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A Knee Arthroscopy Simulator: Design and Validation*

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Abstract—**Many challenges exist when teaching and learning arthroscopic surgery, carrying a high risk of damaging the joint during the learning process. To minimize risk, the use of arthroscopy simulators allows trainees to learn basic skills in a risk-free environment before entering the operating room. A high-fidelity physical knee arthroscopy simulator is proposed to bridge the gap between surgeons and residents. The simulator is composed of modular and replaceable elements and can measure applied forces, instrument position and hand motion, in order to assess performance in real time. A construct validity study was conducted in order to assess the performance improvement of novices after practicing with the simulator. In addition, a face validity study involving expert surgeons indicated that the simulator provides a realistic scenario suitable for teaching basic skills. Future work involves the development of better metrics to assess user performance.**

Index Terms—**Knee Arthroscopy Simulator, skills assessment**

I. Introduction

Arthroscopic surgery is a form of minimally invasive surgery performed with thin instruments through small incisions around the joints. Residents usually learn arthroscopy from experienced surgeons, following the traditional apprenticeship model in the operating room (OR). They face a steep learning curve due to the nature of the surgeries, the tight surgical space and the complexity of the different joints, which complicates the visualization and identification of different structures within the joint [1]. Several years of practice are needed in order to develop the motor skills required to overcome the challenges of learning and performing arthroscopy. Learning in the OR can be stressful for surgeons and residents, and is aggravated by the fact that the risk of causing damage to a patient's joint increases with more inexperienced trainees. This risk can be reduced if basic skills are learned on arthroscopy simulators instead of in the OR [2].

Surgical simulators provide trainees with an alternative to develop surgical skills in a risk-free environment [1–3]. Current simulators are classified as physical, virtual-reality (VR), or augmented-reality [4]. Of these, two types of arthroscopy simulators are currently found on the market: VR and physical simulators, as described below. VR-based simulators display the elements of the joint's anatomy in a computer-simulated environment; some of them are capable of providing performance metrics and some form of force feedback [5–9]. One of the limitations of these simulators is that users are not exposed to the real physical feel, as the tools do not directly interact with the joint elements. Physical simulators on the other hand, represent the joint's anatomy with structures and synthetic tissues, providing a solution to the inaccurate or completely absent force feedback of VR simulators. However, they do not provide real-time feedback on trainee performance or any other metric that allows the user to assess their skills and progress.

II. Motivation and Objectives

In an attempt to overcome the limitations of physical simulators, a nonvirtual system for skill assessment was developed [2]. This knee arthroscopic surgery simulator presents a mobile joint, replaceable parts, and is capable of assessing user performance through the measurement of the forces acting on the instruments and the bones within the simulator (this work was based on previous research related with skills assessment for laparoscopic surgery [10–12]).

Previous experiments [2] with this simulator have indicated several opportunities for improvement, requiring the development of a higher-fidelity simulator, with more robust and realistic elements. In addition, the simulator should allow procedures to be executed in a wet environment, as arthroscopic surgery is performed with the water filling and flushing through the joint capsule.

It is very important to evaluate and validate the effectiveness of the simulator. There are several methods used in determining the validity of arthroscopy simulators [13–14]. These methods include face validity, construct validity, and predictive validity. Face validity is based on the qualitative opinions of experienced arthroscopic surgeons on the realism and usefulness of the simulator. Construct validity reflects the extent to which the simulator produces the intended effect. In this case, construct validation aims to show that practicing on the simulator both teaches the user and produces improvements in user performance. Predictive validity is a measure of how well performance on the simulator corresponds to real world.

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The following sections present the design and development of a prototype knee arthroscopy simulator and the methods used for validating the system.

III. System Development

Based on a previous prototype of the simulator developed at CSTAR [2], the design requirements were stated as follows:

- The joint's anatomy elements should be replaceable so that invasive procedures could be performed.
- The upper leg should be fixed in a base that allows the leg to be positioned in several orientations (from 0° of extension to 120° of flexion).
- The forces acting on the femur and on the arthroscopic instruments should be measured (force range 0–15 N, with a minimum resolution of 0.1 N).
- The materials used to represent the thigh and the calf should be replaced by components that provide a better feel of the leg bones and ligaments.
- The material for the skin surrounding the joint should mimic the interaction between the tools and the portals, while preventing tearing.
- The position and orientation of the different arthroscopic instruments and the hands of the user should be recorded (measured in x, y, and z axes, the range must be a cube of at least 50 mm^3, with a minimum resolution of 0.1 mm).
- The simulator should allow for the execution of procedures in a wet environment.
- All of the measurements and the arthroscopic video feed must be recorded during use.

Based on these specifications, a second prototype of the arthroscopy simulator was developed, as presented below.

A. *Simulator Development*

The prototype high-fidelity physical knee arthroscopy simulator, based on the requirements outlined above, is presented in Fig. 1. The simulator consists of a movable leg, with the femur rigidly attached to an adjustable plastic base, allowing motion of the joint in several positions. Polyurethane foam (2545FR, The Foam Store) was used to mimic the thigh and the calf, and silicone (EcoFlex 30, Sculpture Supply Canada) sheets represent the skin covering the leg. The foam was shaped to resemble a leg and carved on the inside to allow bones (Sawbones, Pacific Research Laboratories) to embed tightly within the foam thigh and calf (Fig. 2). The physical properties of the foam and the silicone allow easy replacement of the bones, as both materials stretch without permanent deformation.

Several notable improvements were made to the leg simulator, as compared to the previous iteration presented in [2]. The first of these was made to the phantom skin surrounding the joint. Due to the portal openings and the motion of the instruments, it was necessary to have a material that stretches without tearing. In order to achieve this, a rectangular sheet of nylon stocking (15 denier) was embedded within the same silicone used to cover the thigh and the calf (Fig. 3). This provides a very strong mesh that prevents tearing, but also stretches with the silicone, allowing it to return to its initial shape. Another feature added to the simulator was to coat the femur and tibia condyles with silicone (Sorta Clear 40, Sculpture Supply Canada) to mimic cartilage and increase realism.

In order to sensorize the simulator, the following equipment was used: a 6-Degree-of-Freedom (DOF) force/torque sensor (Gamma model, ATI Industrial Automation, Inc.) was used to measure the forces applied on the leg [2]; standard arthroscopic instruments were sensorized with strain gauges (EA-06-015DJ-120, Vishay Intertechnolgy) to measure the perpendicular forces acting on the instrument shaft in the x and y directions during the execution of several arthroscopic tasks; position sensors (Aurora Mini 6-DOF Sensor, Northern Digital) were used to track the position and orientation of arthroscopic tools; and the Imperial College Surgical Assessment Device (ICSAD) was used to track hand motion and assess performance.

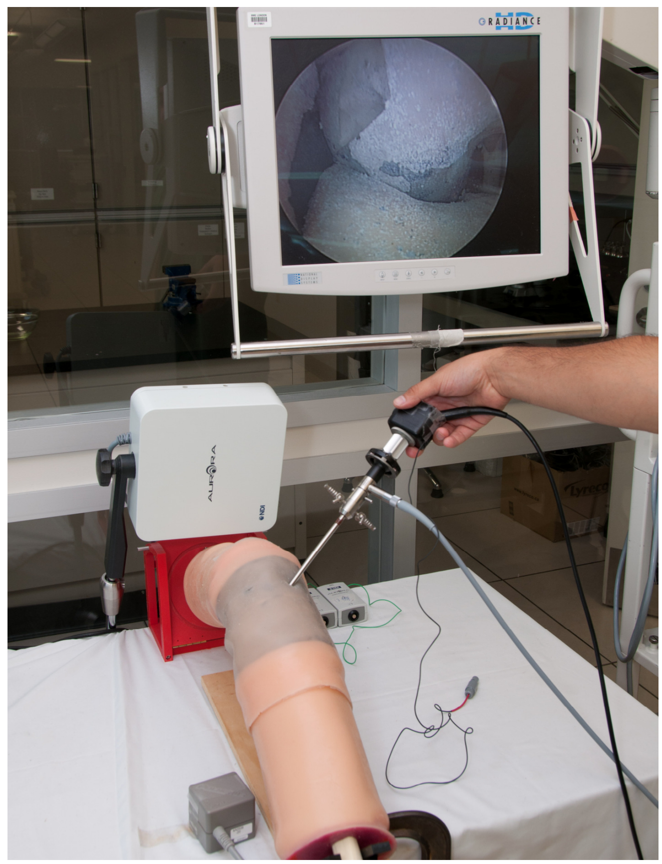

Figure 1. Training simulator for arthroscopic surgery.

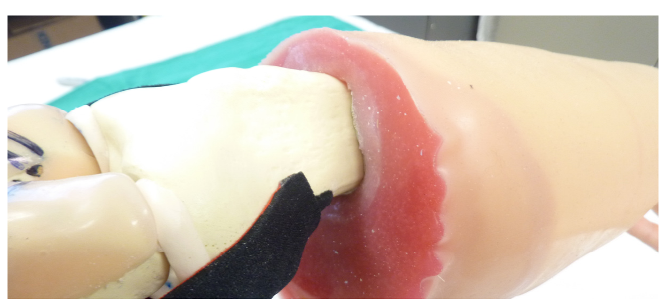

Figure 2. Tibia inserted into the calf.

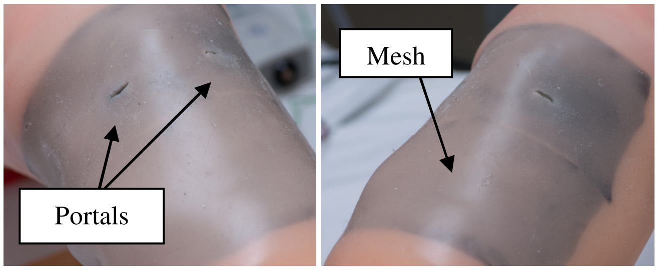

Figure 3. Mesh embedded in the silicone skin surrounding the joint.

In order to allow the simulator to mimic a wet environment, the calf and thigh foam pieces were coated on both ends with a layer of silicone, preventing water from infiltrating the limb (Fig. 2). Quick-release clamps were designed and built to tightly secure the skin surrounding the joint to the calf and the thigh, preventing water from leaking. The instruments were coated with polyurethane coating (M-Coat A, Vishay Intertechnolgy) to waterproof the strain gauges. In order to deliver water to the joint, a water pump was used (PE-PM pump, ValleyLab), the simulator was placed on a standard metal tray, this container collects the water that flows out of the simulated leg, allowing it to be recycled and ensuring that the floor stays dry (Fig 4).

B. *Simulator Validation*

In order to evaluate and validate the effectiveness of the simulator, two different types of validations were performed: construct and face validity. For construct validity, the goal was to evaluate whether practicing on the simulator improved trainee performance. 13 novice subjects, with no previous exposure to the simulator, were asked to execute a pre-test, performing 6 basic arthroscopic tasks (Table I) on the simulator. The subjects were then allowed to practice on the simulator, for a maximum of 30 minutes, those tasks that they felt required improvement. Immediately afterwards, they were asked to execute a post-test, performing the 6 tasks again. Performance was measured by the task completion time and the measured path length of the instruments and the hands. For this part of the experiment, the simulator was used in the dry mode.

For the face validity study, 5 expert surgeons evaluated the effectiveness, realism, and usefulness of the simulator based on their experience and impressions. With no previous exposure to the simulator, each surgeon performed the same 6 tasks described above and then completed a 5-point Likert scale questionnaire to gather their impressions of the simulator. The questionnaire used was prepared based on previous face validity studies [13–14]. For this part of the experiment, the simulator was used in the wet mode. The basic tasks were defined by systematically deconstructing several arthroscopic knee procedures down to the task level and making a Motor and Cognitive Modeling Diagram (MCMD) [15].

IV. RESULTS

Table II presents the results of the construct validity study. This table compares the mean values of the metrics taken for the pre- and post-test. It is noted that some tasks present a statistical difference between both trials. In these cases, the mean values for the post-test are smaller, which indicates a reduction in task completion time, tool path length, or hand path length. It is important to note that for all of the measures, the mean values are lower in the post-test (except *LH Path* for Task 5 and all of the measures for Task 6). However, the data may not have enough statistical power to clearly demonstrate differences between the pre- and post-tests because of the limited number of subjects.

The results for the face validity study are shown in Table III. The experts awarded the simulator an average of 4.16 points out of 5. The experts found the simulator to represent the limb and joint anatomy accurately. The highest score was given to the capability of the simulator to provide sufficient realism to facilitate proper training of basic arthroscopic skills. In addition, most of the experts indicated that they would use the simulator as a complementary tool for teaching arthroscopic surgery to residents.

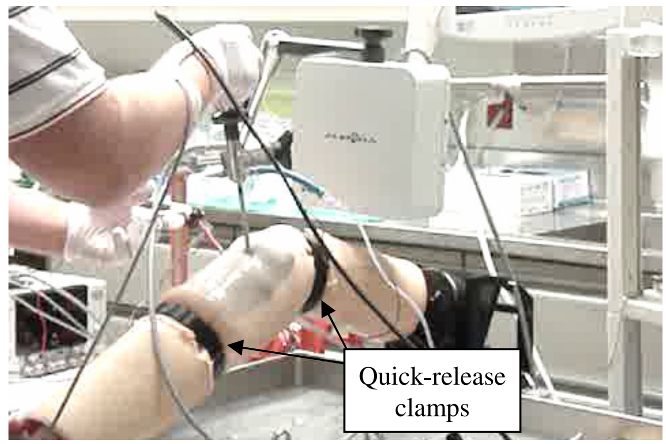

Figure 4. Training simulator in wet mode.

TABLE I. ARTHROSCOPIC TASKS CHOSEN FOR THE VALIDATION.

Task No.	Description
1	Probing: Patella
2	Probing: Medial Femoral Condyle, Medial Tibial Plateau, and Medial Meniscus
3	Probing: Lateral Femoral Condyle, Lateral Tibial Plateau, and Lateral Meniscus
4	Grasping: loose body hidden under Lateral Meniscus
5	Oscillating Shaving: Femoral Condyle
6	Burring (Shaving): Femoral Condyle

TABLE II. COMPARISON OF THE MEAN VALUES OF THE PRE- AND POST-TEST MEASURES. BOLDED VALUES ARE SIGNIFICANT WITH $p < 0.05$.

Measure		Task 1	Task 2	Task 3	Task 4	Task 5	Task 6
Time (s)	PrT	56.57	141.93	67.86	***102.50***	***212.71***	69.64
	PoT	41.36	100.86	53.93	***56.93***	***137.64***	101.00
RH Path (m)	PrT	***5.15***	28.56	15.93	***19.80***	14.84	6.74
	PoT	***1.77***	20.08	11.77	***10.29***	12.13	10.04
LH Path (m)	PrT	***5.14***	13.65	4.02	6.09	18.59	6.78
	PoT	***2.02***	12.38	4.11	5.20	19.39	21.07
Tool Path (m)	PrT	***1.80***	5.96	2.72	***1.95***	3.27	1.31
	PoT	***1.10***	4.11	1.96	***1.02***	3.05	2.71

PrT: pre-test, PoT: post-test, RH: right hand, LH: left hand

TABLE III. Expert surgeons' evaluation of the simulator.

Statement	Mean Score
The system is beneficial to the introduction of basic skills (e.g., triangulation, navigation/orientation within the joint)	4.0
The visual representation of the joint provides sufficient realism for the training of basic skills	4.6
The physical limb model provides sufficient realism for the training of basic skills	4.0
Feel when manipulating instruments	4.0
I would use the system for training or recommend its use	4.2

This questionnaire uses a Likert scale where 1 = strongly disagree and 5 = strongly agree

V. Discussion

After a short period of time practicing on the simulator, subjects showed an improvement in performance, as demonstrated by reduced task completion times and/or shorter path length required to complete the task. In order to evaluate user performance properly, it is important to subdivide procedures into tasks, which have to be carefully selected and identified. The more specific the task is, the easier it is to assess user performance. This is shown by the results obtained for Tasks 1 and 4, compared with the rest of the tasks. Probing the Patella and grasping a loose body are very well defined and simple tasks: the users had to find one target and touch it with a probe or remove it with a grasper. On the other hand, Tasks 2 and 3 consisted on probing several areas on the femur, tibia, and meniscus, and Tasks 5 and 6 required the users to shave cartilage and bone from a relatively large area on the Femoral Condyles. These tasks required the users to execute several hand and tool motions, thereby increasing the complexity of the analysis required to evaluate skills proficiency and performance.

It is important to mention that performance should improve with practice. Practicing on a simulator should allow the users to become more familiar with the joint's anatomy, the operation of tools through portals, and to have a better understanding of the tasks to be performed. In this study, a reduction of the hand motions and tool path was expected after practicing. This result was found in particular for the hand that manipulates the arthroscope (right hand), indicating that the users had to make fewer movements in order to find the different targets within the work volume. With regard to the face validity study, the simulator proved to be useful and effective for teaching basic arthroscopic skills to residents. Improvements to the simulator are continuing in an effort to increase its realism.

VI. Conclusion

This high-fidelity physical simulator has proven to be useful for learning basic arthroscopic skills and for assessing user performance. Physical arthroscopy simulators, such as the one proposed here, can provide trainees with a lower-cost, risk-free environment for learning if incorporated as part of a training curriculum, ultimately leading to improved delivery of health care to patients.

Future work will focus on refining the teaching and assessment methods for very specific basic skills (such as probing and grasping) to enhance the diagnostic capabilities of trainees. In addition, while the measures used for the construct validity study are a good start for skills assessment, an integrated analysis, combining and studying the measures as a group rather than individually, must be developed [16].

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