Review Article

Systematic Review and Meta-Analysis of Computer Based Simulation Training for Non-Technical Skills Training and Knowledge in Postgraduate Medical Education

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Abstract

Introduction: The increase in simulation training across the range of medical education offers a potential route to train non-technical skills and knowledge. More recently, there has been a move towards the use of computer based, including virtual reality, simulation. However, studies evaluating the efficacy of computer based simulation training have used inconsistent methodology, limiting the capacity to construct an overview.

The goal of this study is to systematically review the existing literature and carry out a meta-analysis of the existing randomised controlled trials, evaluating the efficacy of computer based simulation on non-technical skills and knowledge, with sub analysis between doctors in training and those in continuing medical education.

Methods: A scoping search identified the relevant search terms, followed by a comprehensive database search of literature from 2007 until the present on MEDLINE, PubMed, CINHAL, ERIC, BEI, PsychINFO, Proquest Dissertations & Theses and Educational Abstracts databases with hand searching the table of contents of major medical education journals. The inclusion criteria were randomised controlled trials for the meta-analysis and cohort studies for the systematic review, with subjects being postgraduate doctors using a computer based simulation for training and education.

Results: This review found evidence to support the utilisation of computer based simulation for non-technical skills and knowledge and understanding domains.

Discussion: Using computer based simulation offers an opportunity to enhance non-technical aspects of practicing doctors in a safe and effective manner. More high quality controlled studies are required to enable the demarcation of training boundaries.

Keywords: NON-TECHNICAL SKILLS; SIMULATION-BASED TRAINING; SIMULATION- BASED MEDICAL EDUCATION; TECHNOLOGY ENHANCED LEARNING

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Introduction

Simulation has been a part of education as both a method of providing situated learning in a safe environment, as well as assessment of capability and competence. Itself a broad term, simulation aims to replicate and represent a scenario in a faithful manner, with the trainee required to respond in a manner akin to real life. The attraction of simulation is the capacity to provide equal and standardised educational opportunities to all students, offer a controlled and safe environment to explore scenarios, as well as afford the opportunity for repetitive practice. For these reasons, the use of simulation for training purposes has been widespread in a variety of professions from military exercises, technical engineering operations, as well as in the training of healthcare professionals.

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Simulation is resource intensive, in terms of time, staffing and financing (1, 2). Computer based simulation [CBS], including virtual reality simulation, carries additional demands for expertise in design, both in terms of developing the technology and in terms of incorporation into the educational program (3, 4). It can therefore be more difficult to gain adequate educational returns to the resource investment. However, through the rapid rate of technological progress, CBS has become ever-more immersive and reflective of clinical practice. There is the additional potential advantage of increased accessibility to trainees. It therefore follows that CBS offers a method of increasing the fidelity of simulation, with a potential for expanding simulation to encompass a wider range of actions and settings. The initial high development and start up costs associated with CBS may be viewed as a worthwhile one-off investment.

Recently, the expectation that appropriate and comprehensive training will be undertaken before clinical practice, altered models of healthcare delivery, and coupled with a heightened focus on patient safety has led to an overall decrease in clinical exposure to direct clinical care, and thus fewer learning opportunities (5-7). Simulation is seen as a solution to all these aspects through a focused curriculum, with a demonstrable impact on patient and behaviour (8, 9).

The utility of simulation can be broadly divided into two subcategories; the first of these is to provide a summative assessment in a standardised setting, with a view to ensure professional competence; the second setting is in the formative environment, providing an arena for deliberate practice and an opportunity to apply knowledge in a supportive environment, without exposing patients to risk.

The value added by simulation to medical training is reliant on the ability to transfer lessons learnt in the simulation to clinical practice. Therefore, a high degree of fidelity to the clinical environment is required to smooth this transition. As medical sciences have advances and become reliant on an increasing number of technological methods for diagnosis and treatment, this has revolutionised the clinical management of patients. However, this had the side-effect of posing a new challenge to training, as the effective utilisation of these technologies has been shown to incur additional risks to the patient, particularly during the physician's 'learning curve' phase of practice. It has also been suggested that teaching the required skills to use these technologies requires a different approach to standard clinical education.

Technological aids to simulation have been in use for some time, with the initial use of models capable of giving physical and tactile feedback, the most famous of which is the Resusci-Anne model, to much more technologically advanced use of virtual reality simulators for robotic assisted surgery (10). Other technological adjuncts to simulation methods include part-task trainers, computer-based simulators, part-body simulators, model patients and full environment simulation (11-14).

Simulation has been viewed in the past through the lens of various theoretical frameworks, including but not limited to social constructivism, reflective and transformative learning and activity theory (15-18). For the purposes of this study, I take the view that while learning and understanding takes place in a personal sphere, requiring the internalisation of information and interpretation, there is a definite external reality through which responses can be measured and evaluated, allowing for assessment of learning gains and professional development. Furthermore, the personalised response can be predicted and encouraged to develop along an explicit path, as dictated by a combination of external stimulus and prior knowledge. Proceeding along these lines of argument, with specific reference to medical education, leads to the conclusion that there is a 'correct' diagnosis and 'correct' treatment based upon objectively verifiable clinical evidence.

Given that all doctors undertake broadly similar undergraduate training and have comparable postgraduate knowledge, the responses to training programs should be predictable. It can therefore be assumed that simulation training in medical education can utilise specific clinical information to prompt specific line of thought and practice. It therefore follows that the use of standardised, predetermined stimuli in the simulation would maximise the educational value of the scenario and hypothetically, increase the transferability skills and knowledge between simulation and practice (19, 20). From these principles, it can be safe to assume that conclusions reached in this review regarding computer based simulation as a pedagogical technique can be generalised to medical education as a whole.

Research Questions

This review will attempt to evaluate CBS across the breadth of postgraduate medical education, encompassing training grades, as well as certified specialists. No limits will be placed based on specialty.

Scope of Simulation Training

Postgraduate training can be subdivided into three distinct sections, namely knowledge and understanding, technical skills, and non-technical skills (NOTS). This review will examine these aspects in turn. In evaluating technical skills, it is important to evaluate achieving competence, defined here as fewer critical or serious errors and technical proficiency, with time taken to complete a specified procedure serving as a surrogate marker. Furthermore, given that CBS affords the opportunity for the trainee to utilise it independently, this review also evaluated the impact of feedback on performance. Subgroup analysis between trainees and doctors in continuing medical education [CME] post-training was also carried out.

Questions

This review will attempt to define technology-enhanced high fidelity simulation in medical education, and assess the effectiveness of these simulations for medical education.

RQ1: What is the impact of CBS in postgraduate medical training?

RQ1.1: What is the impact of CBS on technical skills?

RQ1.1.1: What is the impact on competence?

RQ1.1.2: What is the impact on proficiency?

RQ1.2: What is the impact of CBS on NOTS?

RQ1.3: What is the impact of CBS on knowledge and understanding?

RQ1.4: How does mentoring and feedback affect CBS training?

Methods

The systematic review was carried out in a step-wise manner, with initial inclusion and exclusion criteria designed to capture relevant research articles, followed by an unstructured scoping search designed to elicit terms to be included in the systematic search terms, and finally applying the search terms through selected databases, chosen to capture relevant literature. Published and unpublished works were included to avoid any publication bias. Details of each step of the process is outlined below. For this systematic review, I will follow the format of the Preferred Reporting Items for Systematic reviews and Meta-analyses [PRISMA], as reported by Moher, Liberati, Tetzlaff, Altman, Group (1). This allows for easily accessible diagrammatic representation of the literature search, and explains the stages of data extraction and inclusion into the final analysis.

Inclusion and Exclusion Criteria

The criteria for inclusion into this review were devised to enable the capture of the breadth of computer based simulation in postgraduate medical education. Articles were eligible for inclusion if they included postgraduate doctors, either as the sole type of participants, or if they included doctors as a subset, where all the relevant information regarding performance and outcomes could be gleaned. The forms of simulation used were limited to computer-based simulation, defined as conducted either wholly through virtual reality, including virtual patients or involving the use of a combination of the above. Furthermore, studies were included only if they were focused on simulation for formative, rather than summative purposes. While the meta-analysis component of this review included only randomised-controlled trails [RCT], other study designs, including cohort, cross-over, and observational studies were included in the qualitative component of the review; additionally, no absolute requirement was placed for the inclusion of a comparator control arm within these studies. No geographical limitations were placed in the inclusion criteria. In order to maintain relevance of the study in the context of rapidly evolving technology, this review only includes studies reported after 2007 up to the present day.

Studies were excluded if they were descriptive, opinion pieces, editorials or review articles, as these were deemed not to contain additional relevant experimental information beyond what would be captured through the literature searches; however, the references and sources of these articles were hand-searched to ensure the inclusion of any additional sources. All studies that were aimed at evaluating a specific computer based simulation itself, rather than its educational value, such as feasibility and validation studies were also excluded. Finally, there was a necessity to limit the review to studies reported in English.

Scoping Search

In order to initially explore and define the concept of computer based simulation in the literature, a scoping search was carried out, to allow for the development of a comprehensive search strategy (21). Initial searches of the terms 'high fidelity simulation' and 'technology enhanced simulation' were conducted via PubMed and ERIC databases in order to identify search terms. The initial fifty results from each search on both databases were scanned to identify the terms.

Search Terms

Based on the scoping search, the search terms in Table 1 were elicited in order to construct the systematic literature search.

Databases and Journals

Table 2 provides a summary of the databases included in the literature search. Table 3 is a list of the journals where table of contents were hand searched for relevant publications.

Results

Literature Search Results

Combining the previously specified inclusion and exclusion criteria with the literature search

Table 1: Literature search terms derived from the initial scoping search

Technological		Simulation	Participants
Computer based	Technology-enhanced	Simulation	Limit to:
Computer-based	TEL	Simulate	Medical student
Virtual reality	Digital	Role play	Doctor
Technology enhanced	Immersive	Role-play	Medical education
			English language

Table 2: Databases included in the literature search

MEDLINE	ERIC	PsychINFO
CINHAL	British Education Index [BEI]	Educational Abstracts
PubMed	ProQuest Dissertations & Theses Global*	

* Additional limits to "higher education" and "healthcare education"

Table 3: Journals hand searched as part of the literature search

Medical Education	BMC Medical Education	Journal of Graduate Medical Education
Medical Teacher	Journal of Continuing Education in Health professions	Perspectives in Medical Education
The Clinical Teacher	Research on Medical Education Outcomes	Teaching and Learning in Medicine
Medical Education Research Network	Advances in Health Professional Education	BMJ Simulation and. Technology Enhanced Learning

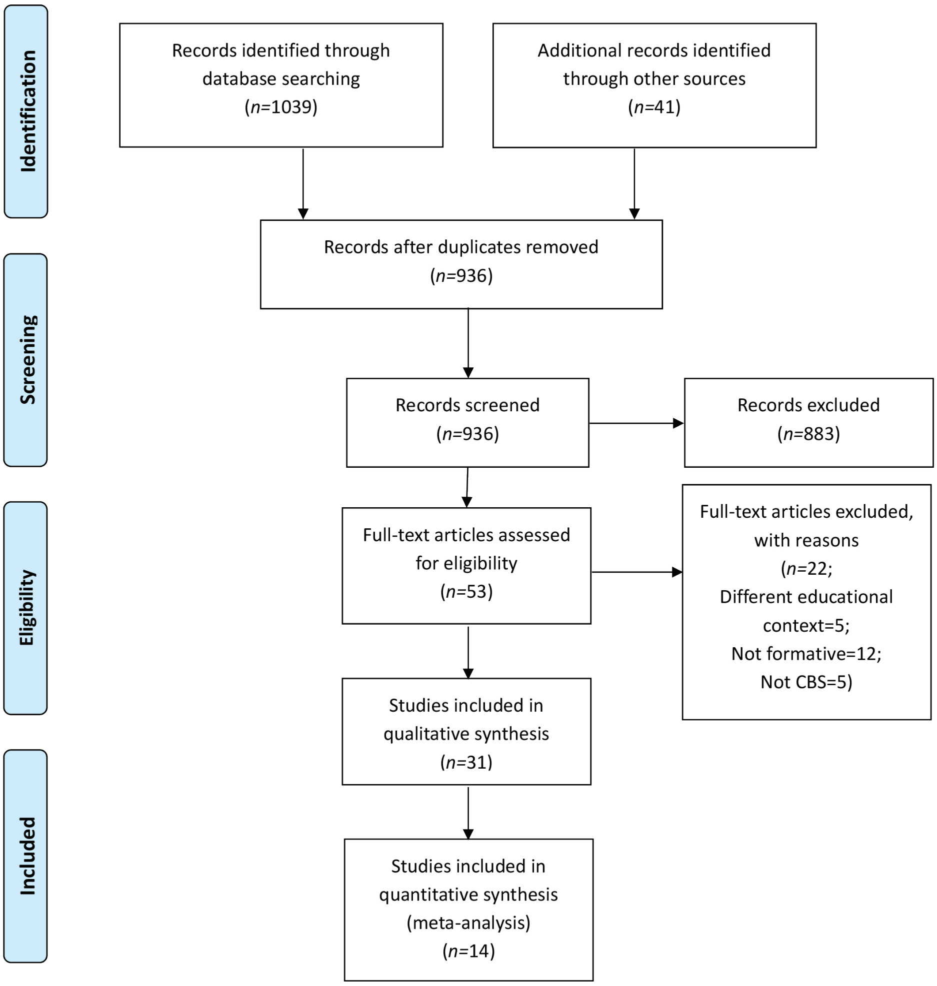

Figure 1: PRISMA flowchart of the search strategy on the use of CBS in postgraduate medical education. Adapted from Moher, Liberati, Tetzlaff, Altman, Group (1).

detailed in sections 5.3 and 5.4 led to the results outlined in Figure 1.

Data Extraction and Analysis

This stage of the review is split between the quantitative and qualitative phases. All included RCTs were individually inputted into *Review Manager 5.3* for statistical analysis, with primary data used when available (22). Data from each trial was inputted with regard to each of the domains of Non-Technical Skills, and Knowledge & Understanding. Statistical analysis, including the generation of the forest plots for each meta-analysis was carried out using the integrated *Review Manager* calculator.

For qualitative assessment, included articles were evaluated for appropriate selection and data sampling techniques, utilisation of appropriate data analysis methods, capacity to generalise the study outcomes to other contexts within medical education and clarity of the study reporting. This was carried out via detailed review for evidence of a justified sampling technique that is likely to be representative of the medical profession as a whole, the use of validated and accepted data extraction and analysis techniques, with attempted minimisation of bias at each stage, and finally, whether the study design and protocol is described in sufficient detail to allow for replication.

The combined results of both the quantitative and qualitative components of this review are subsequently drawn together to enable a conclusion to the impact of CBS at each examined domain, as well as to the magnitude of said impact. The results are described below in the same order as addressed in the research questions

Non-Technical Skills

Non-technical skills were assessed in two identified RCTs and two cohort studies [Appendix 10.5], with all studies set in the postgraduate training context. Non-technical skills examined in these studies were composed entirely of communication skills. Meta-analysis of the two RCTs, Figure 2, reveals an increased odds ratio of improved non-technical skills following CBS training, although this did not quite reach the level of statistical significance.

Qualitative analysis suggested that CBS has a positive impact on trainees' communication skills, with only one study that did not demonstrate a direct relationship between CB training and improved NOTS (23). Trainees reported increased confidence in their communication skills following CBS training (24, 25).

Knowledge and Understanding

Meta-analysis of four RCT is represented in Figure 3, with all RCTs set in the postgraduate training context. The results of the meta-analysis indicated a possible advantage to CBS training for knowledge and learning, but the result did not reach the level of statistical significance. Two further cohort studies were included in the qualitative analysis, with one study examining the CME context. It is interesting to note that two studies compared CBS with live simulation training demonstrated that CBS achieved equivalent outcomes with less training time, suggesting that it is a more effective means of training

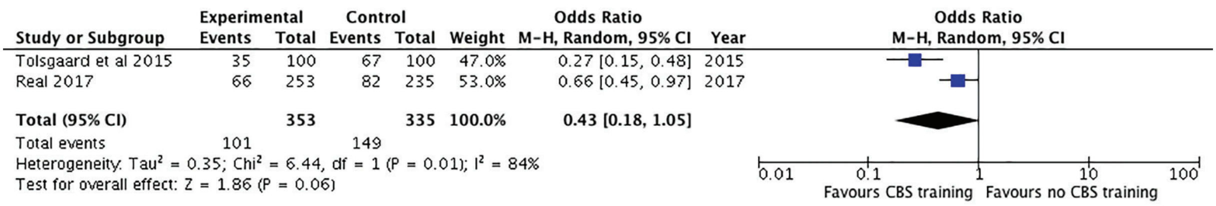

Figure 2: Box plot of the meta-analysis of randomised controlled trials on non-technical skills competence with CBS training. The results approached, but did not reach the level of statistical significance.

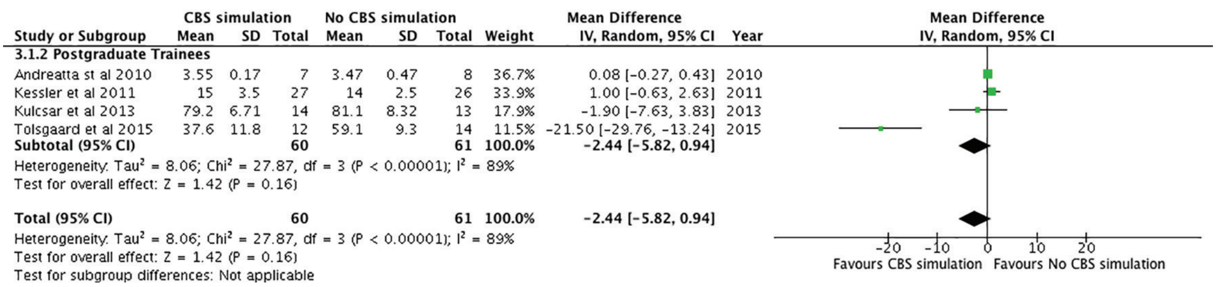

Figure 3: Box plot of the meta-analysis of randomised controlled trials on improving knowledge and understanding with CBS training. The results approached, but did not reach the level of statistical significance.

Discussion

This systematic review examined the use of computer based simulation across postgraduate medical education, in both the training and continuing medical education settings. The training setting was much more extensively studied compared to CME across all of the domains evaluated here.

The advantage of CBS over standard training methodologies, including live simulation, include the potential to allow repeated deliberate practice in a way that would not be possible otherwise. Several studies explored the use of CBS to allow doctors to explore possibilities that would not be feasible using other training methodologies for either pragmatic or ethical reasons, noting the advantage of affording this opportunity on the cognitive development of the trainees allowing the acquisition of 'expert' level skill (24, 26). A significant impact of CBS was on NOTS, as well as the knowledge domains was prominent in the meta-analysis.

This study is by its very nature limited by the available literature, which contained few randomised controlled trials. The rationale for limiting the meta-analysis to RCTs only was based on the premise of providing a high level of evidence in order to guide the use of CBS. While there is no minimum number of studies required for the statistical analysis involved in constructing a meta-analysis, there is a rationale for suggesting a working minimum of three trials, in order to given a meaningful result (27). Due to the small number of trials examining domains other than technical skill, this was not always possible, with a notable absence of RCTs in the assessment of the effect of mentorship entirely.

It is also important to acknowledge that a statistically significant degree of heterogeneity was evident in the meta-analyses for NOTS and knowledge and learning domains, suggesting that the results of these meta-analyses require careful interpretation. It is however worth noting that the results of the systematic review of non-RCT largely corroborated their results. Additionally, while it has been identified in this review that the greatest benefit of CBS is seen in those with least clinical experience, medical students, that group fell outside the scope of this review. It may be extrapolated that CBS may be most effective in that educational context, although this would ideally be explored in the future.

Conclusion

This review explored the use of computer based simulation across the three core domains applicable to each and every career within medical practice, namely non-technical skills and knowledge. The available data was also analysed based on the training level of the trainees.

Effective Computer Based Simulation

From the literature evaluated here, it is clear that while CBS can play a role in most aspects in of postgraduate medical training, in both the training grades and CME settings. There is relatively strong evidence to support the use of CBS in all domains of medical education examined here. The clinical value of non-technical skills in particular is being increasingly recognised, and we can conclude, based on the results presented here that CBS offers an effective method for training. Maximising the efficacy of CBS simulation requires both a well designed simulation, with clearly defined goals, supported by a mechanism for feedback and support development. Crucially, all studies examined here that compared CBS with other forms of simulation, either demonstrated a benefit to using CBS or at the very least confirmed that CBS is non-inferior to standard simulation. This suggests that using CBS may carry advantages over the standard simulation where high level performance is desired, but difficult to rehearse; this may be the primary driving force behind utilising CBS for technical skill training in medical education.

Limitations of Computer Based Simulation

It is important to appreciate the inherent limitations of CBS training, particularly given the high stakes involved in medical education. The first limit encountered is, in common with other forms of simulation training, the requirement for the suspension of disbelief to enable immersion and engagement with the simulation. To some extent this may be countered by utilising higher fidelity simulation, but it remains likely that simulation training is likely to still lack the pressure encountered in the clinical setting. Nevertheless, it is likely that a 'fidelity gap' will remain between simulation and clinical practice.

The initial set up of CBS requires a large investment of expertise, time and expense to develop, significant testing to validate, with an inherently limited shelf life before technological innovation necessitates overhaul and redesign of the simulation platform.

Future Research

There remain several questions regarding the use of CBS that need to be examined to enable a more thorough understanding of the subject, and how best it may be deployed. This is particularly pertinent given that CBS is resource intensive to develop and maintain. Undoubtedly, the key point that requires more rigorous and thorough evaluation is the degree of translation of skills and knowledge acquired in the CBS setting into the context of clinical practice. As this is the end goal of medical education and training, it is vital to retain this focus, and the subsequent impact on patient safety and quality of care provided.

With advancing technological developments, as well as set metrics identified in simulations, there is a potential possibility to develop an automated feedback 'built into' CBS, allowing a true independent learning experience, capable of adapting to more settings and situations.

Conflict of Interest: None Declared.

References

1. Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. Bmj. 2009;339:b2535. Doi: 10.1136/bmj.b2535
2. Kurrek MM, Devitt JH. The cost for construction and operation of a simulation centre. Can J Anaesth. 1997;44:1191-5. Doi: 10.1007/bf03013344
3. Kleinert R, Plum P, Heiermann N, Wahba R, Chang DH, Holscher AH, et al. Embedding a Virtual Patient simulator in an interactive surgical lecture. J Surg Educ. 2016;73:433-41. Doi: 10.1016/j.jsurg.2015.11.006
4. Kleinert R, Heiermann N, Wahba R, Chang DH, Holscher AH, Stippel DL. Design, realization, and first validation of an immersive web-based virtual patient simulator for training clinical decisions in surgery. J Surg Educ. 2015;72:1131-8. Doi: 10.1016/j.jsurg.2015.05.009
5. McManus IC, Richards P, Winder BC. Clinical experience of UK medical students. Lancet. 1998;351:802-3. Doi: 10.1016/s0140-6736(05)78929-7
6. Santen SA, Hemphill RR, McDonald MF, Jo CO. Patients' willingness to allow residents to learn to practice medical procedures. Acad Med. 2004;79:144-7. Doi: 10.1097/00001888-200402000-00010
7. Graber MA, Pierre J, Charlton M. Patient opinions and attitudes toward medical student procedures in the emergency department. Acad Emerg Med. 2003;10:1329-33. Doi: 10.1111/j.1553-2712.2003.tb00006.x
8. Graber MA, Wyatt C, Kasparek L, Xu

Y. Does simulator training for medical students change patient opinions and attitudes toward medical student procedures in the emergency department? Acad Emerg Med. 2005;12:635-9. Doi: 10.1197/j.aem.2005.01.009
9. Joseph N, Nelliyanil M, Jindal S, Utkarsha, Abraham AE, Alok Y, et al. Perception of simulation-based learning among medical students in South India. Ann Med Health Sci Res. 2015;5:247-52. Doi: 10.4103/2141-9248.160186
10. Grenvik A, Schaefer J. From Resusci-Anne to Sim-Man: the evolution of simulators in medicine. Crit Care Med. 2004;32:S56-7. Doi: 10.1097/00003246-200402001-00010
11. Takashina T, Shimizu M, Katayama H. A new cardiology patient simulator. Cardiology. 1997;88:408-13. Doi: 10.1159/000177369
12. Husken N, Schuppe O, Sismanidis E, Beier F. MicroSim - a microsurgical training simulator. Stud Health Technol Inform. 2013;184:205-9.
13. Stillman PL, Regan MB, Philbin M, Haley HL. Results of a survey on the use of standardized patients to teach and evaluate clinical skills. Acad Med. 1990;65:288-92. Doi: 10.1097/00001888-199005000-00002
14. Dacre J, Nicol M, Holroyd D, Ingram D. The development of a clinical skills centre. J R Coll Physicians Lond. 1996;30:318-24.
15. Jarvis P, Holford J, Griffin C. The theory & practice of learning. 2nd ed. London: Kogan Page; 2003.
16. Schon DA. Educating the reflective practitioner. 1st ed. San Francisco: Jossey-Bass; 1987.
17. Mezirow J. Transformative dimensions of adult learning. San Francisco: Jossey-Bass; 1991.
18. Engeström Y, Miettinen R, Punamäki-Gitai R-L. Perspectives on activity theory. Cambridge: Cambridge University Press; 1999.
19. Small SD, Wuerz RC, Simon R, Shapiro N, Conn A, Setnik G. Demonstration of high-fidelity simulation team training for emergency medicine. Acad Emerg Med. 1999;6:312-23. Doi: 10.1111/j.1553-2712.1999.tb00395.x
20. Aggarwal R, Undre S, Moorthy K, Vincent C, Darzi A. The simulated operating theatre: comprehensive training for surgical teams. Qual Saf Health Care. 2004;13 Suppl 1:i27-32. Doi: 10.1136/qhc.13.suppl_1.i27
21. Haig A, Dozier M. BEME Guide no 3: systematic searching for evidence in medical education--Part 1: Sources of information. Med Teach. 2003;25:352-63. Doi: 10.1080/0142159031000136815
22. Review Manager [Computer Program]. Version 5.3. Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration; 2014.
23. Cleland J, Ford R, Hamilton NM, Nabavian S, Walker K. Breaking bad news: an interactive web-based e-learning package. Clin Teach. 2007;4(2):94-9. Doi: 10.1111/j.1743-498x.2007.00157.x
24. Wilson JI. (dissertation). Evaluating the effectiveness of Virtual Patients to promote clinical reasoning. San Diego: Northcentral University; 2011.
25. Gorrindo T, Baer L, Sanders KM, Birnbaum RJ, Fromson JA, Sutton-Skinner KM, et al. Web-based simulation in psychiatry residency training: A pilot study. Acad Psychiatry. 2011;35:232-7. Doi: 10.1176/appi.ap.35.4.232
26. Balasundaram I, Aggarwal R, Darzi A. Short-phase training on a virtual reality simulator improves technical performance in tele-robotic surgery. Int J Med Robot. 2008;4:139-45. Doi: 10.1002/rcs.181
27. Borenstein M. When does it make sense to perform a meta-analysis? In: Borenstein M, Hedges LV, Higgins JPT, Rothstein HR. Introduction to meta-analysis. Hoboken, New Jersey: Wiley; 2009.

Appendices

Appendix 1: Sources included in quantitative analysis

Andreatta PB, Maslowski E, Petty S, Shim W, Marsh M, Hall T, et al. Virtual reality triage training provides a viable solution for disaster-preparedness. Acad Emerg Med. 2010;17:870-6. Doi: 10.1111/j.1553-2712.2010.00728.x

Bagai A, O'Brien S, Al Lawati H, Goyal P, Ball W, Grantcharov T, et al. Mentored simulation training improves procedural skills in cardiac catheterization: a randomized, controlled pilot study. Circ Cardiovasc Interv. 2012;5:672-9. Doi: 10.1161/circinterventions.112.970772

Cates CU, Lönn L, Gallagher AG. Prospective, randomised and blinded comparison of proficiency-based progression full-physics virtual reality simulator training versus invasive vascular experience for learning carotid artery angiography by very experienced operators. BMJ Simul Technol Enhanc Learn. 2016;2:1. Doi: 10.1136/bmjstel-2015-000090

Clarke DB, Kureshi N, Hong M, Sadeghi M, D'Arcy RC. Simulation-based training for burr hole surgery instrument recognition. BMC Med Educ. 2016;16:153. Doi: 10.1186/s12909-016-0669-2

Kessler DO, Arteaga G, Ching K, Haubner L, Kamdar G, Krantz A, et al. Interns' success with clinical procedures in infants after simulation training. Pediatrics. 2013;131:e811-20. Doi: 10.1542/peds.2012-0607

Kessler DO, Auerbach M, Pusic M, Tunik MG, Foltin JC. A randomized trial of simulation-based deliberate practice for infant lumbar puncture skills. Simul Healthc. 2011;6:197-203. Doi: 10.1097/SIH.0b013e318216bfc1

Kiely DJ, Gotlieb WH, Lau S, Zeng X, Samouelian V, Ramanakumar AV, et al. Virtual reality robotic surgery simulation curriculum to teach robotic suturing: A randomized controlled trial. J Robot Surg. 2015;9:179-86. Doi: 10.1007/s11701-015-0513-4

Kulcsar Z, O'Mahony E, Lovquist E, Aboulafia A, Sabova D, Ghori K, et al. Preliminary evaluation of a virtual reality-based simulator for learning spinal anesthesia. J Clin Anesth. 2013;25:98-105. Doi: 10.1016/j.jclinane.2012.06.015

Larsen CR, Soerensen JL, Grantcharov TP, Dalsgaard T, Schouenborg L, Ottosen C, et al. Effect of virtual reality training on laparoscopic surgery: Randomised controlled trial. BMJ. 2009;338:b1802. Doi: 10.1136/bmj.b1802

Real FJ, DeBlasio D, Beck AF, Ollberding NJ, Davis D, Cruse B, et al. A Virtual reality curriculum for pediatric residents decreases rates of influenza vaccine refusal. Acad Pediatr. 2017;17:431-5. Doi: 10.1016/j.acap.2017.01.010

Schout BM, Ananias HJ, Bemelmans BL, d'Ancona FC, Muijtjens AM, Dolmans VE, et al. Transfer of cysto-urethroscopy skills from a virtual-reality simulator to the operating room: A randomized controlled trial. BJU Int. 2010;106:226-31; discussion 31. Doi: 10.1111/j.1464-410X.2009.09049.x

Shirai Y, Yoshida T, Shiraishi R, Okamoto T, Nakamura H, Harada T, et al. Prospective randomized study on the use of a computer-based endoscopic simulator for training in esophagogastroduodenoscopy. J Gastroenterol Hepatol. 2008;23:1046-50. Doi: 10.1111/j.1440-1746.2008.05457.x

Tolsgaard MG, Ringsted C, Dreisler E, Norgaard LN, Petersen JH, Madsen ME, et al. Sustained effect of simulation-based ultrasound training on clinical performance: A randomized trial. Ultrasound Obstet Gynecol. 2015;46:312-8. Doi: 10.1002/uog.14780

Zhao YC, Kennedy G, Yukawa K, Pyman B, O'Leary S. Can virtual reality simulator be used as a training aid to improve cadaver temporal bone dissection? Results of a randomized blinded control trial. Laryngoscope. 2011;121:831-7. Doi: 10.1002/lary.21287

Appendix 2: Sources included in qualitative analysis

Andreatta PB, Maslowski E, Petty S, Shim W, Marsh M, Hall T, et al. Virtual reality triage training provides a viable solution for disaster-preparedness. Acad Emerg Med. 2010;17:870-6. Doi: 10.1111/j.1553-2712.2010.00728.x
Bagai A, O'Brien S, Al Lawati H, Goyal P, Ball W, Grantcharov T, et al. Mentored simulation training improves procedural skills in cardiac catheterization: a randomized, controlled pilot study. Circ Cardiovasc Interv. 2012;5:672-9. Doi: 10.1161/circinterventions.112.970772
Balasundaram I, Aggarwal R, Darzi A. Short-phase training on a virtual reality simulator improves technical performance in tele-robotic surgery. Int J Med Robot. 2008;4:139-45. Doi: 10.1002/rcs.181
Boyle E, O'Keeffe DA, Naughton PA, Hill AD, McDonnell CO, Moneley D. The importance of expert feedback during endovascular simulator training. J Vasc Surg. 2011;54:240-8.e1. Doi: 10.1016/j.jvs.2011.01.058
Burden C, Preshaw J, White P, Draycott TJ, Grant S, Fox R. Usability of virtual-reality simulation training in obstetric ultrasonography: A prospective cohort study. Ultrasound Obstet Gynecol. 2013;42:213-7. Doi: 10.1002/uog.12394
Casey DB, Stewart D, Vidovich MI. Diagnostic coronary angiography: Initial results of a simulation program. Cardiovasc Revasc Med. 2016;17:102-5. Doi: 10.1016/j.carrev.2015.12.010
Cates CU, Lönn L, Gallagher AG. Prospective, randomised and blinded comparison of proficiency-based progression full-physics virtual reality simulator training versus invasive vascular experience for learning carotid artery angiography by very experienced operators. BMJ Simul Technol Enhanc Learn. 2016;2:1. Doi: 10.1136/bmjstel-2015-000090
Clarke DB, Kureshi N, Hong M, Sadeghi M, D'Arcy RC. Simulation-based training for burr hole surgery instrument recognition. BMC Med Educ. 2016;16:153. Doi: 10.1186/s12909-016-0669-2
Cleland J, Ford R, Hamilton NM, Nabavian S, Walker K. Breaking bad news: An interactive web-based e-learning package. Clin Teach. 2007;4(2):94-9. Doi: 10.1111/j.1743-498x.2007.00157.x
Gorrindo T, Baer L, Sanders KM, Birnbaum RJ, Fromson JA, Sutton-Skinner KM, et al. Web-based simulation in psychiatry residency training: A pilot study. Acad Psychiatry. 2011;35:232-7. Doi: 10.1176/appi.ap.35.4.232
Kessler DO, Arteaga G, Ching K, Haubner L, Kamdar G, Krantz A, et al. Interns' success with clinical procedures in infants after simulation training. Pediatrics. 2013;131:e811-20. Doi: 10.1542/peds.2012-0607
Kessler DO, Auerbach M, Pusic M, Tunik MG, Foltin JC. A randomized trial of simulation-based deliberate practice for infant lumbar puncture skills. Simul Healthc. 2011;6:197-203. Doi: 10.1097/SIH.0b013e318216bfc1
Kiely DJ, Gotlieb WH, Lau S, Zeng X, Samouelian V, Ramanakumar AV, et al. Virtual reality robotic surgery simulation curriculum to teach robotic suturing: A randomized controlled trial. J Robot Surg. 2015;9:179-86. Doi: 10.1007/s11701-015-0513-4
Kruglikova I, Grantcharov TP, Drewes AM, Funch-Jensen P. The impact of constructive feedback on training in gastrointestinal endoscopy using high-fidelity Virtual-Reality simulation: A randomised controlled trial. Gut. 2010;59:181-5. Doi: 10.1136/gut.2009.191825
Kulcsar Z, O'Mahony E, Lovquist E, Aboulafia A, Sabova D, Ghori K, et al. Preliminary evaluation of a virtual reality-based simulator for learning spinal anesthesia. J Clin Anesth. 2013;25:98-105. Doi: 10.1016/j.jclinane.2012.06.015
Larsen CR, Soerensen JL, Grantcharov TP, Dalsgaard T, Schouenborg L, Ottosen C, et al. Effect of virtual reality training on laparoscopic surgery: randomised controlled trial. BMJ. 2009;338:b1802. Doi: 10.1136/bmj.b1802
Loukas C, Nikiteas N, Kanakis M, Georgiou E. Deconstructing laparoscopic competence in a virtual reality simulation environment. Surgery. 2011;149:750-60. Doi: 10.1016/j.surg.2010.11.012
McFadden P, Crim A. Comparison of the effectiveness of interactive didactic lecture versus online simulation-based CME Programs directed at improving the diagnostic capabilities of primary care practitioners. J Contin Educ Health Prof. 2016;36:32-7. Doi: 10.1097/ceh.0000000000000061
Patel A, Patel M, Lytle N, Toro JP, Medbery RL, Bluestein S, et al. Can we become better robot surgeons through simulator practice? Surg Endosc. 2014;28:847-53. Doi: 10.1007/s00464-013-3231-x
Pokroy R, Du E, Alzaga A, Khodadadeh S, Steen D, Bachynski B, et al. Impact of simulator training on resident cataract surgery. Graefes Arch Clin Exp Ophthalmol. 2013;251:777-81. Doi: 10.1007/s00417-012-2160-z
Preisner R, Jasti H, Elnicki M, Jeong K. Impact of web-based review on long-term retention of simulation-acquired knee and shoulder aspiration and injection skills. J Grad Med Educ. 2012;4:460-6. Doi: 10.4300/jgme-d-11-00239.1
Real FJ, DeBlasio D, Beck AF, Ollberding NJ, Davis D, Cruse B, et al. A virtual reality curriculum for pediatric residents decreases rates of influenza vaccine refusal. Acad Pediatr. 2017;17:431-5. Doi: 10.1016/j.

acap.2017.01.010
Schout BM, Ananias HJ, Bemelmans BL, d'Ancona FC, Muijtjens AM, Dolmans VE, et al. Transfer of cysto-urethroscopy skills from a virtual-reality simulator to the operating room: A randomized controlled trial. BJU Int. 2010;106:226-31; discussion 31. Doi: 10.1111/j.1464-410X.2009.09049.x
Shirai Y, Yoshida T, Shiraishi R, Okamoto T, Nakamura H, Harada T, et al. Prospective randomized study on the use of a computer-based endoscopic simulator for training in esophagogastroduodenoscopy. J Gastroenterol Hepatol. 2008;23:1046-50. Doi: 10.1111/j.1440-1746.2008.05457.x
Silvennoinen M, Helfenstein S, Ruoranen M, Saariluoma P. Learning basic surgical skills through simulator training. Instr Sci. 2012;40:769-83. Doi: 10.1007/s11251-012-9217-6
Thomsen AS, Bach-Holm D, Kjaerbo H, Hojgaard-Olsen K, Subhi Y, Saleh GM, et al. Operating room performance improves after proficiency-based virtual reality cataract surgery training. Ophthalmology. 2017;124:524-31. Doi: 10.1016/j.ophtha.2016.11.015
Tolsgaard MG, Ringsted C, Dreisler E, Norgaard LN, Petersen JH, Madsen ME, et al. Sustained effect of simulation-based ultrasound training on clinical performance: A randomized trial. Ultrasound Obstet Gynecol. 2015;46:312-8. Doi: 10.1002/uog.14780
Van Herzeele I, Aggarwal R, Neequaye S, Hamady M, Cleveland T, Darzi A, et al. Experienced endovascular interventionalists objectively improve their skills by attending carotid artery stent training courses. Eur J Vasc Endovasc Surg. 2008;35:541-50. Doi: 10.1016/j.ejvs.2007.12.017
Wilson JI. (dissertation). Evaluating the effectiveness of Virtual Patients to promote clinical reasoning. San Diego: Northcentral University; 2011.
Zhao YC, Kennedy G, Yukawa K, Pyman B, O'Leary S. Can virtual reality simulator be used as a training aid to improve cadaver temporal bone dissection? Results of a randomized blinded control trial. Laryngoscope. 2011;121:831-7. Doi: 10.1002/lary.21287
Zigman D, Young M, Chalk C. Using simulation to train junior psychiatry residents to work with agitated patients: A pilot study. Acad Psychiatry. 2013;37:38-41. Doi: 10.1176/appi.ap.11070129

Appendix 3: Sources included in analysis of non-technical skills

Real FJ, DeBlasio D, Beck AF, Ollberding NJ, Davis D, Cruse B, et al. A virtual reality curriculum for pediatric residents decreases rates of influenza vaccine refusal. Acad Pediatr. 2017;17:431-5. Doi: 10.1016/j.acap.2017.01.010
Tolsgaard MG, Ringsted C, Dreisler E, Norgaard LN, Petersen JH, Madsen ME, et al. Sustained effect of simulation-based ultrasound training on clinical performance: A randomized trial. Ultrasound Obstet Gynecol. 2015;46:312-8. Doi: 10.1002/uog.14780