Journal of Medical Robotics Research, Vol. 0, No. 0 (2013) 1–19

A survey on the current status and future challenges towards objective skills assessment in endovascular surgery

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Minimally-invasive endovascular interventions have evolved rapidly over the past decade, facilitated by breakthroughs in medical imaging and sensing, instrumentation and most recently robotics. Catheter based operations are potentially safer and applicable to a wider patient population due to the reduced comorbidity. As a result endovascular surgery has become the preferred treatment option for conditions previously treated with open surgery and as such the number of patients undergoing endovascular interventions is increasing every year. This fact coupled with a proclivity for reduced working hours, results in a requirement for efficient training and assessment of new surgeons, that deviates from the "see one, do one, teach one" model introduced by William Halsted, so that trainees obtain operational expertise in a shorter period. Developing more objective assessment tools based on quantitative metrics is now a recognised need in interventional training and this manuscript reports the current literature for endovascular skills assessment and the associated emerging technologies. A systematic search was performed on PubMed (MEDLINE), Google Scholar, IEEXplore and known journals using the keywords, "endovascular surgery", "surgical skills", "endovascular skills", "surgical training endovascular" and "catheter skills". Focusing explicitly on endovascular surgical skills, we group related works into three categories based on the metrics used; structured scales and checklists, simulation-based and motion-based metrics. This review highlights the key findings in each category and also provides suggestions for new research opportunities towards fully objective and automated surgical assessment solutions.

Keywords: endovascular surgical skills; surgical training; minimally invasive surgery; surgical robotics; medical imaging

1. Introduction

Endovascular interventions have gradually become the preferred method for treating a number of cardiovascular diseases through a minimally invasive surgical (MIS) procedure that involves the percutaneous insertion of a catheter and guidewire. The interventional device is navigated within the patients' vasculature under real-time medical imaging, typically fluoroscopy, to reach the morbid anatomical target in order to deploy repair or replacement therapies for alleviating the condition. Compared to open vascular procedures, endovascular interventions offer the advantage of minimum incision and operation trauma which results in smaller recovery times. Therefore, high-risk patients suffering from comorbidities and regarded as unsuitable for open surgery, can undergo treatment with this MIS endovascular method.

Technological advancements have played a key role in enabling surgery through an endovascular approach. Particularly, the development of medical imaging techniques and miniaturised flexible surgical instrumentation have led towards a convergence between the traditionally disparate disciplines of surgery and interventional radiology.[1,2] As a result, modern endovascular surgeons and interventional radiologists are required to operate instruments that are complex and dexterous, inserted in the vulnerable vascular system, under the presence of friction, due to blood flow, and calcium deposits. Combined with the restricted visualisation of the operating environment, the risk of embolisation and tissue damage (e.g. vessel rupture) is thereby increased. Subsequently, endovascular interventionalists must demonstrate a diverse set of cognitive, clinical and psychomotor skills.[3] The endovascular operating room poses additional challenges in ergonomics required to manage the imaging equipment and in terms of radiation safety for the operating room team.[4] Technical training and competency assessment is crucial to ensure that new interventionalists obtain the required level of dexterity for performing endovascular procedures in a safe and efficient manner.[5] In addition, with the ever increasing complexity of the operating room and the push towards integrated hybrid minimally invasive theatres, training for the whole surgical team is a growing necessity.[6,7]

The traditional and widely practised method for evaluating surgical expertise is through written and oral examinations, procedural and case logs, as well as, expert monitoring of trainees during exercises and studies on cadavers, animals, inanimate models or virtual simulators.[8] A more objective approach is the use of standardized, structured grading scales or checklists which again require an expert to observe and assign grades as the trainee executes an operation in real-time or through reviewing recorded training sessions. This approach of supervised assessment, although necessary and irreplaceable, is inefficient in terms of time, especially for specialist hours and the significant associated costs required. In addition, supervised assessment is inherently subjective to a degree and introduces bias which makes the global standardisation of an acquired level of technical expertise difficult.[9] However, global standardisation is important for large evidence-based medicine and decision making. This fact together with the increasing number of patients, necessitates a shift from the traditional apprentice-style "see one, do one, teach one" paradigm of surgical training introduced by William Halsted.[10] It dictates the establishment of unified objective assessment programmes and tools, capable of evaluating the level of surgical competence in an objective, efficient and quantitative manner.[11,12] The requirements, succinctly summarized by Sidhu et. al[13] and Ahmed et. al.,[14] are that an optimal assessment tool must satisfy feasibility, validity (face, content, construct, concurrent and predictive) reliability and fidelity. It should also satisfy the following characteristics: 1) to be able to discriminate among various skill levels and establish a level upon which operational expertise is attained; 2) to emulate the actual operating conditions so as to be able to predict future performance in the surgical theatre; 3) to be indicative of surgical dexterity skills and not knowledge in the use of supporting technology (e.g. fluoroscopy, surgical robotics); 4) to give repeatable and transferable results irrespective of the experimental parameters (simulation, real operation); 5) to correlate well with the current gold standard (supervised assessment).

A significant research effort has explored various quantitative measures to objectively assess technical skills in surgery with particular emphasis on laparoscopic procedures.[15,16] For endovascular interventions, the development of such an optimised and objective assessment framework can be facilitated by various emerging technologies. Breakthroughs in computing have realised Virtual Reality (VR) systems (see Fig. 1) that are now established tools in endovascular surgical training through simulation.[17,18] Such systems embed a wealth of information to evaluate and provide real-time feedback to trainees but face challenges in realistically all aspects of the physical and visual stimulus of a real procedure. Advanced vision processing algorithms are capable of accurately tracking the position of the distal tip of the catheter/guidewire in radiology images in order to evaluate exercises on phantom models or even sub-tasks in real procedures. However, this provides only the motion of the surgical instrument and does not enable metrics related to context which could be provided by novel sensing modalities, such as catheter tracking sensors,[19,20] real-time anatomical imaging or operating room monitoring,[21–23] which may allow more complex inference of skill evaluation potential. Finally, endovascular robotic systems, like tele-manipulated robotic catheters, offer increased precision and dexterity[24] and are gradually introduced for endovascular procedures which would provide detailed kinematic information throughout the intervention. Such information directly feeds into the main hypothesis that has been explored for quantitative skills analysis, which is that the level of surgical expertise is directly correlated to the motion of the surgical instrument. Through analysis of the motion pattern of the surgical instruments, it has been suggested that it is possible to characterise expert surgeons who manipulate surgical tools characteristically differently and more efficiently than trainees.[25,26]

In the context of endovascular skills assessment the majority of investigations have been conducted on VR simulators and more recently on inanimate models using robotic systems.[27–29] The main reason for this is the complexity of tracking an articulated flexible surgical instrument, such as a catheter, which is technically more difficult than tracking rigid laparoscopic tools. A variety of endovascular procedures, from catheter cannulation of arch vessels to complete stent placement and angioplasty procedures have been used as test cases. In this review study, we describe the most representative works and categorize them based on the assessment strategy that was followed. Our first category contains studies in which performance was evaluated by experts with the use of grading/scoring scales or checklists. The second category pertains to works where a specific set of metrics was used to differentiate skill level without external supervision. These metrics are either automatically generated from the VR simulators or derived from the analysis of the catheter's manipulation during the procedure.

Our focus is on how well the individual criterion or metric correlates with surgical competency, regardless of the experimental environment. Previous relevant reviews

(a) (b) (c)

Fig. 1. Examples of VR simulator systems: (a) Image of the Angio Mentor simulator © Simbionix USA Corp.; Cleveland, OH, USA ; (b) Image of the Procedicus VIST simulator © Mentics AB; Götheburg, Sweden; (c) Image of the CathLabVR simulator © CAE Healthcare; Quebec, Canada.

on methods for assessing surgical skills exist,[15,16,30–32] with a small number focused exclusively on endovascular surgery.[14,33,34] We have structured this article to follow a new taxonomy and we also associate technical criteria from subjective assessment methods (grading scales/checklists) with motion properties. These are obtained from novel sensing modalities and derived after appropriate processing. We believe that these quantitative measures are representative of the qualitative criteria, used by experts in evaluating trainees and therefore have the potential to be indicative of surgical skills in an objective manner. The manuscript is organised as follows: Section 2 provides an overview of the experimental set-ups utilised in endovascular skill evaluation studies, while Section 3 summarizes the key points of robotic systems for endovascular surgery. Section 4 presents works on endovascular skills assessment based on grading scales/checklist. The studies focusing on objective, automatically-derived metrics are given in Section 5 alongside a review of the technologies for catheter tracking. In Section 6 we take a look ahead and suggest areas of future research potential. Concluding remarks are drawn in Section 7.

2. Experimental environments for endovascular surgery training

Various experimental environments are possible for endovascular surgery training. Diagnostic catheterization offers an opportunity for new surgeons to acquire catheter manipulation skills by performing diagnostic actions on patients with appropriate supervision. However, the introduction of non-invasive imaging techniques has decreased the need for catheter-based diagnosis and furthermore technical skills need to be developed prior to patient work. Cadaver and animal models provide a good alternative for training new endovascular interventionalists as they faithfully represent vascular structures, offer some degree of re-usability and in some instances represent physiological dynamics. The difficulty with cadaver and animal model training is due to ethical considerations as well as the significant associated costs for both running the training exercises and for preservation. In some countries and specific training scenarios an additional impediment can be the limited availability of physiological models.[35,36] For these reasons it is increasingly important to find alternative training setups taking advantage of modern systems for simulation as well as for manufacturing phantom models through, for example, 3D printing.[37,38]

2.1. *VR simulators*

VR systems simulate the endovascular operating environment primarily by synthesising fluoroscopic images from stored models of vascular geometry together with models of the surgical tools.[39] An important and complex aspect of simulation is the realistic reproduction of the physiological motion of the synthetic anatomy, the catheter and of their interaction. Most VR simulators include standardized pre-loaded test cases of endovascular intervention which trainees may repeat continuously in order to develop their technical skills and catheter manipulation dexterity. A broad collection of pre-loaded test cases is available comprising of coronary, carotid, iliac and renal arterial occlusions among others. Commercially available endovascular VR simulation systems are shown in Fig. 1 and include the Angio Mentor® (Symbionix, Cleveland, OH, USA), the Procedicus VIST® (Mentice AB, Götheburg, Sweden), the Simantha® (Medical Simulation Corp, Denver, CO, USA) and the CathLabVR® (CAE Healthcare, Quebec, QC, Canada) simulators. Non-commercial experimental simulators include the benchtop Simulator for Testing and Rating Endovascular Skills (STRESS) proposed by Willems et. al.[40] These systems offer a realistic environment for endovascular surgery, while also providing haptic and tactile feedback. One aspect of an endovascular procedure not included in VR simulators is arterial puncture and closure. Most likely this is due to the difficulty in computationally modelling such events. Automated feedback is available in the form of simulator-calculated metrics as well as error reports. These can be broadly categorized into two categories, quantitative metrics and clinical parameters as listed in Table 1. Some VR simulators offer also the ability to generate error reports. Errors are generated from improper instrument handling and incorrect deployment of medical devices. Examples include moving the catheter without guidewire support, pressing catheter/guidewire tip against vessel walls or moving it near lesions, incorrect use of the embolic protection devices and wrong placement of balloons/stents. Such real-time assessment is only possible because in VR simulation all the information about instruments and tissue dynamics, as well as the synthetic patient physiology, are known. The usefulness of VR systems for surgical training is attested by evidence of skill transferability from the simulator platform to animal models and the operating room as reported in.[41,42] However, the limitations in VR which reduce the transfer ratio from VR to practice, are that currently only some aspects (e.g. tool selection, procedure steps, basic target) of the real procedure can be effectively synthesised and transmitted to the trainee.

Table 1. Generated VR simulator metrics.

Metric	Category
Procedure Time (PT)	Quantitative
Fluoroscopy Time (FT)	Quantitative
Volume of contrast fluid (VCF)	Quantitative
Number of cine loops (NCL)	Quantitative
Placement accuracy (PA)	Clinical
Percentage of lesion covered (PLC)	Clinical
Percentage of residual stenosis (PRS)	Clinical
Stent to Vessel ratio (SVR)	Clinical
Post-dilation stenosis (PDS)	Clinical

2.2. *Phantom models for training*

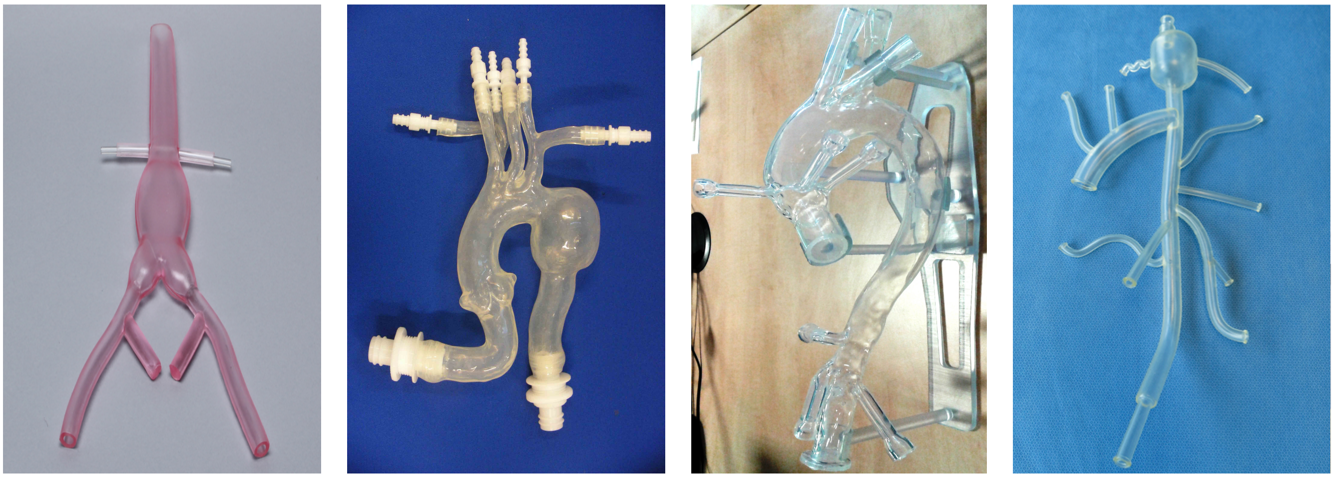
To realistically replicate the physical conditions of an endovascular procedure it is possible to realise a phantom vascular model and use this within a real catheter lab or operating theatre for training. To construct the model it is possible to use tomographic images that can be initially segmented and then reconstructed in 3D to create a digitized model of the captured part of the anatomy. The digitized model can then be processed with molding or 3D printing techniques and produce a life-size anatomical model. Depending on the material used, the resulting life-size model can be rigid or non-rigid.[38,43–45] Non anatomically-accurate vascular inanimate models are also available (e.g. Fundamentals of Endovascular Skills (FEVS) Model) and although these do not represent real vascular structures, they are designed from the perspective of enhancing the training and assessment of endovascular surgeons by focusing on specific tasks.[46] Phantom models are primarily used for obtaining dexterity skills for catheter/guidewire manipulation and stent/baloon deployment, with the advantage over VR simulators in the sense that the surgeon operates on real materials under actual surgical conditions and is placed within a real fluoroscopy suite. The major disadvantage of training using phantom models, is that the trainee is still exposed to radiation within the training environment and that such facilities are rare and costly to maintain. Fig. 2 illustrates representative examples of endovascular phantom models.

3. Robotic systems in endovascular surgery

With the increased adoption of robotic systems for laparoscopic MIS, research interest in the design and application of robotics for endovascular operations is also gaining pace. The motivation stems from the belief that the same advantages of increased precision and tool manipulation, that robotic systems illustrate in laparoscopic MIS can be exploited for endovascular MIS.Steerable robotic catheterization systems, augmented with additional degrees of freedom (DoF) and controlled over master/slave platforms offer enhanced manoeuvrability and stability which is crucial when operating in narrow, tortuous arteries and vessels.[47] In addition, robotic catheters are equipped with a plethora of embedded sensors, assisting interventionalists in completing their tasks. Force, torque and pressure sensors attached to the catheter's tip and other parts, cater for haptic and force feedback, a modality that is absent in conventional catheters, during navigation in the blood stream and interaction with vessel wall.[48] On the other hand, sub-millimeter accurate 6 DoF tracking sensors, provide real-time position and orientation information which combined with intra-operative and pre-operative imaging, facilitate more accurate catheter navigation and path planning.[49]

In recent years, comparative studies investigating the benefits of robotic systems were initiated. Initial outcomes from the use of robotic-steerable catheters in synthetic models, animals and patients, for cardiac ablation, aneurysm repair and stent deployment were very promising, demonstrating reduced operation time, increased precision and safety in terms of causing vascular damage. Moreover, a shorter training period compared to conventional catheters was observed.[24,28,29,50,51] The profusion of sensor data, available in novel endovascular robotic platforms, opens new possibilities for skill assessment studies since operational characteristics, previously uninvestigated, associated with the manipulation of endovascular tools are now available and can be used to quantitatively analyse and characterise expert execution.

The FDA approved commercially available robotic endovascular systems are; the Sensei X® and Magellan® (Hansen Medical Inc.; Mountain View, CA, USA) elec-



(a) (b) (c) (d)

Fig. 2. Examples of endovascular phantom models: (a) Sawbones® Abdominal aortic aneurysm model © Pacific Research Laboratories, Vashon, WA, USA; (b) Flexible aortic arch with aneurysm and exit at the 3-cusp © Elastrat Sàrl, Geneva, Switzerland; (c) Aortic artery phantom model © Materialise NV, Leuven, Belgium; (d) The FEVS model ©2015 Elsevier, reprinted from Duran et. al.[46] with permission from Elsevier and Dr. C. Duran.

tromechanical navigation systems; the Amigo® (Catheter Robotics Inc.; New Jersey, NJ, USA) mechanically driven platform; the CorPath® (Corindus Inc.; Waltham, MA, USA) vascular robotic system and the Niobe® (Stereotaxis Inc.; St Louis, MI, USA) magnetic navigation system .

4. Assessment with structured grading and checklists

Traditional methods of written/oral examinations and procedural logs, used by surgical training programs although successfully evaluate cognitive knowledge and surgical judgment, proved inadequate to assess technical surgical dexterity.[52] The increasing number of patients requiring surgery and the advent of laparoscopy, which requires different skills than open surgery, demanded a shift towards more objective evaluation of technical surgical skills. This subsequently led to the development of performance-based tests for the evaluation of trainee surgeons. To add objectivity and standardization, a number of surgical skill evaluation practices have been proposed based on structured checklists and global rating scales (GRS). These can be used by experts to evaluate trainees abilities as they perform on phantom, animal benchtop models or VR simulations. Checklists decompose a surgical operation into a list of sequential tasks that ought to be performed to lead to its successful completion and evaluators make a binary decision on the adequate fulfillment of each task. A performance score is produced by counting the successfully completed items. On the other hand, grading scales constitute of procedural components of an operation, manually scored by experts on a 5-point Likert scale (1 - very poor, 5 - excellent) based on the performance of the trainee. Adding the individual grades produces the overall score. The use of the Likert scoring system offers an additional layer of resolution to checklists, since the execution of each task is graded on a scale, thus stratifying the surgeon's performance to a greater degree.

In many surgical assessment tools both checklists and grading scales are employed in conjunction. These methods were largely led by the pioneering work of Reznick et. al. who introduced the Objective Structured Assessment of Technical Skills (OSATS) grading scale[52,53] leading to the development of GRS.[54] The OSATS tool, initially limited to open surgery, evaluates both technical and cognitive skills while trainees perform eight fundamental surgical tasks on benchtop models. In addition, it provided a generic framework that was the basis for subsequent studies, like the work of Doyle et. al. that proposed the Global Rating Index for Technical skills (GRITS) which augments the OSATS by adding two additional items, assessed only in laparoscopic procedures.[55] A GRS specifically for laparoscopic surgery is the Global Operative Assessment of Laparoscopic Skills (GOALS) scale defined by Vassiliou et. al.[56] and many researchers have developed operation-specific GRS and checklists, like the Imperial College Evaluation of Procedure-Specific Skill (ICEPS) rating scale to be used in conjunction with OSATS.[57–59]

4.1. *GRS and checklists for endovascular surgery*

So far there is no unified GRS, used on an international level, for endovascular skill assessment. Modified versions of the OSATS-derived generic GRS, like the Modified Reznick Scale (MRS),[60] illustrated in Table. 2 or the GRS for endovascular surgery (GRS-E) proposed by Chaer et. al. in[61]

Table 2. The Modified Reznick scale for generic endovascular skills, reproduced from Hislop et. al.[60]

Respect for Tissue	1 Frequently used unnecessary force on tissue and/or lesion, potential for tissue damage	2	3 Careful handling of tissue and/or lesion, but occasional potential for inadvertent tissue damage	4	5 Consistently handled tissue and/or lesion appropriately with minimal damage to tissue
Time and Motion	1 Many unnecessary moves and/or excessive time	2	3 Efficient time and moves, but some unnecessary moves and/or excessive time	4	5 Clear economy of moves and time with maximum efficiency
Instrument Handling	1 Repeated tentative, awkward, and/or inappropriate moves with instruments	2	3 Competent use of instruments but occasionally appeared stiff or awkward	4	5 Fluid movements with instruments and no stiffness or awkwardness
Flow of Operation	1 Frequently stopped operating and seemed unsure of next move; demonstrated imprecise and/or wrong operative technique	2	3 Demonstrated some forward planning with reasonable progression of procedure; careful operative technique with occasional errors	4	5 Planned course of operation with effortless flow throughout; fluent secure, and correct operative technique in all stages of procedure
Overall Performance	1 Very Poor	2	3 Competent	4	5 Clearly Superior
Final Product	1 Unacceptable quality	2	3 Average quality	4	5 Superior quality

have been investigated in several studies predominately performed in VR simulators. Some operation specific GRS-E have also been investigated, like the Imperial College Complex Cannulation Scoring Tool (IC^{3}ST),[50] mostly following the OSATS model. An example of a GRS that does not explicitly follow the OSATS model is the Structured Assessment of endoVascular Expertise (SAVE) rating scale developed by Bech et. al.[62] Nevertheless SAVE still evaluates technical and cognitive ability and includes many criteria that resemble the ones present in the OSATS-derived GRS. A retribution-based approach was to design error-rating scales comprising a list of incorrect actions that are evaluated and scored on a 5-point Likert scale according to their severity (1 unimportant, 5 life-threatening).[63] The checklists that were utilized to evaluate surgical competence did not have a uniform structure. Typically checklists are procedure specific and depending on the experimental method, some of them were extremely detailed containing up to 54 sequential steps,[64] while others were more consolidated like the iliac artery stenting checklist, by Berry et. al.,[41] shown in Table. 3 .

4.2. *Outcomes in the endovascular domain*

From the works that employ GRS and checklists, the vast majority of studies were conducted on VR simulators with the Procedicus Vist system being the most common platform. Typical experimental scenarios included carotid, renal or iliac artery stenting whereas in some cases only vessel cannulation was used. A number of reviewed works did not intend to directly deduce the level of surgical ability but instead utilized GRS and checklists to evaluate potential beneficial effects that a VR simulator training program has on the skills of endovascular surgeons.[14,34] In those studies, performance was compared before and after training with mostly novices/trainees participating in the study, although some experts were included. Novices displayed higher improvement of their skills, inferred by achieving a larger increase in their GRS scores and benefited more than experts from training on VR simulators, which is logical as experts would be expected to have highly developed core skills. These works indirectly verify the correctness of GRS, since it is typical for surgical skills to be developed and improved through training. While, this observation in itself is not adequate to support that GRS have construct validity, it does attest to the usefulness of VR simulators in the endovascular surgical training curriculum. This is further validated in two studies on the transfer of surgical skills from the simulator to in vivo catheterization (on porcine and human models), which demonstrated that skills acquired in the VR environment can be transferable to the real catheterization lab.[41,61] Similar conclusions on

Table 3. Task-specific checklist: Iliac artery stenting, reproduced from Berry et. al.[41]

Item	Omitted or incorrect	Done correctly	Instruction required
1. Guidewire and diagnostic catheter position correctly ?	0	1	
2. Distal aorta DSA conducted correctly ?	0	1	
3. Proper guidewire technique used to gain contralateral access ?	0	1	
4. Guiding catheter properly placed in the contralateral central iliac artery ?	0	1	
5. “Stenosis” traversed with correct technique ?	0	1	
6. External iliac artery DSA/roadmap conducted properly ?	0	1	
7. Measurements and evaluations performed accurately ?	0	1	
8. Proper stent catheter selection ?	0	1	
9. Stent deployed accurately ?	0	1	
10. Guidewire position maintained across lesion ?	0	1	
11. PTA conducted correctly ?	0	1	
12. Guidewire position maintained across lesion ?	0	1	
13. Control DSA conducted correctly ?	0	1	
14. Extraction of guidewire and guiding catheter performed correctly ?	0	1	

DSA: digital subtraction angiography; PTA: percutaneous transluminal angioplasty

the benefits of VR technology are reached also in the laparoscopic domain.[65,66]

The studies using GRS and checklists have demonstrated the methodology's ability to differentiate dexterity and overall surgical competence. Hislop et. al. applied the MRS scale they introduced, to a cohort of 61 subjects of different skill levels performing arch vessel cannulation in a VR simulator.[60] The MRS showed good correlation with the number of cases performed in a 2-year timespan and had an increasing trend as experience was increasing. The GRS-E for renal angioplasty proposed by Tedesko et. al. divided the procedure into three subcomponents, angiogram, wire access and intervention and was also able to separate residents of different experience.[67] Similarly, GRS-E was used by Van Herzeele et. al. in a study with 21 experienced interventionalists with promising results.[63] Willems et. al. combined elements of the MRS and ICEPS to formulate a scoring scale for the STRESS benchtop simulator they propose. This showed good construct validity in differentiating three levels of surgical ability; novice, intermediate and expert.[40] Nevertheless the STRESS scoring scale is not analytically presented therefore it is unclear which elements of ICEPS, a tool designed for assessment of open surgery skills, were adopted. Construct validity was also achieved by the SAVE scale, which correlated very well with prior endovascular experience. The scale was applied on a group of 20 physicians covering the entire range (complete novice to experts) of endovascular experience.[68] A potential reason for this may be the fact that the SAVE scale includes 29 items, covering general knowledge, cognitive and technical skills. The statistical analysis verified that the SAVE scale is capable of discriminating skills even in subjects of the same skill group that have slightly different experience.

4.3. *Summary of structure grading methods*

Several studies have confirmed that OSATS-based GRS, both generic and operation-specific, demonstrate good content and construct validity in assessing the level of endovascular surgical skill. Their performance is superior to checklists which, because they assess completion/no completion of subtasks, are primarily efficient for discriminating true novice from experienced performance. In GRS the use of a Likert scale theoretically enables the discrimination even among individual members of the same ability group. This makes GRS an ideal candidate for certification examinations. Despite their proven validity, GRS suffer from a number of shortcomings that makes their use impractical and unappealing. To begin with, GRS still adhere to the traditional method of skill evaluation through expert observation. In addition, since the items for evaluation are expressed in a generic manner, different evaluators may follow a different mentality when assigning grades. They therefore are subjective, like oral and written examinations, although the use of a grading scale adds a layer of objectivity. Secondly, some proposed assessment tools comprise of a large number of criteria which results in the scoring process being quite laborious, burdensome and time-consuming. Finally, procedure-specific scales are impractical as they require an expert in a particular operation to perform the manual assessment. Moreover, there cannot be a distinct GRS-E for each different endovascular operation, as this prevents standardization.[33]

5. Assessment with automatically generated metrics

5.1. *VR simulator metrics*

Considering potential practical difficulty of standardising the use of GRS, various studies attempted to investigate automatically generated measures such as descriptors of surgical dexterity supported by the emergence of VR simulator technology. Specialized software, integrated in latest generation VR simulators, enables these systems to automatically measure a number of operation-related parameters. The power of simulation is that all the information about catheter motion and interaction with the anatomical model used, are inherently available for computational analysis. Most of the GRS studies discussed in Section 4, took place on a VR platform and simulator-generated metrics were examined in parallel with GRS and checklists. In this section, we discuss the main conclusions drawn from the analysis of simulator metrics and their overall applicability for surgical skill assessment. As with GRS and checklists, many studies have focused on evaluating the applicability of VR simulators for surgical training, utilizing these metrics to gauge the amount of improvement that training yielded instead of directly assessing the level of endovascular skills.[41,69–73] Due to the fact that the obtained results from the various works are inconsistent, the general consensus is that current VR simulator metrics are only surrogate indexes of surgical competency. Certain metrics (e.g. procedure time and fluoroscopy time), received higher interest than others (e.g. percentage of lesion and residual stenosis) thus not all available metrics are included in all research studies. In the experiments various operation scenarios were employed as test cases. The Procedicus VIST system has been the most-used in endovascular skill assessment studies.

Procedure time (PT) pertains to the time lapsed from the beginning until the completion of the operation. Fluoroscopy time (FT) refers to the amount of time that fluoroscopy was in use during the operation and volume of contrast fluid (VCF) is the total amount of contrast agent used. These three metrics have been included in studies, with participating surgeons of varied experience. PT demonstrates some degree of construct validity in,[64,74–76] where expert/experienced surgeons complete the operations faster than novices/trainees. However, PT appears to be discriminative only between the extreme cases (novices and experts), but fails to differentiate intermediate experience, as reported in.[60,63,67,77] The results of FT are contradictory, since there are works in which FT appears to differentiate novices from experts,[64,75,76,78] but the opposite result is reported in.[67,77] Again FT appears to not be able to discriminate between intermediate experience and expertise. VCF exhibits a similar contradicting behaviour, since it fails in the majority of studies to correlate with surgical experience[64,71,76] and seems to be indicative only of skills improvement after simulator training.[70,72] In summary, the above metrics have demonstrated the ability to evaluate surgical training progress but do not appear capable of judging the acquired level of surgical expertise. Additional criticism in the content validity of these metrics stems from the fact that faster PT does not necessarily translates to obtained expertise especially for novice/trainees, because the notion of completing a procedure "as quickly as possible" may lead to operational hazards (damage of vessel walls, crossing lesions, dislodging plaque debris). Therefore it has been suggested that only surgeons of an established level should be evaluated based on PT, as speed can not be favoured over quality. For FT and VCF the criticism focuses on whether these metrics measure true surgical quality or simply personal surgical style and efficiency in the use of the imaging modalities. To this day, the reported clinical results for these simulator metrics suffer from the lack of consistency and reliability which does not permit their use in establishing explicit levels that reflect gained surgical skills and prohibits their use in accreditation examinations.

The rest of the simulator generated metrics, number of cine loops (NCL), placement accuracy (PA), percentage of lesion covered (PLC), percentage of residual stenosis (PRS), stent-to-vessel ratio (SVR) and post-dilation stenosis (PDS), have received considerably less interest. From the obtained results, no direct correlation between the value of these metrics and the level of surgical ability has been established.[67,74,76] Similarly to PT,FT and CV these metrics have been shown to be indicative of the improvement on the skills of novice surgeons after undertaking training.[71] This however should be considered with caution because the ability to effectively measure the incidence of events can be difficult and would exhibit variation across patients as well as across the operating practitioner.

5.2. *Kinematic analysis of endovascular catheter motion*

While very useful from an analysis point of view VR simulation still has limitations in portraying the full complexity and sensory stimuli arising from a real procedure. This has motivated a number of recent research efforts to examine alternative approaches for objective surgical skill evaluation through making measurements during real procedures or phantom training exercises with the primary focus being on the kinematic analysis of the surgical instruments during the endovascular operation. This is largely inspired by the documented success of motion-based features in laparoscopic surgery. Various studies have shown that motion-derived features can effectively discriminate the level of surgical skills in different experimental set-ups (robotic, VR simulator, box models).[25,79–82] The kinematic analysis of surgical instruments is predicated on the ability to accurately track their position on a given coordinate system. Over the years, a number of different technologies have been developed and tested for tracking tools in endovascular surgery and these are discussed in the following sections.

5.2.1. *Electromagnetic tracking*

Tracking surgical tools with Electromagnetic (EM) systems is a technology that employs an EM source for generating a field with known 3D geometry within which EM sensors can be localized. These sensors typically comprise of a small coil and the induced voltage (measured in the sensor) is proportional to the magnetic flux of the field. This property allows for the position and orientation (6 DoF), with reference to the source, of the EM sensors to be calculated.[83] Categorization of EM tracking systems is done based on the use of AC or DC current in the source and the type of sensors, active or passive (permanent magnets) they use. This technology targeted at providing an alternative to optical based tracking systems, which although more accurate in general, require clear line-of-sight, which is seldom feasible in surgical procedures. In the endovascular domain, the need to track the position of flexible instruments (catheters) in the human body, renders EM systems ideal for this task. The major drawback of EM tracking system is their susceptibility to EM distortions caused by neighboring devices that either become magnetized (ferromagnetic materials) or produce magnetic fields (computer drives).[84] Nevertheless, methods for distortion compensation are available and kinematic features that are relative in nature and not absolute, would not be influenced by this. The Aurora® tracker (Northern Digital Inc., Waterloo, Canada) is the most extensively used EM tracking system in MIS.

5.2.2. *Tracking instruments in ultrasound*

Recently an alternative to EM tracking, based on Ultrasound (US) waves has been proposed. A miniature US transducer is attached to the tip of the catheter and emits US waves which are then captured by an array of sensors positioned on the outer skin surface. Specialised gel is applied on the skin enabling coupling between transmitter and sensors. Both the catheter and the array of sensors are connected to a computer platform which excites the transducer, through a pulser, at regular intervals and receives the data captured by the array of sensors.[20] The location of the transmitter is then calculated through trilateration after an initial step where the distance between the transducer and the sensors is approximated from the time of arrival (TOA) of the emitted US waves.[85] After the tip is localized it can then be registered to intra-operative images.

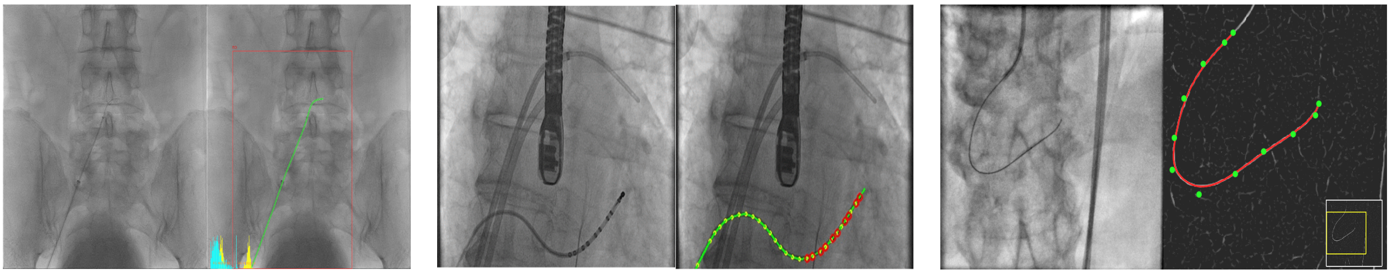
5.2.3. *Tracking instruments in fluoroscopy*

With significant recent advances in computer vision and image processing, methods have been developed for the detection and tracking of surgical tools in medical images.[86] Typically the problem is posed as a two-stage process where initially classification is used to identify the pixels that correspond to the surgical instrument and separate them from the background anatomy. Following, the location of the catheter is extracted in each frame by fitting and then optimizing a model of the instrument, which for catheters/guidewires is normally a spline parameterisation of their shape.[87] A number of approaches choose to only track the distal point (tip), as this is deemed the most important point of the catheter/guidewire.[88–90] A plethora of different processing methods based on machine learning, filtering and template matching, Hidden Markov Models (HMM), has been proposed for the tracking of catheters/guidewires and other surgical instruments (e.g. stents) in fluoroscopy as well as in magnetic resonance images and echocardiography with accuracy of a few millimetres.[89,91–97] Recently a number of methods have been developed for tracking the full shape of catheters/guidewires in fluoroscopy.[87,96,97] Three different approaches to achieve this are illustrated in Fig. 3. Fig. 4 shows the trajectory of the catheter/guidewire tip as it is tracked in different frames of a video sequence during the cannulation of an aorta phantom model by a novice (Fig.4(a)-Fig.4(e)) and an expert (Fig.4(f)-Fig.4(j)) surgeon. The resulting trajectories are indicative of the expert surgeon's ability to operates the catheter more efficiently than the novice. One limitation of image-based tracking is that the actual 3D position of the catheter is localized on a 2D image thus loosing the depth information. Reconstruction of the catheter's position in 3D is possible if multiple 2D fluoroscopic images are obtained, for example using bi-planar fluoroscopy, or 3D pre-operative imaging is used.[98–100]

5.2.4. *Optical shape sensing*

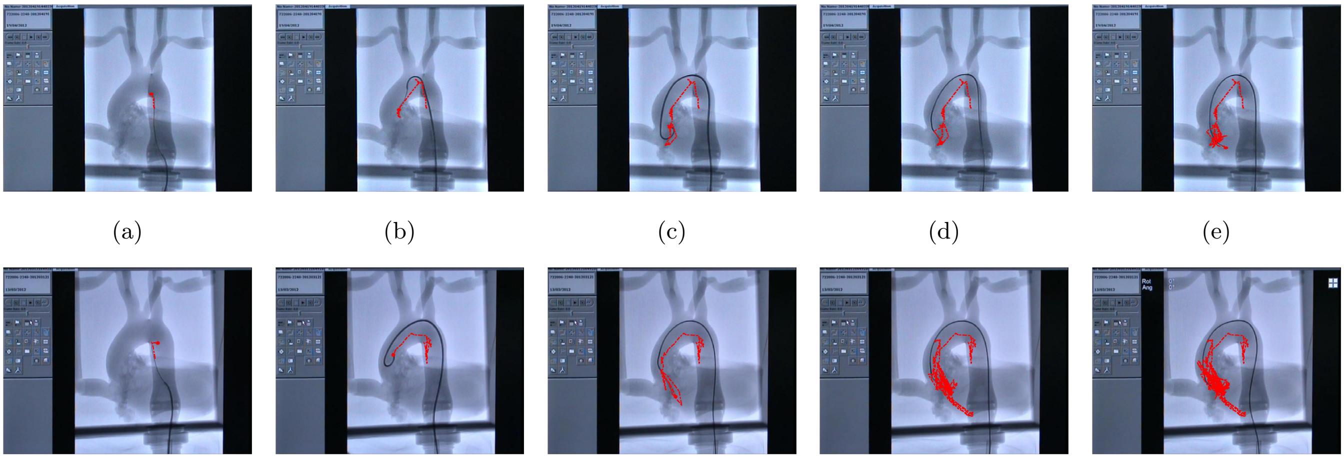
An emerging technology for tracking catheters and other medical devices is optical shape sensing. With this method, optical fibres that allow for spatially-resolved strain measurements are integrated into the devices. Strain at different positions in the optical fibres can be measured with interferometric techniques. Using this series of strain measurements, the overall shape can be determined with a reconstruction algorithm.[101–103] Interrogation and processing methods are currently sufficiently fast for the determination of the 3D shape of catheters in real-time.

Fibre Bragg Gratings (FBGs) have been shown to be a viable interferometric technique for strain monitoring in the context of optical shape sensing.[104–106] The reflection spectrum of a FBG varies with strain, and signals from FBGs at different positions can be resolved using the principles of Optical Frequency Domain Reflectometry (OFDR). Multicore optical fibres can be used to measure strain in two orthogonal directions.[107] At least two cores are required for 3D shape measurements; additional cores can be used to compensate for temperature variations. As an alternative to FBGs as reflective structures within fibre cores, Rayleigh scattering can be used.[108] This approach offers the potential advantage of simpler manufacturing methods and denser spatial sampling, though weak reflectance signals can present challenges.



(a) (b) (c)

Fig. 3. Examples of shape catheter tracking methods in fluoroscopic images: (a) Pixel-wise posterior optimisation of a b-spline model;[87] (b) Propagation of blob and tubular shapes with patch analysis and Kalman Filtering ©2015 IEEE, reprinted from Wu et. al.[97] with IEEE permission; (c) B-spline model optimisation using discrete Markov random fields ©2013 IEEE reprinted from Heibel et. al.[96] with IEEE permission.



(a) (b) (c) (d) (e)

(f) (g) (h) (i) (j)

Fig. 4. Sequential tracks of a catheter/guidewire tip in different times during the cannulation of an aorta phantom model: (a)-(e) are from a novice surgeon and (f)-(j) from an expert. It is evident that, as the catheter progress in the aortic arch, the expert surgeon manipulates the catheter/guidewire in a significantly more efficient way than the novice, resulting in smoother trajectory.

Optical shape sensing could be valuable for objective skills assessment, particularly if it is successfully commercialised. As implemented for catheter tracking, this technology is still in its infancy and the dependencies between the spatial accuracy and factors such as the number of cores, the catheter shape, and the reconstruction algorithm remain to be determined. Optical shape sensing for non-robotic applications is being commercialised by Philips Healthcare NV, as part of a development agreement with Luna Innovations Inc. (Roanoke, VA, USA),[109] while the robotic rights are owned by Intuitive Surgical Inc. (Sunnyvale, CA, USA).

5.3. *Surgical skill assessment from catheter motion metrics*

Investigation on the potential applicability of motion-based metrics, for assessing endovascular surgical skills, has recently attracted research interest. In principal such metrics are very similar to VR simulation data but they are derived from phantom or real procedural data using the tracking techniques described in the previous sections. Rolls et. al. utilized semi-automated software to track the position of the catheter's tip in carotid artery stenting experiments with the Procedicus VIST simulator. The total path length of the catheter's tip was investigated for its potential to discriminate surgical competence. Results from 21 interventionalists of varying surgical experience showed good construct validity and correlated well with manually scored GRS.[110] Estrada et. al. performed an investigation with 20 surgeons (residents/novices, fellows/intermediate and attending surgeons/experts) performing four basic endovascular tasks (cannulation of specific vessels) on two experimental platforms, a phantom non-anatomical model and the Angiomentor® (Simbionix USA Corp.) simulator. The location of the catheter's tip was recorded using the

Aurora EM tracking system on the phantom and from video processing on simulator images. Based on previous studies on extracting the quality of motor control hand tasks, the authors propose a list of 21 features obtained from analyzing the catheter's tip trajectory. In their experiments surgical performance was initially evaluated manually with a GRS-E and following the correlation level of each motion-based feature to the GRS-E score was calculated. From this analysis, four features, reflecting smoothness of motion, are identified as potential good indicators of surgical ability; non-dimensional jerk, spectral arc length, number of submovements, average submovement duration. Previously used metrics like total procedure time and path length did not show strong correlation with skill level. This was attributed to the fact that simple vessel cannulation tasks were performed, which did not require complex operations (stent/balloon deployments) thus completion time and path length did not deviate significantly among participants.[111] In a subsequent study by the same group of researchers, a similar protocol was followed (the same inanimate model and cannulation tasks were used) but with experiments taking place on a Hansen Medical Magellan® robotic system. In this case, 21 participating surgeons (of varying endovascular experience) were categorized based on their prior experience with the robotic system as competent/non-competent. The four smoothness metrics derived in the previous study were used and a distinction between competent/non-competent participants was possible from these. The metrics were also indicative of the surgeon's improvement in the operation of the robotic system. However, they did not correlate well with manually scored GRS-E leading to the authors concluding that GRS-E is a tool formulated to evaluate manual catheter handling and therefore may not be as efficient in assessing robotic manipulation ability.[27] Rafii-Tari et. al. advocated that discrimination of technical skills is possible by measuring the force and torque loads exerted on the catheter by endovascular operators. To examine this, a force/torque sensor, capable of measuring axial and torsional forces, was developed and attached to a robotic catheter, while EM sensors (NDI Aurora) provided kinematic information of the catheter's tip. Eight surgeons grouped as inexperienced/experienced performed cannulation tasks in an aorta phantom model, with a laparoscopic camera simulating the fluoroscopy imaging. Obtained results are indicative of the different force/torque load exerted on the catheter by experienced and inexperienced operators, particularly during the cannulation of the carotid artery in the phantom. In total, five features; median speed, the mean value of displacement, push force, torque and the number of twists demonstrated good correlation with surgical skills. Each feature proved more significant in specific parts (descending aorta, aortic arch, carotid artery) of the catheterization procedure.[112] In a recent work, by the same group, motion and contact force information were used to train two separated HMM classifiers (a motion skill and a contact force skill model) in order to classify cannulation tasks executed on the aorta phantom from novice and expert surgeons. Cross-validation was performed following the leave-one-out strategy and both systems demonstrated good ($> 83\%$) classification accuracy, with the contact force model achieving higher ($> 90\%$) overall rates.[113] In,[114] catheter motion properties combined with the interaction of the tip with the vascular wall, were first investigated for skill analysis. The authors developed a customised endovascular phantom (saccular aneurysm) and used optical encoders to capture the motion of the catheter's tip and EM sensors attached on the surgeons hands, to measure hand motion. The stress applied on the wall by the tip was measured through photoelastic stress analysis, facilitated by the material (urethane resin PL-6) used to build the phantom. The performance in terms of motion economy and respect for vessel wall was evaluated in a population of 6 novices and a single expert. The differences in both areas were visible among the expert and the novice participants as well as between novices, since a number of them consistently exhibited superior performance than the others.

6. Future research potential

Computer technology and robotics are increasingly providing new tools to facilitate the analysis of surgery and surgical competence and skill. For endovascular surgery the opportunity is to identify the key signatures and features that quantify technical dexterity in an objective manner. Research on endovascular skills assessment is at a state where many significant contributions have provided a solid background, so that future studies can attempt to develop a fully objective and automated assessment tool. Starting from the fundamental principle that endovascular dexterous skills are primarily imprinted in the handling and use of surgical instruments, we focus here on three directions that to the authors belief, present significant research potential in this area. Our suggestions stem from the manually-scored items in GRS and checklists in which we have identified several concomitant criteria across different GRS that correspond to technical skills and that may potentially be represented by quantitative measures derived from image and video processing, negating the need for expert observation.

In essence, both GRS and checklists evaluate four fundamental technical abilities: 1) avoiding vessel wall damage through catheter manipulation, especially when approaching lesions, aneurysms or sclerotic areas; 2) accurate positioning and deployment of therapeutic devices; 3) precise, smooth motion in a timely fashion without unnecessary or awkward movements; 4) efficient use of the imaging modalities and especially moderate use of contrast agents and fluoroscopy. This is of particular importance for endovascular interventions since the dose of absorbed ionizing radiation must be as little as possible.[115] The description of these key attributes may be different among the GRS and checklists employed but they are present in all of them (e.g. the MRS shown in Table. 2). This prompts us to make the assumption that potential quantitative measures extracted from analyzing medical images as well as from tracking the instruments trajectory and combined appropriately, will contain the necessary information to discriminate the levels of surgical competence. One should expect such metrics to demonstrate similar levels of construct validity as GRS and checklists. The rest of the items appearing on GRS and checklist pertain to cognitive abilities, like preparation and knowledge of the procedure steps and the anatomy, proper selection of surgical equipment (catheter/guidewire type and size and baloon/stent size) and overall quality of surgical output. These attributes can only be assessed from an expert external observer, although a selection of unsuitable instruments should be reflected during their navigation and deployment.

6.1. *Enhanced tool-motion analysis*

Currently metrics based on kinematic analysis of the catheter/guidewire have been limited to data recovered from tracking of the catheter's tip. Although, the distal tip is the most important part of the catheter, it may be of value to augment this analysis by tracking the kinematic pattern of the entire catheter inserted in the vasculature. Moreover, tracking the position of other surgical equipment (stents/balloons) during deployment can also be beneficial. Accomplishing such elaborate tracking of surgical tools will lead to a plethora of new information regarding the handling of the catheter and other equipment that may prove extremely useful for discriminating surgical performance.[116] Many methods for segmenting and tracking the entire shape of the catheter in fluoroscopic video sequences have been proposed as reviewed in Section 5. VR simulation systems can also be equipped with specialized software to include this type of navigation information in their feedback.

6.2. *Evaluating safe interaction with the vascular wall*

Another criterion assessed in GRS and checklists, is the safe navigation of the catheter without exposing adjacent tissue to danger. It is therefore expected that a potential investigation of the catheter's path with respect to the vascular wall would reflect this principle and provide indicative measures of the operators aptitude to perform safely. This is not yet studied comprehensively and in our view this is a key direction with the potential to provide essential information for discriminating surgical skills. A great challenge in achieving this would be the ability to segment the vascular wall and the catheter in noisy fluoroscopy images in which the visibility of the vasculature is restricted. Experimentation can also be carried out with video sequences from transparent phantom models, where segmentation of the vasculature and the catheter is straightforward. Moreover, research in this direction can be facilitated by employing sensors to measure the amount of force exerted to the vascular wall, as initial results have been promising. Finally this is another type of information, which would be beneficial to be included in future VR simulator systems.

6.3. *Machine learning*

The third direction we wish to highlight pertains to the application of machine learning for endovascular surgical skill assessment. In machine learning, specific mathematical models can be adjusted, through training with existing information and then used as classifiers to effectively categorize new incoming information (supervised, unsupervised learning) or generate an optimal strategy/policy to be followed given a specific initial state (reinforcement learning). Machine learning techniques can have profound application for skill assessment, where the increasing amount of multi-modal sensor information integrated in next-generation endovascular surgical systems, provides an abundance of input data for developing learning models that mathematically represent expert tool manipulation and optimal overall surgical execution.[117] Recently a new direction, termed "deep learning", was introduced whereby mathematical models are formulated (trained) with multi-layered combinations of abstract feature representations extracted from the raw input data, instead of handcrafted generated feature-values.[118,119] Deep learning methods (e.g. deep neural networks, convolutional neural networs) offer the opportunity to directly classify surgical performance using training data patterns and higher level information obtained from imaging, tracking, force and other sensor modalities. In laparoscopic MIS a few works exist where machine learning approaches have been applied for evaluating surgical skills.[120–123] On the other hand, similar methods have not been extensively studied for endovascular surgery. Only in[113] the authors employed an HMM classifier to discriminate among experts and novices. Overall, machine learning methods provide the framework for interpreting and inferring surgical knowledge from sensed operational information, thereby facilitating breakthroughs towards a safer, more efficient and robust endovascular surgical paradigm.

7. Summary and Conclusions

The role of experts in surgical training is critical because skills such as basic knowledge, leadership, critical thinking, communication and decision making, can only be acquired and evaluated through academic teaching and interaction with senior surgeons. In this sense the apprenticeship model of surgical training is very effective. Supervised and guided acquisition of experience is a crucial component of the process but there are significant challenges in managing the costs and volume of such training practices. On the other hand, technical skills involving manual dexterity can be developed without the constant observation and guidance of an expert. These are crucial for operating instruments, devices and imaging equipment within the operating room.

Table 4. Strengths and weaknesses of the methodologies applied in evaluating endovascular skills.

Methodologies	Features	Strengths	Weaknesses
Structured methods 40, 41, 50, 60, 61, 63, 64, 67, 68			
Rating Scales (global and procedure specific)	Global or operation specific scales composed of a number of skills criteria rated on a 5-point Likert scale	Good construct, face and content validity, evaluate level of performance, capture technical dexterity, offers stratification	Require expert evaluators, time-consuming and laborious, subjective to a degree.
Checklists	Procedure specific checklists that evaluate correct fulfillment or incorrect/no fulfillment of tasks	Present content and face validity, able to discriminate novice experience, access proper sequence of tasks	Unable to evaluate level of performance, do not separate high level of expertise, vary in structure/number of items for different procedures, time-consuming and laborious.
VR Simulator metrics 60, 63, 64, 67, 69–78	Automatically generated metrics, presented as feedback to operators	Indicative of skill improvement during training, instantly available	Limited construct validity, contradictory results, surrogate markers of surgical expertise.
Motion-based analysis 27, 110–113	Kinematic-based metrics derived after appropriate processing	Discriminate levels of surgical dexterity, significant research potential	Limited evaluation.

The focus of this review was to present the current state-of-the-art in endovascular skills assessment and provide a perspective on methods that appear to be promising towards the development of an objective and automated evaluation system.

Initial attempts at establishing objective practices for surgical evaluation focused on structured scoring scales (OSATS, GRS) and checklists, which have been modified to reflect the specific challenges of endovascular interventions. Although subjective to some extent, these are considered the current gold standard for assessment. The problem in their use arises due to inefficiency issues since they are quite laborious and time-consuming. An additional impediment is the fact that different GRS have been proposed for different operations. Despite their shortcomings, these methods can act as the blueprint upon which objective surgical assessment can be formulated. After presenting the relevant studies, we identified the technical attributes examined in GRS-E and checklists that can be represented with quantifiable metrics, produced after appropriate processing and reveal similar technical characteristics. We concluded on three areas; safe use of the instruments without damaging the vasculature, correct, efficient and economical handling of the instruments and proper use of imaging modalities.

This review also summarized the available literature on endovascular skill assessment with objective measures. We grouped these works into two categories based on the metrics that were employed. VR simulator metrics have proven to not be generally capable of discriminating inexperienced from expert level procedures. Their applicability is limited to measuring the improvement in the skills of novice surgeons during training with VR systems. The second category included the recent attempts in developing assessment tools from the kinematic analysis of the catheter. This direction has so far generated some very promising outcomes and practically verifies our assumption that the technical criteria present in GRS pertain to this type of motion-based analysis. Further investigation of the instruments' kinematic properties while in operation, presents great potential to generate measures that are strongly correlated with surgical ability. A summary of the methodologies used in endovascular skills assessment is provided in Table.4.

Ultimately, a long-term target is to develop the understanding and measure of competence and produce a standardized automatic skill assessment system which is as independent as possible of the type of endovascular operation performed, the operation environment (real operation, cadavers, inanimate models, simulators) and technology used (conventional or robotic endovascular surgery). Such a system will practically encompass the knowledge of expert surgeons on how to optimally perform an endovascular procedure. This will be incredibly beneficial and cost-effective in the training process of new surgeons. Additionally it may pave the way for the design of intelligent surgical robot systems, capable of performing autonomously, initially for sub-procedural tasks but in the end potentially full cases, under the supervision of expert surgeons.

Acknowledgments

This work was supported in part by the European Commissions 7th Framework Programme FP7-ICT, by Grant Agreement #601021, under the project name "CASCADE: Cognitive AutonomouS CAtheters operating in Dynamic Environments".

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