Diagnostic Requirements for Efficient, Adaptive Robotic Surgery Training

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Abstract. Robot-assisted surgery training is shifting towards simulation-based training. Challenges that accompany this shift are high costs, working hour regulations and the high stakes aspects of the surgery domain. Adaptive training could be a possible solution to reduce the problems. First, an adaptive system needs diagnostic data with which the system can make an action selection. A scoping literature search was performed to give an overview of the state of the research regarding diagnostic requirements. Diagnostic metrics should be (a) useful for formative and not only summative assessment of trainee progress, (b) valid and reliable, (c) as nonintrusive as possible for the trainee, (d) predictive of future performance in the operating theater (e) explanatory, and (f) suitable for real-time assessment of trainee's learning state. For a more in-depth understanding, further research is needed into which simulator parameters can be used as diagnostic metrics that can be assessed in real-time. A possible framework for adaptive training systems is discussed, and future research topics are presented.

Keywords: Adaptive training · Robotic surgical training · Robotic surgery · Real-time assessment

1 Introduction

Robot-assisted surgery (RAS) is the next step in the evolution of the surgery domain. It is accompanied by a major paradigm change for surgery training. Traditionally, residents are trained 'on-the-job', which nowadays shifts to simulation-based training [1, 2]. According to Schreuder and Verheijen [3] the main benefits of RAS are "better ergonomics of the surgeon" and "improved dexterity" among others ([2], p. 201). However, the fast introduction of new technology and methods into the operating theater (OT) comes with a number of challenges, some of which resemble the challenges encountered with the swift introduction of laparoscopic surgery. Brunt, a founding member of the fundamentals of laparoscopy training describes these as follows: "(1) a huge group of surgeons required training, as did residents, in an environment where not a lot of teachers were available; and (2) surgeons were being trained through industry-funded courses that were highly variable in terms of their format"

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([4], p. 11). Without a different training paradigm, such as simulation-based training, the described situation led to surgeons who were inexperienced with the surgical technique and applied it in the OT on actual patients. The situation resulted in patients being harmed and in some circumstances it even resulted in death [5]. These so-called adverse events had put classical minimal invasive surgery into jeopardy, despite the advantages it has to offer. In response, standardized basic minimal invasive surgery training, for example, the fundamentals of laparoscopy, were introduced for credentialing surgeons [4].

Similar problems are reported for RAS. In a retrospective U. S. Food and Drug Administration (FDA) study, data of self-reported critical incidents and adverse events between 2000 and 2013 were analyzed [6]. A total of 10 624 adverse events were gathered that occurred during 1 735 000 robotic surgeries. There were 1 391 injuries and 144 reported deaths of patients. The surgeons or staff caused only 7% of the events. However, the incidents and events were often the results of a combination of different causes, for example, surgeon mistakes and device malfunctions. Further, 50% of events resulting in death were reported without a categorization, possibly due to legal issues. The "common flawed operational practices used by the surgical team that contributed to catastrophic events during surgery" are interesting ([6], p. 14) (Table 1).

Table 1. Practices that contributed to adverse events during robotic assisted surgeries reported by Alemzadeh et al. [6].

Causes for catastrophic events during robot assisted surgery
"Inadequate experience with handling emergency situations
Lack of training with specific system features
Inadequate troubleshooting of technical problems
Inadequate system/instrument checks before procedure
Incorrect port placement
Incorrect electro-cautery settings
Incorrect cable connections
Inadequate manipulation of robot master controls
Inadequate manipulation between hand & foot movements
Incorrect manipulation or exchange of instruments" ([6], p. 14)

One conclusion of the authors is to provide real-time assessment of the team's actions for simulation training and during surgery to prevent some of the causes of adverse events. The problems mentioned above are just the tip of the iceberg regarding challenges of modern surgery training programs for RAS. High costs of the robot system and longer anesthesia times for the patients during training make on-the-job training inefficient [7, 8]. A systematic approach is needed to create appropriate training programs in time and to prevent a technology-practice gap as has happened with laparoscopy. Therefore, a state-of-the-art simulation-based robotic surgery standardized training has to be developed, taking a human factors perspective into account.

1.1 A Human Factors Approach to Efficient, Effective and Safe Robotic Surgery Training

Literature reviews [9–11] were used as a starting point for a broader literature search to identify the characteristics of current robotic surgery training programs, which is described in the report by Witte [12]. As a result of the review, the core requirements for a RAS Training curriculum and the main components of a training are summarized: A RAS curriculum should be (a) cognitive science and expert literature based, (b) proficiency-based, (c) simulation based, (d) standardized, (e) validated, and (f) adaptive to the experience level of the trainee. A training should contain: (a) technical and non-technical skill modules, (b) emergency training, and (c) recursive proficiency-based assessments and credentialing of surgeons. Developing, maintaining and providing RAS training according to the requirements consists of three processes that act upon the curriculum and receive information from it: (a) training development, (b) training and (c) iterative updates for new surgery technology (see Fig. 1).

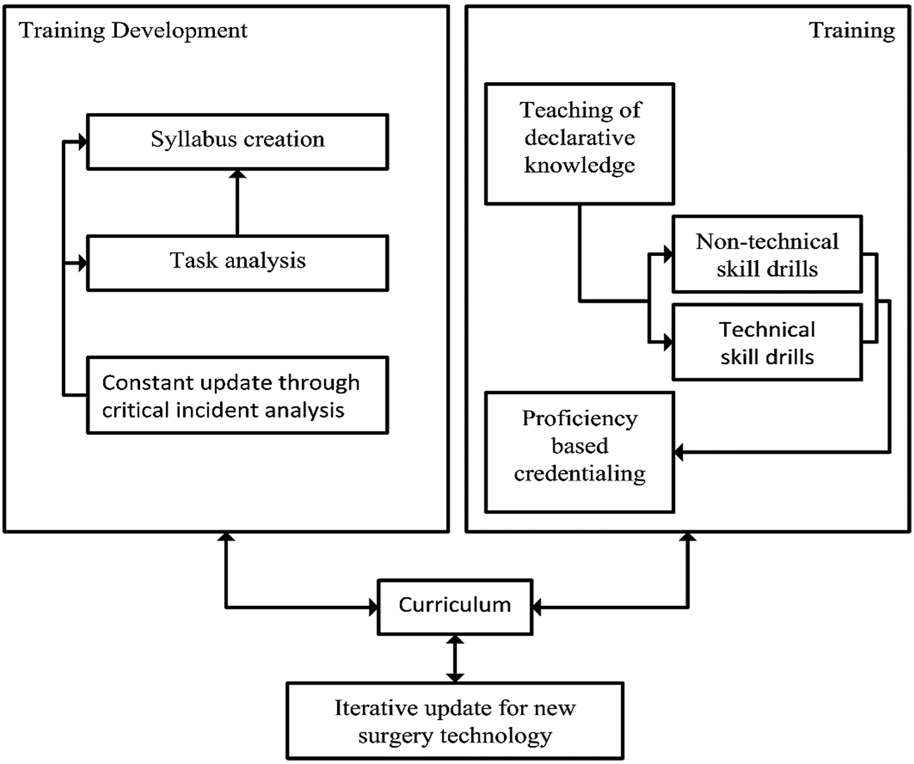

Fig. 1. Prototypical surgery training curriculum creation process [12].

From a human factors point of view, the training development begins with a task analysis, incorporating critical incident analysis [13]. With the results of the task analysis, a syllabus of the declarative and procedural knowledge a surgeon should obtain is created. For the training itself, training modalities and the scheduling of the training are important aspects to consider. Further, the credentialing process should be standardized to ensure the quality of the training. Methods and technologies newly introduced or updated for the use in the OT should be regularly and systematically evaluated to trigger a new task analysis. The requirement that training should be adaptive to the trainee's experience level and the recommendation as mentioned above of providing real-time assessment of the trainee makes the training design even more complex. The simplified creation process of Fig. 1 is used in this paper to discriminate diagnostic requirements for the different aspects of an adaptive RAS training design.

1.2 Information Processing Model for Robotic Assisted Surgery

According to Cao and Rogers [13], the surgeon and technical system can be seen as information processing systems. The "efficiency can be associated with the amount of information an operator can process per unit time. Also, task difficulty can be viewed in terms of the amount of information and the rate at which information is presented" [13, p. 76].

An information processing model for RAS is summarized in Fig. 2. To perform the surgery on the patient, the surgeon controls the manipulators such as a camera and instruments via a console, without haptic feedback. The output of the manipulation is filtered via a three-dimensional display that contains the video feed of the camera within the patient. Also, the haptic feedback is filtered, because of the lack of haptic feedback and the lack of the fulcrum effect. In traditional minimal invasive surgery, the surgeon's movement is reversed to the movement of the tip of an instrument. In RAS this effect is compensated by the robot. The surgeon first receives the sensory information, which is mainly visually, but also auditory and then perceives it through encoding of the data. The perceived information is then used for decision making for the next motor response or memory storage for later decisions. In the final step, "response execution requires the call up, release, and generation of motor sequences with muscle activation" [13, p. 77]. After the introduction of requirements for RAS training in general and the description of a proposed information processing model for the RAS tasks, the next section will introduce the adaptive aspects of RAS training.

1.3 Adaptive Robotic Surgery

An "adaptive training is training in which the problem, the stimulus, or the task is varied as a function of how well the trainee performs" ([15], p. 547). With an adaptive training, issues like the "lack of training with specific features of the system" or "inadequate troubleshooting of technical problems" ([6], p. 14) that have led to adverse events in the past could be trained on an individual basis.

Diagnostic Requirements for Robotic Assisted Surgery Training. An adaptive training, based on the earlier mentioned requirements for RAS training, could help to solve the problems of today's surgical training. It is a means of optimizing the training by modeling the learning curve representing a trainee's progress and providing

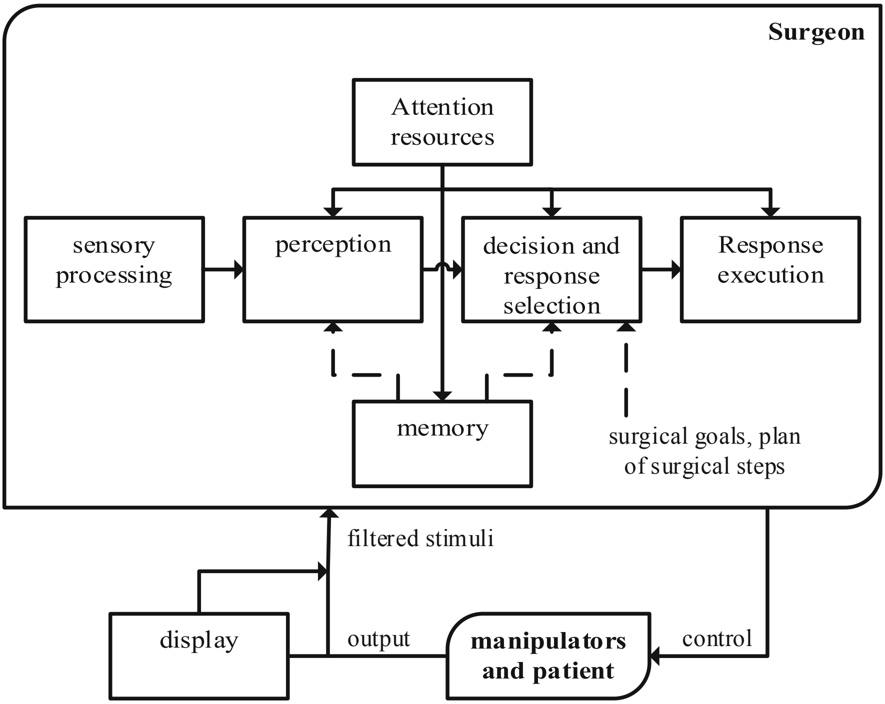

Fig. 2. The information processing model for robotic-assisted surgery from Cao and Rogers [13], modified, based on Wickens [14].

individualized training to account for individual differences in ability and experience. Schwarz and Fuchs [16, 17] propose a framework for a multidimensional real-time assessment of user state and performance for adaptive systems. The simplified version shows that the adaptive technical system interacts with the operator, or in the case of RAS training the trainee, and the environment (see Fig. 3). The state regulatory process is responsible for the adaptation of the technical system to the trainee. First, data should be gathered from multiple sources for a reliable basis to evaluate the data in the next step. State assessment is then responsible for the valid diagnostic results that can be displayed as feedback for the trainee and be used as input for the action selection. By the diagnostics the system can make decisions to support the trainee and then execute those decisions in the last step. Without reliable and valid diagnostic data, the adaptation process can become ineffective or even destructive.

1.4 Summary

The literature reviews on RAS training as mentioned earlier lacks information about the status of *adaptive* robotic-assisted surgery training. Hence, the focus of a scoping literature review that was performed in this paper lies on the adaptive training topic to fill in this gap. Further, diagnostic requirements for metrical data of trainees and

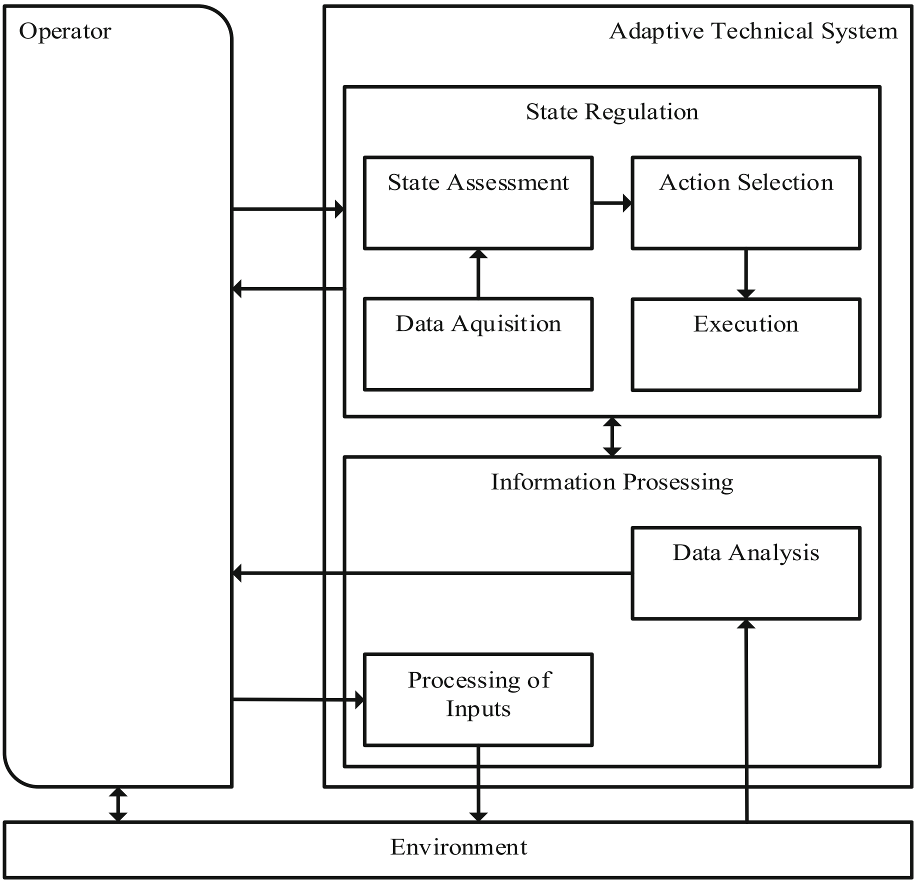

Fig. 3. A simplified model of a generic adaptation framework of Schwarz and Fuchs [16]

surgeons are needed for an adaptive training framework. These data can be used for training system adaptations specific to the state of the trainee. To broaden the scope of the literature reviews for RAS the following sections focus on the question: what are the diagnostic requirements for efficient, adaptive robotic surgery training?

One key feature of adaptive training is to assess trainee performance; otherwise, a fine-grained adaptation of the training program for the trainee's needs would not be possible. Valid and reliable real-time robotic-assisted surgical performance assessment is the first step for further systematic research on the topic of adaptive robotic surgery training. By combining the previously described literature review [12] with the scoping review, the current state in literature is analyzed and summarized.

2 Method

A scoping literature review was performed to identify requirements for adaptive RAS training. Two search engines were used to broaden the results: (a) Web of Science, and (b) Scopus with integrated PubMed Hits. Search results were evaluated in phases: (1) by title, (2) by abstract and (3) by full text. After deleting duplicates, a reference check of the hits was performed to add missing hits. Peer-reviewed articles or books with the keywords surgery adaptive training, surgery adaptive curriculum, diagnostic requirements surgery training and requirements adaptive surgery training were considered as hits.

3 Results

The search resulted in a total of 1241 initial documents that were reviewed for further analysis. Figure 4 gives an overview of the search process. Of the 65 full texts included, two were books, and 63 were peer-reviewed journal articles. After categorization, the information from 65 documents contained in the analysis was summarized and used to compare the introduced models of training creation, adaption framework, and surgical information processing model in the context of adaptive surgery training.

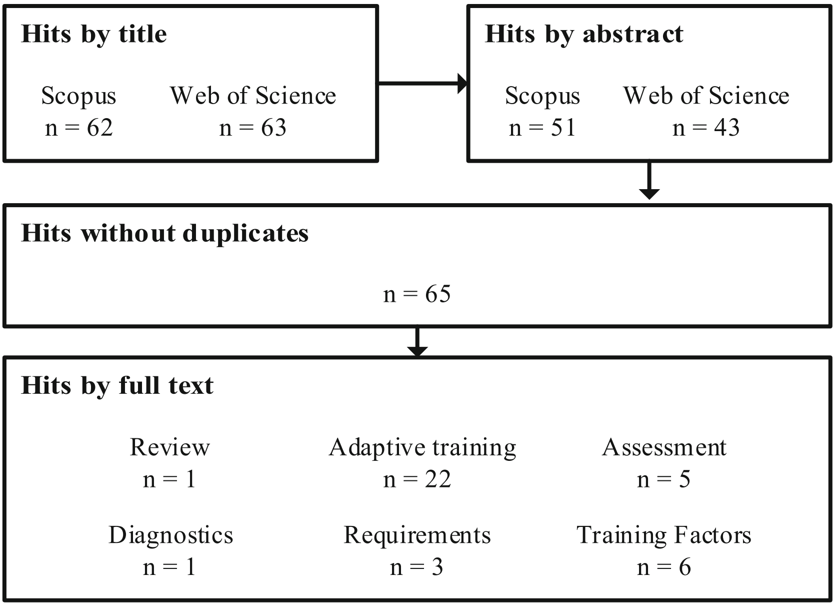

Fig. 4. Search process for hits regarding adaptive surgery training

3.1 Adaptive Surgery Training

Vaughan et al. [18] are providing an overview of self-adaptive technologies for virtual reality. According to them the field of adaptive training contains the aspects: (a) "Mechanisms for adaptive learning about a user's requirements", (b) "adaptive and reactive features to enhance trainee's learning efficiency", (c) "autonomous training using simulation", (d) "intelligent monitoring of a trainee's progress", and (e) "various types of adaptive content can be included" ([18], p. 5). After providing the pros and cons of virtual reality training in the context of medical training, the review does not give details on the status quo of adaptive surgical training. Five adaptive motor skill training courses for surgery were described in the documents [19–23]. These pieces of training are not fully fletched training programs, but mostly a research vehicle for adaptive training. Another line of research is adaptive training with the expert in the loop [24]. On the one hand these findings contradict those of cost efficiency and working hour regulations, but on the other hand, it can increase the efficiency of complex task training.

Reliable and valid diagnostic data is the basis for a successful adaptive strategy. Because of the limited information about adaptive surgical training in general and robot surgery training in particular, it is essential to begin with the first step and summarize the diagnostic strategies used so far by the authors of the articles found in the literature search. The 2005 publication by Pham et al. [21] was the first to describe an adaptive simulated surgical training. In their paper, the authors discuss the Yerkes-Dodson Principle that states "that in situations of high or low stress, learning and performance are compromised" [21, p. 385]. If the difficulty level does not match the need of the learner, frustration or boredom can occur, which makes the training inefficient. With the so-called Smart Tutor software, the task difficulty was kept in an "optimal learning zone" [21, p. 386] regarding frustration and boredom. Results of an empirical study indicated no increase in the learning rate. However, participants of the adaptive training were less frustrated compared to the non-adaptive training group. Pham et al. conclude that more research is needed to refine the algorithm. However, no specific diagnostic metrics or method were disclosed.

More recently, Mariani et al. [20] describe a training model where participants first perform a complex bimanual visuo-motor task to obtain a baseline performance measurement. A ring had to be moved virtually along a wire without touching it. This complex task was split into simpler subtasks. Performance data were compared to experts performing the same task. The adaptive system then evaluated which subtasks needed further training. The diagnostic metrics used were: (a) "distance between tool and target", (b) time to completion, (c) "distance between the actual and the ideal position", (c) "angular difference between the actual and the ideal pose", and (e) "number of drops while performing an object transfer" [20, p. 2163]. A group of trainees showed higher performance in the adaptive training condition compared to a self-managed training group.

Siu et al. [22] propose an adaptive virtual reality training for surgery skills, based on the Adaptive Control of Thought/Rational (ACT-R) cognitive architecture and point out a particular need for military medical training. The needed skill set can differ significantly from deployment to deployment and should be effectively approached via new training. They demonstrated a preliminary model based on their adaptive training framework that can predict "the majority of variance in the human performance data" ([22], p. 218). However, they also conclude that they did not account for fatigue. The data suggest a slowdown caused by fatigue after a couple of trials. A more holistic approach with multiple dimensions for the user state assessment is supported by this finding. Further, their framework aims to "predict the decay effect and maximize the training experience by monitoring the occurrence of mistakes during skill acquisition and retention" ([22], p. 217). The framework does not provide explanations for real-time performance problems or critical states of the trainee, which could lead to more fine-grained adaptive training. Kinematic data, time to task completion, total distance traveled, and average speed are used as diagnostic metrics. Also, muscle effort of four muscles was recorded. According to the authors, the ACT-R based model fits better than a logarithmic regression model.

Another technique found in literature on monitoring a surgeon's performance is the cumulative sum technique [19, 23, 25]. "The acceptable outcome rate, the unacceptable outcome rate, the Type I error rate and the Type II error rate" [24, p. 583] needs to be set in advance. The basis is data of experts with which the trainee performance will be statistically compared.

3.2 Assessment Strategies

Assessment of a trainee is closely related to the diagnostic requirements of adaptive robotic surgery. In the past, assessments were mostly used for selection of aspiring surgeons, tracking of overall learning progress and credentialing. In the traditional apprenticeship training model, experts evaluate learning progress during actual surgeries performed by the trainee and adapt the intensity and complexity of the learning experience and environment for the trainee. With simulation-based training, this role has to be compensated. One option is to let trainees self-evaluate their progress; another option is to use a one-size-fits-all strategy. The self-evaluation strategy can lead to higher cognitive load during training because trainees have to determine their own learning needs for the training sessions [20]. The one-size-fits-all approach cannot account for individual differences of the trainees, which requires a homogeneous trainee group in terms of prior knowledge, ability, and experience. Taking the changing surgical techniques and technologies in the OT, varied experience levels and different learning needs of trainees into account, implementing an efficient, effective and safe training can be cumbersome.

These developments call for robust and evidence-based adaptive training. This training requires real-time monitoring of trainee performance. As discussed in the previous section, most documents from the literature search concentrate on the comparison of diagnostic metrics regarding movement, errors and time to completion to expert data [26]. Diagnostic parameters such as cognitive aptitude [27] are also considered as valuable for real-time assessment. Requirements for the assessments are: (a) "reliability; if the test were to be administered to the same individual on separate days, in the absence of any learning, the results obtained should be similar," (b) "feasible; the test must be practical and straightforward to administer, (c) "fair; the results from any assessment process should be reproducible", (d) "objective" and (e) "valid" [28].

4 Discussion

Research into adaptive surgical training and more specific robotic surgery training is scarce. The literature search did not lead to a concise picture of a coherent model taking all relevant human and technological factors into account. There is no consensus about which diagnostic metrics are best suited to be implemented in adaptive robotic surgery training, despite the multitude of performance data that is generated by the simulation devices.

Given the current state of the literature, the following requirements for diagnostic metrics for adaptive robotic surgery are proposed. Diagnostic parameters should be (a) useful for formative assessment of trainee progress and not only summative assessment, (b) valid and reliable, (c) as nonintrusive as possible for the trainee, (d) predictive of future performance in the OT, (e) explanatory, and (e) suitable for real-time assessment of trainee's learning state.

These requirements and the outcomes of the literature search have multiple implications for curriculum design in robotic surgery, and the components of real-time user-state assessment [16]. The task analysis process should be performed with adaptive training in mind. The syllabus that feeds the curriculum should contain explanatory information about the tasks, skills, and knowledge that are required for robotic surgery. Furthermore, the syllabus should have a form, that an adaptive training system can evaluate the trainee by the causalities of the containing items. More precisely this means, that a digital training system should be capable of deeply understanding the surgery domain to provide meaningful training tasks to the trainee. For a full adaptive training program, diagnostic metrics of non-technical skills, such as communication, leadership, and teamwork, should also be considered and not only metrics of technical skill performance.

We propose an implementation of a simplified model of a generic adaptation framework of Schwarz and Fuchs [16], see Fig. 5. The technical system detects critical states of the system's operator and assists by simplifying the task. When it comes to training, the system should not only assist but also keep the trainee within the optimal training zone. This means that the training system is introduced as a third component. The trainee, who is an adaptive information processing system too, interacts via the training system with the training environment. For the operational use of the framework the problem of two interacting systems was solved by only acting when an operator performs at a critical level. In a training scenario, the trainee has to be kept challenged, and the learning process itself can be seen as a constant adaptation. This implicates that the baseline has to be evaluated constantly; otherwise, the adaptations of the training system can be counterproductive. The framework uses six dimensions for evaluating the user state: (a) situation awareness, (b) attention, (c) fatigue, (d) emotional state, (e) workload, and (f) motivation [16]. The involvement of attention, fatigue, emotional state, and workload for the surgical task, and learning to perform it, was described in the information processing model and the documents about adaptive surgical training.

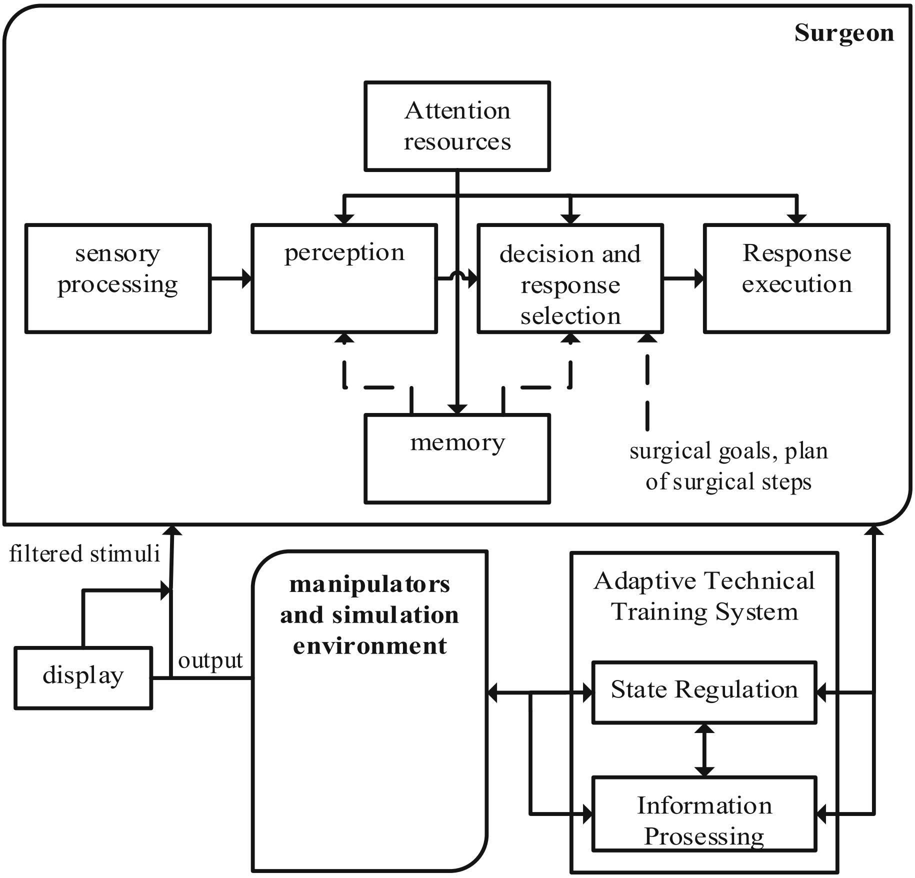

Fig. 5. Framework for future research for adaptive robotic surgery based on Cao and Rogers [13] and Schwarz and Fuchs [16] (modified)

5 Conclusion

The scoping literature review revealed promising developments for adaptive robotic surgery. Current developments in surgical training and technological advancements indicate a need for real-time user-state-assessment during training. Research on diagnostic requirements for RAS training lacks a systematic approach. For future research, the generic adaptation framework of Schwarz and Fuchs [16] shows promising first support by the literature and therefore should be considered as a starting point for more complex investigations of interactions of factors for learning and performing RAS. The challenges facing the development of adaptive training are still numerous and complex. Many questions remain: Which diagnostic metrics are best suited for real- time evaluation?; How to define the best individual, proximal learning zone?; How to structure the curriculum for constant updating without restarting the design phase all over again?

Our literature review shows that research into adaptive robotic surgical training is still in its infancy. The first attempts of formulating requirements seem to be promising and could potentially make robotic surgery more efficient, effective and safe.

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