 4 points	- Time - Accuracy of cutting on the 3 marks (manual evaluation)	- Time - Forces - Accuracy of cutting inside the line (percentage of total cut-length)	- Time - Forces - Vessel- injury (manual evaluation) - Proper cut
Sensors and methods	None	- Load cells - Capacitive proximity sensor - Hall-sensor	- Load cells - Capacitive proximity sensor - Hall-sensors	- Load cells - Touch sensors	- Self evaluation via Graphical User Interface (GUI)	- Load cells - Image processing	- Load cells - Continuity-sensor

by external sensors. They were mostly related to the surgical instruments and tools (instrument-collision, instruments out of field of view, dropping the needle etc.) since it was not recommended to apply any sensors onto the robot or process the endoscope's image. Furthermore ”Docking/Instrument Insertion” (the 1^{st} of the 7 FRS tasks) was excluded from the project, since it is entirely related to the instruments.

B. Software and devices

Force-measurement is always important for RAMIS skill assessment, thus a force-gauging system was designed, that measures the resultant external forces acting on the dome along 3 perpendicular axes. The system consists of 3 serially connected beam load cells (maximum load: 20 kg each) with 3 analog–digital converters (HX711 model: 24 bit, 80 SPS). The load cells are located under the dome, and are connected to a self-made aluminium lid (replacing the original blue lid), thus the modified dome stands on a new mounting. All new mechanical parts were designed using SolidWorks and manufactured in IROB laboratory of Obuda University.

The maximum applied force and the completion-time are the first two metrics for all tasks (the full datasets of force-measurements are being saved, but not yet analyzed). After the force-gauging system, we focused on the unique metrics of the different FRS tasks. The 2^{nd} and 3^{rd} tasks (Ring Transfer and Knot Tying) are both using the ”towers” on the dome (Fig. 1), so similar sensors are used. The movement of the towers are measured by AH503 linear analog Hall-sensors, since magnets hold them on the surface of the dome. The towers' upper thin metal parts are connected in a parallel RC circuit as capacitors, so anything touching the towers (either the metal ring, an instrument or another tower) can be detected by measuring the time-constant of the RC circuit.

For the evaluation of Puzzle Piece Dissection task, image-processing is used. A Matlab (v2018, MathWorks Inc.) script calculates the ratio of the lengths of proper and missed cuts, based on a photo of the cut-out puzzle piece. At the Suturing and the Vessel Dissection tasks simple contact-sensing is used, while the 4^{th} Arm Cutting task only requires self-evaluation.

All sensors are connected to an Arduino Nano microcontroller, on which a C++ program manages low- and high-level signal processing, calculates the results, and communicates with the main program running on a connected PC. The main program was developed in LabView (v2018, National Instruments Corporation), it handles user-commands and file-management, calls the implemented image-processing Matlab-script, communicates with the Arduino through serial connection (USB port) and shows the results to the user (Fig. 2).

C. Validation method

After the sensorization process, the new system had to be validated. The effectiveness of training on the FRS Dome had already been proven, thus in this study, validation only covered examination about the correlation of the calculated scores and the quality of the performance [12].

There are several different types of measured results that rate the performance of the subject together on a given FRS task. For example, at the Ring Transfer task completion time, maximum force, tower movements, number of tower falls, number of ring-tower contacts and total contact-time all describe the performance from different aspects. All metrics are chosen based on the official instructions of the original FRS psychomotor skills curriculum, thus it was presumed that they genuinely correlate with the quality of the performance. Based on this assumption, the correlation between the directly measured metrics (e.g., completion time, or the number of ring-

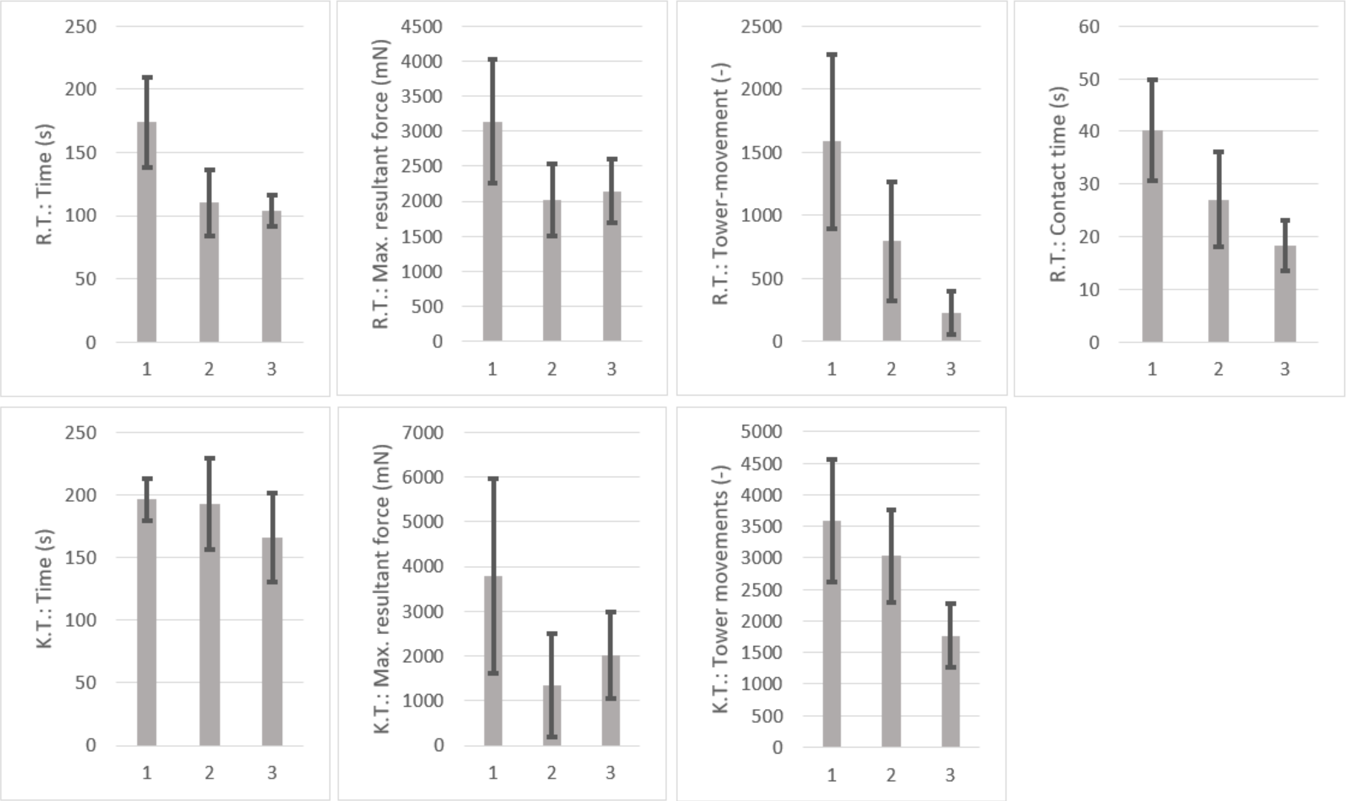

Fig. 3. Results of the ring transfer and knot tying tasks based on number of attempts (horizontal axes). R.T. and K.T. denote the metrics of ring transfer and knot tying tasks respectively.

tower contacts at the Ring Transfer task) and level of expertise did not have to be studied. However, there are several metrics that are not precisely defined by the FRS group, or require more complex calculations, like tower-movements during Ring Transfer and Knot Tying tasks, or the ”accuracy of remaining within the lines” at the Puzzle-piece Dissection task, that is computed using image-processing. Regarding these more complex metrics, the principle and method of the computations should be verified, meaning that the correlation between these calculated results and the quality of the performance should be proven.

Ideal statistical verification could be carried out by comparing the scores of a group of expert robotic surgeons with the scores of beginners and finding significant difference between the performance of the two groups. However – because of the lack of expert robotic surgeons in Hungary – this validation method will be only carried out in the future.

As an alternative method, we chose to derive the learning curve of beginners (some of them have already practised with the da Vinci robot before). However, the first tests revealed, that some of the FRS tasks are too difficult for many subjects who had no prior experience with laparoscopic or robotic surgery. First-time users mostly could not perform the suturing and the puzzle-piece dissection tasks at all (or made many fatal errors), thus it was decided to only examine the first two tasks (ring transfer and knot tying) among beginners.

D. Results

The summarized results of 37 measurements are presented on Fig. 3. Most subjects performed the ring transfer and knot tying tasks 3 consecutive times, the graphs show the averaged scores of each measured metrics (lower scores mean better performance in every case). The improvement of performances were examined using one-sided t-tests between the first and the third attempts. The improvements were significant at the following metrics ($\alpha = 0.05$):

- Ring transfer: completion time ($p = 0.016$)
- Ring transfer: tower movement ($p = 0.015$)
- Ring transfer: tower-instrument contact time ($p = 0.01$)
- Knot tying: tower movement ($p = 0.023$)

Additionally, there were only 9 detected tower-falls throughout the 37 measurements (the maximum number of falls was 2), all but one occurring at the first attempts, which can be interpreted as clear improvement too. Regarding the knot tying task, the desired contact between the two towers (after the knot is tied) is also monitored, but there was only one measurement when the subject failed to completely pull together the two towers (during a second attempt), thus this metric can not be statistically analyzed.

The improvement of scores at the remaining metrics were not significant based on this dataset, although all averages noticeably decreased on Fig. 3. This could be explained with the relatively high variances that might be the results of the relatively low number of measurements.

As stated in 4/C, this paper focuses on the metrics that require more complex measurement-methods (either from hardware or software-side). Regarding the two examined tasks, these were the quantification of the tower-movements (using Hall-sensors and a moving average-based scoring method), the tower-instrument contact detection (with capacitive sensors) and the scoring of force-handling.

The tower-movement scores improved in both tasks, which means that the method of measuring and scoring of the tower-movements is sufficient. Beside, the total time of tower-instrument contacts at the ring-transfer task decreased significantly too, which also means that a capacitive sensor is suitable for contact-detection. However, the analysis showed, that evaluation of the force-handling should not be done by accounting only the maximal force applied during a performance, deeper mathematical analysis of the force data-series should be performed.

V. CONCLUSIONS AND FUTURE WORK

This paper presented a surgical phantom that is capable of technical skill assessment for surgical training. The device was created by modifying an existing RAMIS training tool, the FRS Dome. Several common and task-specific sensors were applied on the original phantom, and connected to a microcontroller and a PC, hence the subjects could receive direct feedback about their performance. The system became capable of automated technical skill assessment and created the opportunity for further statistical analyses too, since it saves all results into a database with the necessary metadata. The layout of the system is shown on Fig. 2.

The validation of the system has already started, part of the initial results are shown on Fig. 3. Beside collecting more data about the changing of the scores between consecutive performances from the same person, other validating methods will be carried out too. In the future, the correlation between the achieved scores and the level of expertise will also be examined, and the system will be tested with laparoscopic methods too. Assuming that the achieved scores will show statistical correlation with the quality of the performance the device might be able to help in further skill assessment researches too, for example the efficiency of different suturing or knot-tying techniques could be compared.

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