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Arthroscopic simulation-The future of surgical training, A systematic review of the literature

--Manuscript Draft--

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Blinded Author Response

1. Line 3 has a statement; my question is whether the need for simulation training is due to worktime regulation and non-standardized "apprenticeship training model". Is the need for simulation truly based on these two factors? Are they the driving forces for simulation?

   Arthroscopic simulation has rapidly evolved over the last ten years with the introduction of higher fidelity simulation models such as virtual reality simulators which provide trainees an environment to practise skills without causing undue harm to patients.

2. line 112 How is this conclusion drawn in the fact that we have had the pressure of duty hours for some 20 years now. Not all programs are apprenticeship models, would they not benefit from simulation training. Is it not the explosion of technology that requires much higher order training to excel at highly technical and technology dependent operative procedures? Adaption of training to these types of skills is what you ID'd in subsequent statements. Your premise that simulation training has evolved since 2014-2019 and the need for the analysis should have the same corollary that surgical training programs have evolved also, and the plethora of cited research supports that supposition.

3. **There was some slight confusion as to what this was suggesting. Further clarification would be really helpful so I can make the necessary changes.**

   The "see one, do one, teach one" admonition of Halsted a turn of the century medical educator of the early twentieth century is almost spoken tongue in cheek these days. What is your data that says that this is the current widely accepted training mantra? Is this method real and borne out by the facts of this level I paper?

   The explosion of technology that has come with modern advances in bioengineering means that standard teaching models are in need of modification to adapt to the growing modernisation of health care

Reviewer 2:

My comments are listed below:

4.The authors have mentioned 27 papers were included in analysis. However, it is not really clear what kind of analysis was done and what were the outcomes.

The tools used to measure outcomes were also enumerated which were most commonly the ASSET[7] (Arthroscopic Surgical Skill Evaluation Tool) score, GRS[8] (Global Rating Scale) and time taken to complete task.

5. In table 2, two systems of categorization of the level of evidence were used (one used the

numeric system used by the Oxford CEBM as mentioned in the manuscript, and the other system is the Latin one used at the end of the table with no reference or clarification of what system used or why)

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6. Concerning the level of evidence of the study, I believe it should be II (not level 1 as they stated), keeping in mind the nature of heterogeneity of this study (as mentioned in the limitations) and including other studies which are not level 1 evidence such as the cohort studies.

Level of Evidence II

7. Only English articles were included, and this was kindly mentioned in the limitations section. However, no justification was made to exclude other articles. Please make sure to justify as it is considered a publication bias.

Any articles that didn't have comparative results either before or after arthroscopic simulation were excluded. Studies which did not include comparisons between novices and orthopaedic consultants were also excluded. The aim of this review is to evaluate the efficacy of simulation as a tool for arthroscopy training and simple observational data would not add to the scope of the review.

8. Concerning the quality assessment for the included studies in the SR, I believe it is better to include it as per the Cochrane guidelines for SRs.

The randomised controlled trials in this subset were subsequently assessed for their internal validity by the Cochrane collaboration's tool for assessing risk of bias[9]

9. It will be good to now the level of experience of surgeons who used these simulators

The design and methodology of the studies used were summarised which included the levels of experience of the participants involved: novice medical students, junior orthopaedic residents and senior orthopaedic consultants.

10. The number of selected papers is not clear. Line 81 in Methods you said, "In conclusion, 27 articles were deemed to be suitable for analysis (Fig. 1)". While table 1 shows 44 studies and you said, in line 93 "A total of 44 studies were included in the study (Table 2)".

In conclusion, 44 articles were deemed to be suitable for analysis (Fig. 1).

11. I need to know which of these simulators are in use and which one are still prototypes or confined to lab experimentation?

All the arthroscopic simulators covered in this study are currently being used in practice and consist of 3 types: physical, virtual reality (VR), or a mixture of the two[13].

12. What tasks these simulators could do such as grasping, clamping, or cutting. Do they demonstrate bleeding or leaking fluids?

One of the most common VR simulators[11] is the ArthroS VR simulator which is equipped with a camera, hook, cutter, grasper and a high-quality display to visualise the process.[50]

13. The outcome of your study should include a comparison between different regions (shoulders, hips, knees, ankles), as every region has different anatomy, different technical demands and skills for arthroscopy

The knee arthroscopy simulators demonstrated the highest proportion of construct validity (60%). The knee and shoulder combined simulators demonstrated transfer validity in 50% of studies. The highest proportion of content validity (11%) and face validity (33%) was found in hip arthroscopy simulators.

14. I could not see any technical details for these simulators. For example, I like to know some details on the haptic mechanism, visual and tactile properties, presence of force feedback, intuitive user interfaces, interactive animation, etc.

A key quality of virtual simulation is passive haptic tactile feedback which gives the user of the simulator an impression of where the surgical instruments are by providing resistance forces when they come into contact with physical objects. VR can also provide performance feedback on the level of pressure applied to the articular surface. Other more novel metrics include information on instrument loss, triangulation time and positioning of the joint in space.

15. In your conclusion, there was no statements on different types of simulators such as VR or low fidelity bench-top models. Also, the conclusion is mostly general and not specific or completely based on your results.

First, the evidence validating simulation in arthroscopic training is growing as 95% of all studies included showed a significant improvement in arthroscopic performance. Efficiency is also improved with the use of simulator training resulting in less time taken to complete tasks, fewer errors and improved triangulation. The studies have demonstrated increased construct and transfer validity in particular. Second, a large variety of simulator models and tasks are being validated for training purposes. The promise of lower fidelity benchtop models bring hope that simulation can become mainstream in their use in training programmes due to their high levels of efficacy in acquiring psychomotor skills and their relatively low cost in comparison to more sophisticated VR technology. Third, based on evidence of the different skills acquired from each modality, a standardized training framework is required to implement arthroscopic simulation.

16. Minor points: In line 142, it was mentioned that there is 2 simulators that cost 50 $. It is not clear which two simulators specifically.

Consequently, we are now seeing the development and validation of increasingly simplistic and new arthroscopic simulators, with this review highlighting 2 simulators, costing less than $50: **novel dry arthroscopic training CBAT benchtop model and the grapefruit training model (GTM)** [31,54].

17. Starting from line 120, I believe there is a problem with the "," and all the commas are replaced with the number "5".

Fourty-two studies (64.6%) demonstrated construct validity[19,20,27-30,32-40,43-47,49,50,61-73, 79, 81, 83, 84, 85, 94, 95], 24 (36.9%) demonstrated transfer validity[26,31,41,42,48,51,61,62,67,68,72-78, 82, 84, 88, 89, 90, 91, 92], 14 (21.5%) showed face validity [29, 30, 37, 38, 40, 44, 45, 61, 79, 80 83, 85, 87, 93], and 5 (7.6%) showed content validity[44, 62, 79, 86, 87]. Twenty one (32.3%) of these studies utilized solely virtual reality (VR)-based technology [32,33,35,36,41,42,48-50,79,80,83,85,86,87,88,90- 95], whereas 19 (29.2%) evaluated solely benchtop simulators [19,20,26-31,34,37,39,43-47,84,89,91]. Moreover, 1 study (2%) incorporated the two modalities into a new hybrid simulator[38]. 1 study (2%) used an animal (porcine) model[40].

18. I am wondering if the study had a registered protocol in PROSPERO, Cochrane, or other SR databases?

We did not have a registered protocol for this study

19. Line 104 & 105: 1 study (1.5%) used an animal (porcine) cadaveric model. Animal is different from cadaveric. The latter usually refers to human cadaver and not animal cadavers. Also, the % is 2 rather than 1.5

Moreover, 1 study (2%) incorporated the two modalities into a new hybrid simulator[38]

20. line 192. What is "increasingly noticing", is this not just some form of observer bias/confirmation bias that has little place in conclusions from this paper.

Thirdly, research has shown that skill acquisition varies using different modalities

21. In table, please insert a new column at far-left side to list the serial number of all studies from 1 to 44. To get more space, you can reduce the size of level of evidence column

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Reviewer 3:

Congratulations to the authors of this manuscript. I found it to be an interesting read on the current state of surgical simulation for residents in training. The methodology used for the review was sound. The discussion was also quite thorough.

22. For orthopedic residency training, there seems to be significant research focus on arthroscopic skills for surgical simulation. There isn't the same amount of published literature for surgical simulation in joint replacement, hand, foot/ankle, trauma, or pediatric surgery. The authors indicated that this is because arthroscopy requires a different skills set: manual dexterity, triangulation, and depth perception. I'm not sure that the different skills sets is the reason for orthopedic surgical simulators being focused primarily on arthroscopy. But, then the authors went on to say that "...there is a steep learning curve associated with it," implying that the learning curve for arthroscopy is different than the learning curve for other orthopedic procedures. Do the authors have any evidence to support that statement? I'm a sports medicine arthroscopist, and have trained many, many residents -- I don't believe that the learning curve for arthroscopy is any different than the other subspecialties.

Arthroscopy, like all procedures in surgery, demands manual dexterity and more specifically the qualities of triangulation and depth perception[17,18]. All the arthroscopic simulators covered in this study are currently being used in practice and consist of 3 types: physical, virtual reality (VR), or a mixture of the two

23. Introduction, line 35: "The use of surgical simulation offers trainees a safe space and standardized environment." While I agree that surgical simulators offer trainees a standardized environment, I don't think that they're a safer environment (for the trainee) than

the operating room. Also, the term "safe space" is somewhat of a politically charged term in the United States for institutions of higher learning. Probably should avoid using it in this context.

The use of simulation offers trainees a standardized environment[12,13] in which they can efficiently acquire skills outside the operating theatre[10]under less pressure.

Unblinded Title Page

Arthroscopic simulation-The future of surgical training: A systematic review

Investigation performed at the Royal Free Hospital in affiliation with University College London Medical School, London, United Kingdom

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Abstract

Background

Arthroscopic simulation has rapidly evolved over the last ten years with the introduction of higher fidelity simulation models such as virtual reality simulators which provide trainees an environment to practise skills without causing undue harm to patients. Simulation training also offers a uniform approach to learn surgical skills with immediate feedback. The aim of this article is to review the recent research investigating the use of arthroscopic simulators in training and the teaching of surgical skills.

Methods

A systematic review of the Embase, Medline and Cochrane Library databases for articles published before December 2019 was conducted. The search terms included arthroscopy or arthroscopic, in combination with simulation or simulator with the filter English language only applied.

Results

We identified a total of 44 relevant studies involving bench top or virtually simulated ankle, knee, shoulder and hip arthroscopy environments. The majority of these studies demonstrated construct and transfer validity, meanwhile only a few studies demonstrated content and face validity.

Conclusions

From our review, we can see that there is a considerable evidence base regarding the use of arthroscopic simulators for training purposes. Further work should focus on the development

of a more uniform simulator training course that can be compared with current intraoperative training in large-scale tertiary centre trials with long-term follow-up.

Introduction

The explosion of technology that has come with modern advances in bioengineering means that standard teaching models are in need of modification to adapt to the growing modernisation of medicine[1]. The traditional teaching model relied heavily on operating room (OR) exposure, which is more costly, prolongs OR times and can increase the risk of harm to the patient[2-4]. Furthermore, the learning opportunities can be varied depending on the instructor which means there is less consistency in the techniques taught, how trainees are assessed, and the level of feedback offered.[5]

A possible solution is to incorporate arthroscopic simulators into traditional training models. Arthroscopic simulators provide the opportunity to practise surgical skills outside the OR environment under less pressure.[12,13] An alternative approach has been created through simulation to facilitate the translation of technical skills into better outcomes and shorter OR times.[14] In the last two decades, increasing evidence in the support of simulation has been reciprocated by health care professionals[15] and patients[16] as well. The leaders of medical education in both the UK and USA are recommending the use of simulation in training programmes.[1,6]

Arthroscopy, like all procedures in surgery, demands manual dexterity and more specifically the qualities of triangulation and depth perception[17,18]. All the arthroscopic simulators covered in this study are currently being used in practice and consist of three models: physical models, virtual reality models (VR) or a VR-physical model.[13] Physical models can be from human cadavers, porcine or artificial “benchtop” simulators. Certain models can be analysed by a characteristic called fidelity (a measure of how closely the simulators resemble real life scenarios)[20] and the higher the fidelity, the more realistic the experience as with cadaveric specimens. **One of the most common VR simulators[11] is the ArthroS VR simulator which is equipped with a camera, hook, cutter, grasper and a high-quality display to visualise the process.[50] A key quality of virtual simulation is passive haptic tactile feedback which gives the user of the simulator an impression of where the surgical instruments are by providing resistance forces when they come into contact with physical objects. VR can also provide performance feedback on the level of pressure applied to the articular surface. Other more novel metrics include information on instrument loss, triangulation time and positioning of the joint in space.**

Simulators are evaluated by the different types of validity attained through a series of sequential steps (Table 1). Concurrent validity is a measure of the degree to which the performance of the simulator matches up to the reference standard in a particular field which is potentially the first priority when it comes to evaluating efficacy. One of the challenges that arise with simulators is that there is no established consensus for a “gold standard” which is why transfer validity is the most crucial factor in judging the efficacy of arthroscopic simulators[13].

Numerous articles highlighted advances in simulation and its role in training orthopaedic residents.[21-23] These articles were written in the pre-2014 era, which is why the table is updated with types of validity found in articles published more recently up until December 2019. A review of the data published prior to 2014 and articles published after that date until December 2019 can be seen in (Table 1). However, because simulation is a modern innovation, there has increasingly been more findings and discoveries in the field, hence it was felt that an updated systematic review of the literature was required.

The goal of this review was to collate all the recent studies on arthroscopic simulator models and incorporate those findings with previously published work to produce an updated review of the role of arthroscopic simulation in the future of surgical training.

Search Method

The search strategy for this article consisted of systematically reviewing the Medline, Embase and Cochrane databases for articles with the terms arthroscopy or arthroscopic in combination with simulation or simulator. Only English language articles published before December 2019 were selected for review.

Selection Criteria

Articles evaluating current or new arthroscopic simulators for their role in surgical skills training were selected. Only English articles were included and any review papers, case studies and editorial commentaries were excluded. Articles that were referenced from these articles were also filtered using the criteria specified for the primary data collection and subsequently included for analysis in the systematic review. PRISMA (Preferred Reporting Items for Systematic Reviews) guidelines[24] was used to remove duplicate articles and the remainder of the articles were analysed for relevance. **Any articles that didn't have comparative results either before or after arthroscopic simulation were excluded. Studies which did not include comparisons between novices and orthopaedic consultants were also excluded. The aim of this review is to evaluate the efficacy of simulation as a tool for arthroscopy training and simple observational data would not add to the scope of the review.** In conclusion, **44** studies were included as the final data set. (Fig. 1). **The randomised controlled trials in this subset were subsequently assessed**

for their internal validity by the Cochrane collaboration's tool for assessing risk of bias[9].

Data Analysis

We used several criteria to analyse the articles. First, we analysed the outcomes for types of validity demonstrated. The four types of validity are summarised in Table 1 which also enumerates the differing proportions of validity types in the studies filtered from our database search. The design and methodology of the studies used were summarised **which included the levels of experience of the participants involved: novice medical students, junior orthopaedic residents and senior orthopaedic consultants. The tools used to measure outcomes were also enumerated which were most commonly the ASSET[7] (Arthroscopic Surgical Skill Evaluation Tool) score, GRS[8] (Global Rating Scale) and time taken to complete task**. Each study was ranked according to the level of evidence as per the Oxford Centre for Evidence-Based Medicine: Levels of Evidence guidelines.[25] The highest level of evidence is awarded to systematic reviews with homogeneity of level 1 evidence studies such as Randomised Control Trials.

No funding was required to support this systematic review

Results

A total of 44 studies were included in the investigation (Table 2). Of the 44 studies, one analysed ankle arthroscopic simulators[26], eight analysed simulated box arthroscopy[19,20,27-32], six analysed hip arthroscopic simulators[33,34,84,85,87,93], six analysed knee arthroscopic simulators[35-40,79-83,89,90,92,95] and seven analysed shoulder arthroscopic simulators[41-47,80,90]. Four papers[48-50,90] analysed shoulder and knee arthroscopic simulators in combination.

The knee arthroscopy simulators demonstrated the highest proportion of construct validity (60%). The knee and shoulder combined simulators demonstrated transfer validity in 50% of studies. The highest proportion of content validity (11%) and face validity (33%) was found in hip arthroscopy simulators.

Forty-two studies (64.6%) assessed construct validity[19,20,27-30,32-40,43-47,49,50,61-73, 79, 81, 83, 84, 85, 94, 95], 24 (36.9%) assessed transfer validity[26,31,41,42,48,51,61,62,67,68,72-78, 82, 84, 88, 89, 90, 91, 92], 14 (21.5%) showed face validity [29, 30, 37, 38, 40, 44, 45, 61, 79, 80 83, 85, 87, 93], and 5 (7.6%) showed content validity[44, 62, 79, 86, 87]. Twenty one (32.3%) papers only analysed VR arthroscopic simulators [32,33,35,36,41,42,48-50,79,80,83,85,86,87,88,90- 95], whereas 19 (29.2%) evaluated solely benchtop simulators [19,20,26-31,34,37,39,43-47,84,89,91]. Moreover, 1 study (**2**%) incorporated the two models in the new combination VR-benchtop model[38]. One article (2%) created a **porcine** prototype[40]**.**

All of the studies included were between 1 and 4 in terms of evidence level [19,20,26-50,79-95], with 26 studies (59%) in the higher tiers of evidence (level 1 and 2)[20,26,30,31,35,38,39,41,42,44,48,50]. The results from these studies were amalgamated with the papers collated prior to 2014 allowing us to provide a holistic perspective of the development of arthroscopy simulators in the last two decades (Table 1).

Discussion

Simulators are becoming increasingly more lifelike and correspond closer the operating environment and the majority of studies demonstrate construct validity which is a measure of the extent to which simulators can differentiate experienced users with novices based on the results. There has been increasing evidence in support of the improved transfer validity of arthroscopy simulators[26,31,41,42,48] and the highest rise has been seen in intraoperative performance[41,42]. Initially, only one study [51]was shown to have demonstrated an improvement in intraoperative assessment when the arthroscopic simulator cohort was assessed against the control cohort. From the findings of this report, we managed to identify a further two articles showing the same change in performance upon using arthroscopic simulation.[41,42] One study[42] showed that the intervention completed tasks in less time and were more safe than the cohort that did not receive the arthroscopic simulator training. Another study[41]also revealed that the intervention cohort were faster and had higher proficiency when completing tasks compared to the group receiving regular training. The aforementioned articles used a recognised tool called the Arthroscopic Surgical Skill Evaluation Tool (ASSET)[52]. A further three papers showed increased transfer validity on simulation in models from human cadavers[26,31,48]. This could be considered the final stage before commencing intraoperative assessment. However, there is still uncertainty about how transferrable skills developed from cadaveric models are to the intraoperative environment[13].

The number of studies using virtual reality simulators post 2014 (52.7%) was compared with the pre-2014 period (69.6%), demonstrating a 16.9% decrease. This can be explained by the rise in the use of low-fidelity physical models; hence, more focus has been placed on their development in articles published after 2014. This is could be due to the underreporting of the price of virtual reality simulators in papers published previously but most probably because they are much cheaper to maintain and are extremely user friendly in comparison to more complex virtual reality models. As a result of this, an increasing number of more simple, user friendly arthroscopy models are being manufactured that cost less than $50: **novel dry arthroscopic training CBAT benchtop model and the grapefruit training model (GTM)** [31,54].

Even though there has been increasing evidence suggesting that arthroscopic simulators are becoming more widespread in their use in training, there is still a lack of clarity on how to integrate the different modes of simulation in teaching programmes for them to provide the most benefit[35]. There is evidence on both sides suggesting the efficacy of virtual reality and bench-top simulators in improving intraoperative performance but there are varying opinions as to which model leads to the greatest improvement in acquiring skills[55].

Recently, growing research into physical benchtop simulators has shown that groups using these models demonstrated better acquisition of skills since they had improved outcomes on virtual reality simulators compared to the virtual reality simulator only group[56]. This trend was noticed in not only orthopaedic simulation but in other fields too[57,58] which has resulted in the creation of the PBP framework (proficiency-based progression). This method involves first using physical benchtop simulators to master the fundamental competencies required and then progressing to virtual simulation and this has model has been applied in numerous training programmes[59]. It has proved to be more efficacious than standard training programmes that are not graduated in their progression[44].

Diagnostic procedures have increasingly been used to evaluate the validity of simulation training[46] because they do not cause significant disruption to the tissues in cadaveric models and they can easily be evaluated against reference standards. More varied and complex tasks can be evaluated though simulation such as knot-tying[30], repairing rotator cuff injuries, labral tears[46], 3-suture-anchor of Bankart lesions[44,47] and ACL repair[39]. Many of these procedures have been performed using dry lab models. However, in **dry lab models, there are no fluids such as blood or saline which is complex to simulate, a limitation in mimicking real life situations**. In future, dry models need to be developed to have increased face and transfer validity to make them more translatable to the intraoperative environment.

Limitations

There are some limitations that can be found in this systematic review. Firstly, English language only articles were selected for review, which represents a possible publication bias. Secondly, although the data collected represents a huge proportion of the research available, one cannot assume it to be entirely representative of everything that has been published on arthroscopic simulation. Perhaps this is because of the selection criteria that was used by this review and previous studies included. Also, due to the heterogeneity of the studies included in this review, it presents a challenge for the generalizability of the findings. A streamlined arthroscopic simulation curriculum has not been established using evidenced based protocols as there is much variation in the types of simulators available and duration of training courses[31,41,48]. Prospectively, a standardized training programme needs to be established especially because recent evidence has highlighted that skills acquisition from simulators decreases with time[30,41]. Many of the studies included tend to compare experienced orthopaedic consultants with beginners from medical school who are at polar opposites of the spectrum which reduces the reliability of the outcomes when assessing the construct validity of simulators[60]. Having a larger number of participants would also help to confirm transfer validity of simulators since it increases the chances of proving a significant difference between the control and intervention group [29,33,41,48]

Conclusion

A rigorous analysis of the data yielded numerous findings. Firstly, **approximately 95% of all studies included showed an improvement in arthroscopic performance. Efficiency is also improved with the use of simulator training resulting in less time taken to complete tasks, fewer errors and improved triangulation. The studies have demonstrated increased construct and transfer validity in particular. Secondly, many arthroscopic simulators of varying types and modalities are being evaluated for training purposes. The promise of lower fidelity benchtop models bring hope that simulation can become mainstream in their use in training programmes due to their high levels of efficacy in acquiring psychomotor skills and their relatively low cost in comparison to more sophisticated VR technology.** Thirdly, research has shown that skill acquisition varies using different modalities, therefore, **a standardized training framework is required** to implement arthroscopic simulators in training programmes. Further research needs to be aimed at reducing discrepancies in simulation training to create a streamlined curriculum which can allow for cross comparisons with traditional training models in tertiary centre trials with long term follow up.

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Table 1

Summary of the Different Types of Validity Demonstrated by All Articles Pre-2019

Table 1

Summary of the Different Types of Validity Demonstrated by All Articles Pre-2019			
	Definitions	**Number of Studies**	**Reference**
Face Validity	The degree to which the simulator reflects reality intraoperatively	14	29, 30, 37, 38, 40, 44, 45, 61, 79, 80 83, 85, 87, 93
Content Validity	Assesses whether the metric used to measure performance by the simulator is accurately measuring the criterion or domain required.	5	44, 62, 79, 86, 87
Construct Validity	Capability of the simulator to differentiate between varying levels of expertise	42	19,20,27-30,32-40,43-47,49,50,61-73, 79, 81, 83, 84, 85, 94, 95
Transfer Validity	A measurement of how effective the simulator is in carrying out its purpose (i.e. whether the simulator is able to produce a learning effect and improve performance with continued use)	24	26,31,41,42,48,51,61,62,67,68,72-78, 82, 84, 88, 89, 90, 91, 92

Table 2

Summary of All the Articles that Fulfilled the Inclusion Criteria

Table 2

	Study	Model	Validity Demonstrated	No. and Type of Participants	Method	Measured Outcomes	Evidence Level	Salient Results
1	Martin et al. Article no.26 Date published: 2015	Ankle Sawbones arthroscopic training benchtop model (by Pacific Research Laboratories) (low fidelity)	Transfer validity	**Number of participants:** **29 orthopaedic surgical trainees**	Simulation group (n 5 14) received 4 simulation training sessions, whereas the control group (n 5 15) didn't receive any simulation training. Pre- and post-training cadaveric diagnostic arthroscopies were performed.	Total ARTHROSCOPIC SURGERY SKILL EVALUATION TOOL score, individual ASSET domain scores, 15- point diagnostic arthroscopy anatomic checklist, time taken to complete task	1	The simulation group was significantly better than the control group in all 4 measured domains
2	Coughlin et al. Article no.20 Date published: 2015	Novel dry arthroscopic training benchtop model (low fidelity)	Construct validity	**Number of participants:** **49 medical students, orthopaedic resi- dents, and arthro- scopic surgeons**	Novice (n 5 15), junior orthopaedic resident (n 5 12), senior orthopaedic resident (n 5 16), and consultant (n 5 6) groups each performed 6 basic arthroscopic tasks: (1) probing, (2) grasping (3) tissue resection (4) shaving (5) tissue liberation and suture passing, and (6) tissue approximation and arthroscopic knot-tying	Global Rating Scale (timing score minus penalty score)	2	Mean Global Rating Scale improved significantly between groups with successively increasing level of expertise
3	Bouaicha et al. Article no.27 Date published: 2017	ArthroBox dry arthroscopic training benchtop model (Arthrex) (low fidelity)	Construct validity	**Number of participants:** **46 orthopaedic surgeons**	Novice (n 5 12), intermediate skill level (n 5 12), and expert skill level (n 5 22) groups performed a single arthroscopic dexterity task	Time taken to complete task, portal replacements of the camera and probe	3	Novices performed the task significantly slower than the intermediate skill level and expert level groups. Portal changes were significantly more common in novice and intermediates groups than in expert group

4	Lopez at al. Article no.28 Date published: 2016	Benchtop model dry arthroscopic training (low fidelity)	Construct validity	**Number of participants:** **75 medical students and junior and senior orthopaedic residents and fellows**	Medical student (n 5 20), junior resident (n 5 27), senior resident (n 5 19), and surgical fellow (n 5 9) groups performed a number of tasks e.g. testing peg transfer, circle drawing, and suture-retrieval skills	Time taken to complete task, score for object transfer from dominant to nondominant hand, score for suture retrieval	3	Medical students and junior residents attained significantly lower scores on object transfer at both 60° and 180°. These 2 groups took significantly longer to complete the tasks compared to the 2 more senior groups
5	Goyal et al. Article no.19 Date published: 2016	Sawbones “FAST” dry arthroscopic training benchtop model (Pacific Research Lab- oratories) (low fidelity)	Construct validity	**Number of participants:** **20 orthopaedic surgeons (trainees, fellows, and arthroscopic and non-arthroscopic specialists)**	Novice (n 5 9), beginner level (n 5 4), intermediate level (n 5 3), and advanced level (n 5 4) groups per- formed a number of tasks including maze navigation, number probing, object handling, and partial meniscectomy (transparent and opaque domes)	Time taken to complete task, no. of errors	3	less experienced participants were significantly slower in relation to increased experience in every task (opaque dome), no. of errors also decreased with advancing experience
6	Braman et al. Article no.29 Date published: 2015	Dry arthroscopic training benchtop model (low fidelity)	Face and construct validity	**Number of participants:** **16 medical stu-dents (novices) and arthroscopic sur- geons (experts)**	Novice (n 5 8) and expert (n 5 8) groups performed 2 tasks: the first was based on triangulation and the second on object manipulation	Time taken to complete task, no. of errors, no. of trials to steady state (i.e., perform 2 trials within 10% of each other for time and errors)	3	The expert group performed both tasks significantly quicker and with significantly less errors; many more experts were able to demonstrate steady state
7	Wong et al. Article no.30 Date published: 2015	Novel dry benchtop model, arthroscopy knot trainer (AKT) (low fidelity)	Construct and face validity	**Number of participants:** **37 orthopaedic residents and surgeons**	Junior orthopaedic resident (n 5 21), senior orthopaedic resident (n 5 11), and expert orthopaedic surgeon (n 5 5) groups performed 2 knot-tying exercises. Repeated after 6 months	Time taken to tie first knot; total number of knots tied within ten minutes	2	Non-experienced residents took a significantly longer period of time to tie knots than experienced residents
8	Sandberget al. Article no.31 Date published: 2017	Sawbones (by Pacific Research Laboratories) and novel dry arthroscopic training CBAT benchtop models (low fidelity)	Transfer validity	**Number of participants:** **24 medical students assigned to CBAT training, AKAT training, or control group**	CBAT (n 5 8) and AKAT (n 5 8) groups received 4 hours of training on their respective models. Control group (n 5 8) received no training. All the groups were then assessed during diagnostic	Basic Arthroscopic Knee Skill Scoring System	2	There were significantly more subjects in CBAT and AKAT groups (75% each) succeeded in reaching the minimum proficiency in the allotted time compared with the control group (25%)

					knee arthroscopy on cadaveric specimen			
9	Rose and Pedowitz. Article no.32 Date published: 2015	ArthroVision Virtual reality box simulator (Swemac,Linkopin, Sweden)(low fidelity)	Construct validity	**Number of participants:** **30 medical students, orthopaedic trainees, fellows, and staff surgeons**	Novice (n 5 10), intermediate level (n 5 10), and expert level (n 5 10) groups performed all 3 tasks based on image centering, triangulation, and coordination in separate simulators. All performed with dominant hand then repeated with the nondominant hand	Time taken to complete task, probe path length	3	In the coordination task, both intermediate and expert groups were on average significantly faster than the novice group when using both dominant and nondominant hands. In the triangulation task, there was a significant difference in times taken for completion in nondominant hand across all groups
10	Khanduja et al. Article no.33 Date published: 2017	Arthro Mentor Virtual reality trainer (Simbionix) (high fidelity)	Construct validity	**Number of participants:** **19 orthopaedic trainees and experienced surgeons**	Novice (n 5 10) and expert level (n 5 9) groups each performed one basic visualization task followed by another basic probe task	Time taken to complete task, no. of soft tissue and bone collisions, distance travelled by instruments	3	The expert group performed significantly better than the novice groups in all metrics on visualization task and were significantly quicker on the probe task
11	Phillips et al. Article no.34 Date published: 2017	Sawbones dry arthroscopic training benchtop model (Arthrex) (low fidelity)	Construct validity	**Number of participants:** **47 orthopaedic** **trainees, fellows,** **and staff surgeons**	Junior orthopaedic resident (n 5 27), senior orthopaedic resident (n 5 10), fellow (n 5 5), and surgical staff (n 5 5) groups performed a hip arthroscopic acetabulum labral repair	Total ARTHROSCOPIC SURGERY SKILL EVALUATION TOOL score, overall GLOBAL RATING SCALE score, time taken to complete task, task-specific checklist	3	Total ARTHROSCOPIC SURGERY SKILL EVALUATION TOOL and overall GRS scores significantly different between junior and senior residents, between senior residents and fellows, and between fellows and staff surgeons; staff surgeons significantly faster than both junior and senior residents
12	Jacobsenet al. Article no.35 Date published: 2015	Arthro Mentor Vitrual reality trainer (Simbionix) (high fidelity)	Construct validity	**Number of participants:** **26 orthopaedic trainees (novices) and experienced orthopaedic surgeons (experts)**	Novice (n 5 13) and expert level (n 5 13) groups completed five different knee arthroscopy procedures	Time taken to complete task, camera distance and roughness, probe distance and roughness, combined Z-scores	2	Combined Z-scores across the 2 groups were significantly different, time taken for completion of the task was also significantly different between the 2 groups across all procedures
13	Stunt et al. Article no.36	VirtaMed ArthroS Vitrual reality trainer (VirtaMed) (high fidelity)	Construct validity	**Number of participants:** **27 orthopaedic surgeons with varying**	Beginner level (n 5 9), intermediate level (n 5 9), and expert level (n 5 9) groups performed 5 trials of a timed navigation task and 3 diverse	Time taken to complete task	3	Novice group was significantly slower than the orthopaedic surgeons on all 5 trials of the navigation task

	Date published: 2015			**arthroscopic experience**	tasks for objective feedback			
14	Stunt et al. Article no.37 Date published: 2016	Passport V2 dry arthroscopic training benchtop simulator (MediShield BV) (high fidelity)	Face and Construct validity	**Number of participants:** **31 orthopaedic surgeons with varying arthroscopic experience**	Beginner level (n 5 15), intermediate level (n 5 8), and expert level (n 5 8) groups performed 5 trials of a timed navigation task and 2 diverse tasks for objective feedback	Time taken to complete task	3	Novice group was significantly slower than the orthopaedic surgeons on all 5 trials of the navigation task, beginner group was significantly slower than the intermediate group on trials 2 and 4 (of 5)
15	Fucenteseet al. Article no.38 Date published: 2015	Novel Virtual Reality - benchtop hybrid simulator (ETH Zurich & VirtaMed) (high fidelity)	Face and construct validity	**Number of participants:** **68 orthopaedic surgeons with varying arthroscopic experience**	Novice (n 5 33), intermediate level (n 5 19), and expert level (n 5 16) groups performed diagnostic knee arthroscopy followed by an object removal task. A separate meniscal resection task was also performed	Time taken to complete task, camera path length	2	The orthopaedic surgeons had significantly faster total operation and removal times as well as significantly less distance travelled by the camera
16	Dwyer et al. Article no.39 Date published: 2015	Sawbones dry arthroscopic training benchtop model (Pacific Research Laboratories) (low fidelity)	Construct validity	**Number of participants:** **40 orthopaedic trainees, fellows and staff surgeons**	Orthopaedic Resident (n529), surgical fellow (n 5 5), and surgical staff (n 5 6) groups all performed a hamstring ACLR	Total ARTHROSCOPIC SURGERY SKILL EVALUATION TOOL score, GLOBAL RATING SCALE score, task specific checklist	2	Significant difference based on year of training for total checklist and total ARTHROSCOPIC SURGERY SKILL EVALUATION TOOL score, significant difference in GRS and checklist score between junior and senior residents and between senior residents and fellows

17	Martin et al. Article no.40 Date published: 2016	Animal model – derived from porcine tissue (high fidelity)	Face and Construct validity	**Number of participants:** **14 orthopaedic trainees, fellows and staff surgeons**	Each participant in orthopaedic junior resident (n 5 5), senior orthopaedic resident (n 5 6), and expert level (n 5 4) groups performed a diagnostic knee arthroscopy on a human cadaveric knee and a porcine model in random order, then performed a partial meniscectomy in a porcine specimen	Objective Assessment of Arthroscopic Skills score, diagnostic arthroscopy checklist score	3	No difference in total or overall OBJECTIVE ASSESSMENT OF ARTHROSCOPIC SKILLS scores between groups performing on either the human or porcine specimens; significantly higher total OAAS scores in human and porcine models with increasing number of sports medicine rotations
18	Rebolledoet al. Article no.48 Date published: 2015	Insight Arthro Virtual reality trainer (GMV) (high fidelity)	Transfer validity	**Number of participants:** **14 junior orthopaedic residents**	Simulation group (n58) received two and a half hours of training on both shoulder and knee arthroscopic simulators. Control group (n 5 6) received 2 hours of classical didactic teaching. Both then performed cadaveric knee and shoulder diagnostic arthroscopy	Time taken to complete task, generated IGI graded 1-10	2	Simulation group significantly outperformed the control group in terms of time taken to complete task and Injury Grading Index score for shoulder arthroscopy; trend toward improved time taken to complete task and IGI score for knee arthroscopy
19	Tofte et al. Article no.49 Date published: 2017	VirtaMed ArthroS Virtual reality trainer (VirtaMed) (high fidelity)	Construct validity	**Number of participants:** **35 orthopaedic trainees, fellows and faculty members**	Each participant completed 3 FAST training modules, alongside completing diagnostic knee and shoulder arthroscopies	Total operation time, camera path length, composite total score	3	Significant correlation of both training year and knee and shoulder arthroscopy experience with all 3 metrics during both diagnostic tasks; significant correlation with training year for Fundamentals of Arthroscopic Surgery Training activities for all 3 metrics
20	Garfjeld Roberts et al. Article no.50 Date published: 2017	VirtaMed ArthroS Virtual reality trainer (VirtaMed) (high fidelity)	Construct validity	**Number of participants:** **60 medical students, surgical and nonsurgical trainees, senior fellows, and consultant surgeons**	Divided into novice (n 5 30), intermediate level (n 5 20), and expert level (n 5 10) groups. 1 of each type of group performed tasks on either a knee or shoulder simulator (knee: guided diagnostic, triangulation, and	Time taken to complete task, Total ARTHROSCOPIC SURGERY SKILL EVALUATION TOOL	2	Time to complete and Total ARTHROSCOPIC SURGERY SKILL EVALUATION TOOL scores were significantly different among all experience groups on all tasks

					meniscectomy tasks) (shoulder: guided diagnostic and two triangulation tasks)			
21	Dunnet al. Article no.41 Date published: 2015	Arthro Virtual reality trainer (Simbionix) (high fidelity)	Transfer validity	**Number of participants:** **17 orthopaedic surgery residents**	Experimental group received four sessions of simulator training, whereas control group didn't receive any simulator training. Pretraining simulation assessment and post-training in vivo intraoperative diagnostic arthroscopy performed	Total ARTHROSCOPIC SURGERY SKILL EVALUATION TOOL score, ASSET safety score, time taken to complete task	1	Simulation group showed significant improvement in terms of total mean ARTHROSCOPIC SURGERY SKILL EVALUATION TOOL score and time taken to complete task on in vivo testing after training; control group only improved in terms of time taken to complete task after training
22	Watermavet al. Article no.42 Date published: 2016	Arthro Virtual reality trainer (Simbionix) (high fidelity)	Transfer validity	**Number of participants:** **22 orthopaedic trainees in simulation and control groups**	Simulation group (n 5 12) received 4 sessions of simulator training, whereas the control group (n 5 10) didn't receive any simulation training. Diagnostic shoulder arthroscopy performed in simulator and in vivo intraoperatively before and after training	Total ARTHROSCOPIC SURGERY SKILL EVALUATION TOOL score, ASSET safety score, 14-point anatomical checklist score, time taken to complete task	1	Both groups significantly improved total ARTHROSCOPIC SURGERY SKILL EVALUATION TOOL score on 2nd in vivo testing. Simulation group was also significantly faster on 2nd simulation to pre-intervention time. The Simulation group scored a significantly higher ARTHROSCOPIC SURGERY SKILL EVALUATION TOOL score compared with control group on retesting in vivo. Simulation group also significantly faster compared with control group on second simulation
23	Colaco et al. Article no.43 Date published: 2017	Dry arthroscopic training benchtop model (low fidelity)	Construct validity	**Number of participants:** **28 medical students, surgical and nonsurgical trainees, and consultant orthopaedic surgeons**	Students group (n 5 9), orthopaedic trainee group (n 5 12), and orthopaedic consultant group (n 5 7) all groups performed 6 consecutive attempts at an abstract 6-step triangulation task	Time taken to complete task; no. of times participants looked at their hands	3	Medical students were significantly slower than both orthopaedic trainees and orthopaedic consultant groups in terms of time to completion; senior trainees (subgroup of trainee group) were significantly faster than student group; fastest attempt time was significantly faster in relation to experience
24	Angelovet al. Article no.44	Physical dry arthroscopic training benchtop model (low fidelity)	Content and Construct validity	**Number of participants:** **44 senior orthopaedic trainees**	Group A (n514), Group B (n514), and Group C (n5 16) received traditional, simulator, and proficiency-based progression	Time taken to complete task, no. of steps completed, no. of errors	1	Those groups receiving simulation training (Groups B and C) generally performed better than Group A. Group C completed significantly more tasks than the other 2 groups and made significantly less errors than the other two groups

	Date published: 2015				(including simulation) training, respectively, after baseline assessment. A three suture-anchor Arthroscopic Bankart repair on a cadaveric model was performed after receiving simulation training			
25	McCracn et al. Article no.45 Date published: 2018	CSTAR dry arthroscopic training benchtop model (high fidelity)	Face and Construct validity	**Number of participants:** **23 novices (students and orthopaedic trainees) and experts (fellowship-trained orthopaedic surgeons**	Novice group (n 5 17) and expert group (n56) performed 3 arthroscopic tasks (2 probing and 1 grasping)	Time taken to complete task, probe distance travelled, probe force	3	The Expert group performed all three tasks significantly quicker than novice group and with significantly shorter probe distances in tasks one and two
26	Dwyer et al. Article no.46 Date published: 2017	Sawbones dry arthroscopic training benchtop model (by Pacific Research Laboratories) (low fidelity)	Construct validity	**Number of participants:** **51 orthopaedic trainees, fellows and staff surgeons**	All junior orthopaedic residents (n 5 23), senior orthopaedic residents (n5 16), surgical fellows (n 5 7), and staff surgeons (n 5 5) performed an arthroscopic rotator cuff repair and of these, 46 performed a separate arthroscopic labral repair	Total ARTHROSCOPIC SURGERY SKILL EVALUATION TOOL score, total of task-specific checklist scores, overall 5-point GLOBAL RATING SCALE	3	A significant difference was found by year of training for total ARTHROSCOPIC SURGERY SKILL EVALUATION TOOL, total checklist, and overall GLOBAL RATING SCALE scores for both rotator cuff repair and labral repair
27	Angelo et al. Article no.47 Date published: 2015	Sawbones dry arthroscopic training benchtop model (by Pacific Research Laboratories) (low fidelity	Construct validity	**Number of participants:** **19 orthopaedic trainees (novice) and experienced surgeons (expert)**	Novice (n 5 7) and expert (n 5 12) groups performed a diagnostic arthroscopy followed by a three-suture-anchor Bankart repair for the shoulder joint	Time taken to complete task, no. of errors	3	The more experienced surgeons (expert group) made significantly fewer errors and completed the tasks in significantly less time

28	Antonis J et al. 79	VR Knee ArthroS TM simulator	Content, construct and face	**21 participants from the orthopaedic deparmement.**	Novices (16) and experts (5) groups performed an ACL reconstruction task after a prtial mensicectomy which is 5 minutes long	Time taken to complete task, Total ASSET score, Likert scale questionnaire	**2**	There was no statistically significant differences between novices and experts.
29	Ariyana A et al.80	VR Shoulder TolTech Arthrosim	Face	**24 orthopaedic trainees who have not done arthroscopy before**	The trainees did the same procedure 6 times in one hour using VR with haptic feedback	Time taken to complete task	**3**	There was a significant reduction in the time taken to complete the arthroscopic procedure especially after the second time (42.69%)
30	Ode G et al.81	Cadaveric wrist arthroscopy and VR knee arthroscopy simulator	Construct	**27 orthopaedic resident- 10 interns, 10 juniors and 7 seniors who were assessed by 3 hand surgeons**	To see the effect of doing virtual reality knee arthroscopy on their skills at doing a wrist arthroscopy	Total ASSET score	**2**	No statistically significant improvement in Total ARTHROSCOPIC SURGERY SKILL EVALUATION TOOL score
31	Cychosz CC et al.82	Non anatomic simulator and high fidelity virtual reality knee arthroscopy	Transfer	**43 medical students (novices)**	Students conducted some self-directed training modules and then did a diagnostic knee arthroscopy afterwards to see if there was a difference	Composite score, time, damage to tibial and femoral cartilage, camera path length time	**1**	In all the criteria there was a significant improvement in performance apart from cartilage damage to femoral and tibial cartilage
32	Van der Heijden L.L.M et al.83	Simendo knee arthroscopy virtual reality simulator	Face and construct	**60 participants were divided into three groups according to their exposure. Novices- 0, intermediates 1-59 arthroscopies) and experts (60 or more arthroscopies)**	60 participants conducted 5 navigation trials for 10 minutes and results were tested for before and after	Educational value, Face validity, User-friendliness	**2**	There was a statistically significant difference between each of the groups. 95% said sufficient user-friendliness. 92% approved its use for surgica inspection
33	Erturan G et al.84	Bench top simulated hip arthroscopy	Construct and transfer	**52 participatns- 20 novices, 28 trianees and 4 consultants**	A cross sectional survey assessing difference in performance on bench top simulated hip arthroscopy	GRS	**3**	The number of procedures necessary to get an expert GLOBAL RATING SCALE score is 610 arthroscopies previously
34	Bauer D.E et al.85	VR Hip arthroscopy	Construct and face	**42 participant. 9 experts, 33 non experts**	The two groups conduced 3 different tasks on the VR arthroscopy simulator and assessed	Total ASSET score	**2**	There was a statistically significant difference between the expert and nonexpert group. (9.7). Simulator showed high face and construct validity

35	Frank R.M et al.86	ArthroVision VR simulator	Content	**28 participants- all novices**	Everybody takes a pre-test on the simulator and one group receives training with the simulator and the results are compared with the control group	Total ASSET score	**1**	There was a significant difference between the training group and the control group in terms of time for completion
36	Gallagher K et al.87	VR Hip arthroscopy Simulaor	Face, content	**22 participans. Novice- 16 and expert- 6**	Both groups were given time to prepare themselves and the completed a diagnostic procedure for 5 minutes	Detailed Visualization, Safety, Economy, Operation time, Overall score, Liker-scale questionnaire	**2**	Questionnaire revealed face and content validity. All areas showed statistically significant difference except Detailed Visualization (p=0.097)
37	Keith K et al.88	VR simulator	Transfer	**58 orthopaedic residents**	58 residents were sent a questionnaire to fill about the perceived value using VR simulators in training	12 questions Likert-type responses Yes and no responses	**3**	72% of the residents had done their first arthroscopy in their first year and 93% of them didn't feel comfortable doing it.
38	An VVG et al.89	Bench top model	Transfer	**16 participants from 2, one day knee arthroscopie s**	The participants did a task before the course and certain variables were measured such as time completion, gaze fixation on the arthroscopic stack or away from the model	Completion time Gaze fixation Proportion of time gaze fixated on screen or knee model	**2**	There was a statistically significant decrease in time taken for completion and a significant increase in time spent gazing at the screen vs knee model
39	Rahm S et al.90	VR knee and shoulder arthroscopy simulator	Transfer	**25 participants. Residents- 20, Experts- 5**	Both groups had to do a task on a VR knee simulator and shoulder arthroscopy simulator. They both had undergone a competency based training programme and then retested	Total ASSET score	**2**	All of the residents had a significant improvement in ARTHROSCOPIC SURGERY SKILL EVALUATION TOOL scores from the training (20%)
40	Canbeyli D et al.91	Bench top simulator	Transfer	**100 fifth year medical students from 22-33 years old.**	The 100 med students were split up into 5 groups: bench-top simulator, reading the technique only, or reading plus watching a surgical video, video only and control. They then had to complete tasks on the two models	Successful completion of tasks Time taken to complete task	**1**	The rate of successful tasks was highest in the group that was trained on the bench top simulator compared to all the other training methods.
41	Baumann Q et al.92	VirtaMed ArthroSTM simulator	Transfer	**34 orthopaedic surgeons**	34 participants divided into two groups: experts and non-experts. Expert>20 knee arthroscopies. Non-experts <20 arthroscopies	Operative time Camera path length	**2**	There was a significant improvement in all the areas identified, however, some major anatomical landmarks were not completely visualised which poses a question about the level of accuracy arthroscopic explorations.

					and both underwent training programmes in simulation.	Tibial and femoral cartilage damage		
42	Bartlett J.D et al.93	VR hip arthroscopy simulator	Face	**25 orthopaedic surgeons. Residents-18. Faculty members- 7.**	All of the surgeons had to perform a supine diagnostic arthroscopy using 70 degree arthroscope and they filled out a questionnaire for feedback.	Verisimilitude of simulator Training environment 10 point likert scale Level of realism	**2**	The hip arthroscopy training was beneficial and realistic except it lacked haptic capabilities. The study established that the VR simulator had face validity
43	Frank R.M et al.94	Arthroscopic triangulation simulation model	Construct	**36 participants with no previous exposure to arthroscopy training.**	16 participants were split into training group (17) and non-training group (19).	Completion time Efficiency of movement	**1**	After a week of training there was a significant difference in completion time between training group and control group.
44	Dammerer D et al.95	VR knee arthroscopy simulator	Construct	**19 participants. Medical students-10. Residents-9**	Both groups were analysed based on several measures to assess the difference in steepness between the learning curves of medical students vs orthopaedic residents.	Completion time Camera and probe movement Roughness	**2**	Medical students on average showed a steeper learning curve because they started from little or no experience. The residents were a lot smoother and faster and touched cortical tissue less.

Figure 1

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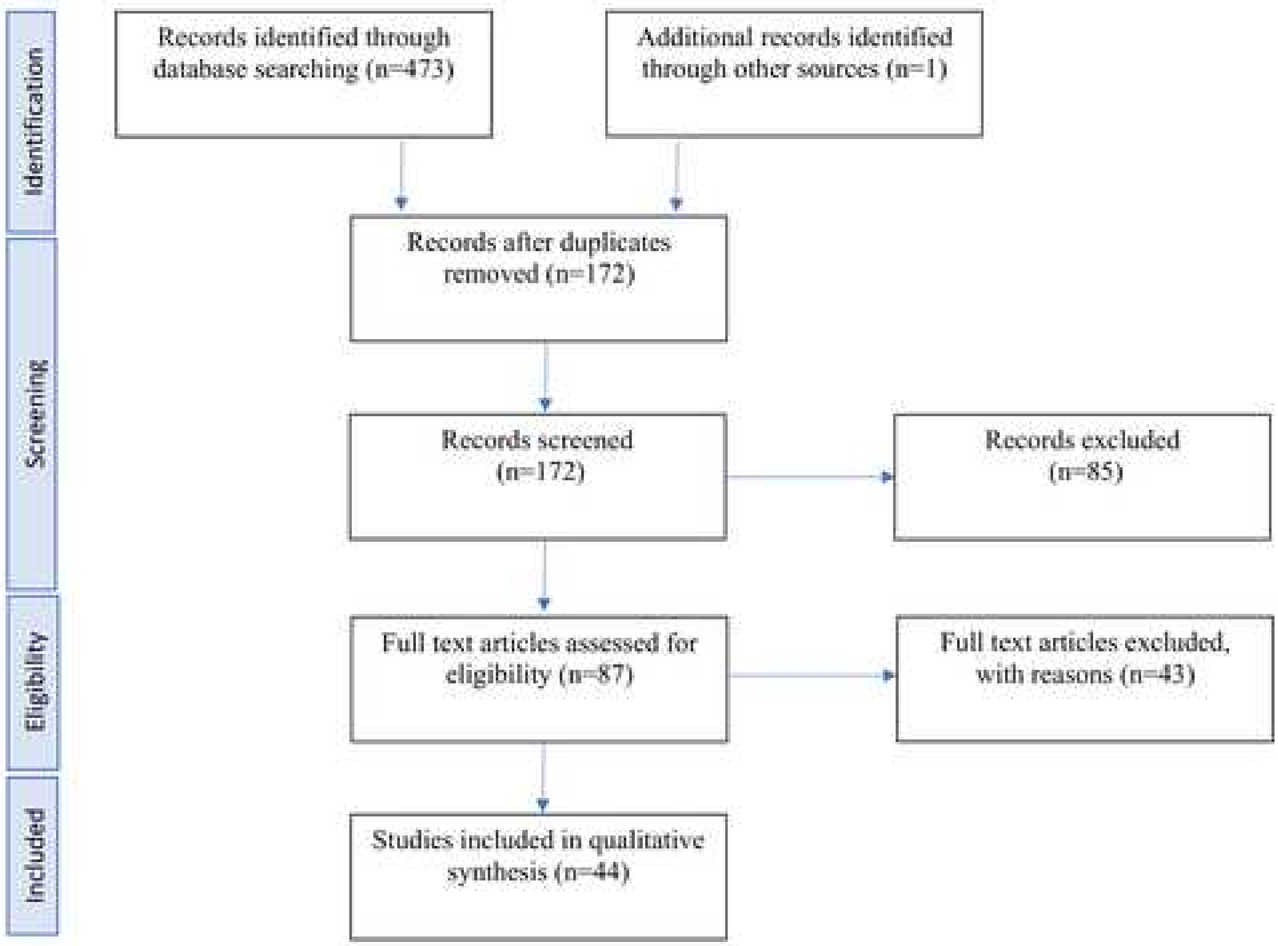
Fig. 1



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Question 1

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II. Question: (A patient-care scenario is preferred when appropriate; see *Guidelines* link above)

Which of the following arthroscopic simulators show the greatest acquisition of psychomotor skills?

III. Options: *(In alphabetical or logical order.* ***Please do not use "all of the above" or "none of the above" as potential answer choices.****)*

A.	Animal
B.	Bench-top
C.	Cadaveric
D.	Hybrid
E.	Virtual-Reality

IV. Answer: (must be *clearly* the best of the options)

☐ A. ☒ B. ☐ C. ☐ D. ☐ E.

V. Correct Answer Location: Please identify the manuscript section where the correct answer is located (e.g. “Results” or “Discussion”)

Discussion

VI. Supporting Statement: Please include one sentence from the section identified above supporting the correct answer.

Recently, increasing evidence has suggested that lower-fidelity benchtop models offer greater efficacy in acquisition of psychomotor skills, with trainees who received benchtop training demonstrating improved performance on VR simulation when compared with those who only received VR training.

Question 2

V. Does this question have an associated image or images?

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VI. Question: (A patient-care scenario is preferred when appropriate; see *Guidelines* link above)

What is the most common type of validity demonstrated by arthroscopic simulators?

VII. Options: *(In alphabetical or logical order.* ***Please do not use "all of the above" or "none of the above" as potential answer choices.****)*

A.	Construct
B.	Content
C.	Face
D.	Transfer
E.	Translational

VIII. Answer: (must be *clearly* the best of the options)

☒ A. ☐ B. ☐ C. ☐ D. ☐ E.

V. Correct Answer Location: Please identify the manuscript section where the correct answer is located (e.g. "Results" or "Discussion")

Results

VI. Supporting Statement: Please include one sentence from the section identified above supporting the correct answer.

Fourty-two studies (64.6%) demonstrated construct validity

Question 3

IX. Does this question have an associated image or images?

☐ Yes ☐ No

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X. Question: (A patient-care scenario is preferred when appropriate; see *Guidelines* link above)

Which of these statements best describes transfer validity?

XI. Options: *(In alphabetical or logical order.* ***Please do not use "all of the above" or "none of the above" as potential answer choices.****)*

A.	The degree to which the simulator reflects reality intraoperatively
B.	Assesses whether the metric used to measure performance by the simulator is accurately measuring the criterion or domain required
C.	Capability of the simulator to differentiate between varying levels of expertise
D.	A measurement of how effective the simulator is in carrying out its purpose (i.e. whether the simulator is able to produce a learning effect and improve performance with continued use)
E.	The degree of flexibility of the simulator in its range of motion

XII. Answer: (must be *clearly* the best of the options)

☐ A. ☐ B. ☐ C. ☒ D. ☐ E.

V. Correct Answer Location: Please identify the manuscript section where the correct answer is located (e.g. "Results" or "Discussion")

Table 1

VI. Supporting Statement: Please include one sentence from the section identified above supporting the correct answer.

A measurement of how effective the simulator is in carrying out its purpose (i.e. whether the simulator is able to produce a learning effect and improve performance with continued use)

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Article Title (the "Work")

Arthroscopic simulation-The future of surgical training, A systematic review of the literature
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Corresponding Author Name (the "Author")

Saad Lakhani   Journal of Bone and Joint Surgery
____
Name of Journal in which Work is to be Published

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Background:

Arthroscopic simulation has rapidly evolved recently with the introduction of higher-fidelity simulation models, such as virtual reality simulators, which provide trainees an environment to practice skills without causing undue harm to patients. Simulation training also offers a uniform approach to learn surgical skills with immediate feedback. The aim of this article is to review the recent research investigating the use of arthroscopy simulators in training and the teaching of surgical skills.

Methods:

A systematic review of the Embase, MEDLINE, and Cochrane Library databases for English-language articles published before December 2019 was conducted. The search terms included arthroscopy or arthroscopic in combination with simulation or simulator.

Results:

We identified a total of 44 relevant studies involving benchtop or virtually simulated ankle, knee, shoulder, and hip arthroscopy environments. The majority of these studies demonstrated construct and transfer validity; considerably fewer studies demonstrated content and face validity.

Conclusions:

Our review indicates that there is a considerable evidence base regarding the use of arthroscopy simulators for training purposes. Further work should focus on the development of a more uniform simulator training course that can be compared with current intraoperative training in large-scale trials with long-term follow-up at tertiary centers.

The explosion of technology that has come with modern advances in bioengineering means that standard teaching models are in need of modification to adapt to the growing modernization of medicine[1]. The traditional teaching model relied heavily on operating room (OR) exposure, which is more costly, prolongs OR times, and can increase the risk of harm to the patient[2-4]. Furthermore, the learning opportunities can be varied depending on the instructor, which means that there is less consistency in how the techniques are taught, how trainees are assessed, and the level of feedback offered[5].

A possible solution is to incorporate arthroscopy simulators into traditional training models. Arthroscopy simulators provide the opportunity to practice surgical skills outside the OR environment under less pressure[6,7]. An alternative approach has been created through simulation to facilitate the translation of technical skills into better outcomes and shorter OR times[8]. In the last 2 decades, increasing evidence in support of simulation has been brought to the attention of health-care professionals[9] and patients[10] as well. The leaders of medical education in both the United Kingdom and United States are recommending the use of simulation in training programs[1,11].

Arthroscopy, like all procedures in surgery, demands manual dexterity and more specifically the qualities of triangulation and depth perception[12,13]. All of the arthroscopy simulators covered in the present study are currently being used in practice and fall into 3 categories: physical models, virtual reality (VR) models, and 1 VR-physical model[7]. Physical models can be designed based on human or animal models or artificial “benchtop” simulators. Certain models can be analyzed on the basis of a characteristic called fidelity (a measure of how closely the simulators resemble real-life scenarios)[14]; the higher the fidelity, the more realistic the experience, as with cadaveric specimens. One of the most common VR simulators[15] is the ArthroS VR simulator (VirtaMed), which is equipped with a camera, hook, cutter, and grasper and a high-quality display to visualize the process[16]. A key quality of VR simulation is passive haptic tactile feedback, which gives the user of the simulator an impression of where the surgical instruments are by providing resistance forces when they come into contact with physical objects. VR can also provide performance feedback by simulating the level of pressure applied to the articular surface. Other more novel metrics include information on instrument loss, triangulation time, and positioning of the joint in space.

Simulators are evaluated on the basis of various types of validity assessed through a series of sequential steps (Table I). Concurrent validity is a measure of the degree to which the performance of the simulator matches that of the reference standard in a particular field, which is potentially the first priority when it comes to evaluating efficacy. One of the challenges arising with simulators is that there is no established consensus on a “gold standard,” which is why transfer validity is the next most crucial factor in judging the efficacy of arthroscopy simulators[7].

Numerous articles written up until the year 2014 highlighted advances in simulation and its role in training orthopaedic residents[17-19]. However, because simulation is a modern innovation, there have been an increasing number of findings and discoveries in the field, and we felt that an updated systematic review of the literature regarding the various types of validity was required. A review of articles published up until the year 2014 and those published after that date, until December 2019, is given in Table I.

The goal of this review was to collate all of the recent studies on arthroscopy simulator models and incorporate previously published work to produce an updated review of the role of arthroscopic simulation in the future of surgical training.

Search Method

The search strategy for this article consisted of systematically reviewing the MEDLINE, Embase, and Cochrane databases for articles with the terms arthroscopy or arthroscopic in combination with simulation or simulator. Only English-language articles published before December 2019 were selected for review.

Selection Criteria

Articles evaluating current or new arthroscopy simulators for their role in surgical skills training were selected. Any review articles, case studies, and editorial commentaries were excluded. In addition, the references cited in the included articles also underwent the same selection process and were included if applicable. Duplicate articles were removed, and the remaining articles were analyzed for relevance in accordance with the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) guidelines[20]. The aim of this review was to evaluate the efficacy of simulation as a tool for arthroscopy training, and simple observational data would not add to the scope of the review. Therefore, any articles that did not present a comparison of results before and after arthroscopic simulation, as well as studies that did not include comparisons between novices and orthopaedic consultants, were excluded. The final data set included 44 studies (Fig. 1).

Data Analysis

Several criteria were used to analyze the articles. First, the outcomes were analyzed to identify the types of validity demonstrated (Table I). The design and methodology of the studies were summarized, including the levels of experience of the participants involved: novice medical students, junior orthopaedic residents, and senior orthopaedic consultants. The tools used to measure outcomes were also enumerated; the most commonly used were the ASSET (Arthroscopic Surgical Skill Evaluation Tool) score[21], GRS (Global Rating Scale)[22], and time taken to complete the task. The level of evidence of each study was assessed according to the Oxford Centre for Evidence-Based Medicine Levels of Evidence guidelines[23]. The highest level of evidence is awarded to systematic reviews of studies with Level-I evidence, such as randomized controlled trials, that show homogeneous results.

Results

A total of 44 studies were included in the investigation (Table II). The level of evidence in the included studies ranged from I to IV[14,16,24-65]; 27 studies (61%) had a higher level of evidence (I or II)[14,16,24,29-31,35-38,41,42,44,46-54,56,60,62,64,65].

Of these, 1 analyzed ankle arthroscopy simulators[24], 20 analyzed benchtop simulators[14,24-30,33,34,40-42,49,55-59,64], 23 analyzed VR arthroscopy simulators[16,31,32,35-39,41,44-48,50-54,60,61,63,65], 6 analyzed hip arthroscopy simulators[32-37], 10 analyzed knee arthroscopy simulators[38,41,43,44,46-49,51,52], and 8 analyzed shoulder arthroscopy simulators[45,53-59]. Five studies[16,50,60,61,64] analyzed both shoulder and knee arthroscopy simulators, and 1 analyzed an arthroscopic triangulation simulation model[62].

The knee arthroscopy simulator studies had the highest proportion that demonstrated construct validity (70%). The combined knee and shoulder simulators demonstrated transfer validity in 60% of studies. The highest proportions of content validity (17%) and face validity (33%) were found in hip arthroscopy simulators.

The results of these studies were combined with the studies published up until the year 2014, resulting in a total of 63 studies[14,16,24-84]. This will hopefully provide a holistic perspective of the development of arthroscopy simulators in the last 2 decades (Table I). Forty-two studies (67%) demonstrated construct validity[14,16,25-29,31-35,38-44,46,48,52,55-59,61,62,66-78], 24 (38%) demonstrated transfer validity[24,30,34,43,47,49-51,54,60,63,64,66,67,72,73,77-84], 14 (22%) demonstrated face validity[28,29,35-37,40,41,43-45,48,56,57,66], and 5 (8%) demonstrated content validity[36,40,56,65,67]. Twenty-three (37%) of the studies only analyzed VR arthroscopy simulators[16,31,32,35-39,44-48,50-54,60,61,63-65], whereas 19 (30%) only evaluated benchtop simulators[14,24-30,33,34,40,42,49,55-59,64]. One study (2%) incorporated the 2 types in a new combination VR-benchtop model[41], and 1 article (2%) created a porcine prototype[43].

Discussion

Simulators are becoming increasingly more lifelike and correspond more closely to the operating environment, and the majority of studies demonstrated construct validity, which is a measure of the extent to which the simulator's results can differentiate between experienced users and novices. There has been increasing evidence in support of the improved transfer validity of arthroscopy simulators due to improved simulator design[24,30,53,54,60], which has been evidenced by intraoperative performance[53,54]. Initially, only 1 study[79] was shown to have demonstrated an improvement in intraoperative assessment when the arthroscopy simulator cohort was assessed against the control cohort. From the findings of that report, we were able to identify 2 additional articles showing the same change in performance with use of arthroscopic simulation[53,54]. One of these studies[54] showed that the members of the intervention cohort completed tasks in less time and more safely than the cohort that did not receive the arthroscopy simulator training. The other study[53] also revealed that the members of the intervention cohort were faster and had greater proficiency when completing tasks compared with the group receiving regular training. These 3 studies used a recognized tool called the

Arthroscopic Surgical Skill Evaluation Tool, or ASSET[21]. Three additional studies showed superior transfer validity with simulation in models utilizing human cadavers[24,30,60]. This could be considered the final stage before commencing intraoperative assessment of a student's performance. However, there is still uncertainty about how well skills developed from cadaveric models can be transferred to the intraoperative environment[7].

The proportion of studies using VR simulators after 2014 (52%) was compared with studies conducted up to 2014 (68%), demonstrating a 16% decrease. This can be explained by the rise in the use of low-fidelity physical models; hence, more focus has been placed on their development in articles published after 2014. The reduction in use of VR simulators could be explained by the underreporting of the purchase price disadvantage of VR simulators in the older set of articles. Also, low-fidelity physical models are much cheaper to maintain and are extremely user-friendly in comparison with more complex VR models. As a result of this, an increasing number of simpler, user-friendly arthroscopy models are being manufactured that cost less than $50, such as the novel dry arthroscopic training cigar box arthroscopy trainer (CBAT) benchtop model and the grapefruit training model (GTM)[30,85].

Even though there has been evidence suggesting that use of arthroscopy simulators in training is becoming more widespread, there is still a lack of clarity regarding how to integrate the different modes of simulation into teaching programs in a way that provides the most benefit[38]. There is evidence suggesting the efficacy of both VR and benchtop simulators in improving intraoperative performance, but differing opinions as to which model leads to the greatest improvement in acquiring skills[86].

Recently, growing research into physical benchtop simulators has shown that groups using these models demonstrated better acquisition of skills, since they subsequently had better outcomes on VR simulators compared with groups using the VR simulator only[87]. This trend has been noted not only in orthopaedic simulation but in other fields[88,89], which has resulted in the creation of the PBP (proficiency-based progression) framework. This method involves first using physical benchtop simulators to master the fundamental competencies required and then progressing to virtual simulation, and has been applied in numerous training programs[90]. It has proved to be more efficacious than standard training programs that do not involve graduated progression[56].

Diagnostic procedures have increasingly been selected in evaluating the validity of simulation training[58] because they do not cause much disruption to the tissues in cadaveric models and performance of these procedures can easily be evaluated against reference standards. More varied and complex tasks such as knot-tying[29], repairing rotator cuff injuries, labral tears[58], 3-suture-anchor repair of Bankart lesions[56,59], and anterior cruciate ligament repair[42] can be evaluated through simulation. Many of these procedures have been performed using dry laboratory models. However, the absence of fluids such as blood (which is complex to simulate) or even saline solution represents a limitation in the ability of dry laboratory models to mimic real-life situations. In the future, dry models with increased face and transfer validity need to be developed, to make them more translatable to the intraoperative environment.

Limitations

This systematic review has some limitations. First, only English-language articles were selected for review, which represents a possible publication bias. Second, even though the collected data represent a very large proportion of the research available, they cannot be assumed to be entirely representative of everything that has been published on arthroscopic simulation, because of the selection criteria that were used in this review and previous included reviews. Also, the heterogeneity of the studies included in this review makes generalization of the findings challenging. A streamlined arthroscopic simulation curriculum has not been established using evidenced-based protocols, as there is much variation in the types of simulators available and the duration of training courses[30,53,60]. A standardized training program needs to be established for future trainees, especially because recent evidence has highlighted that skills acquisition from simulators decreases with time[29,53]. Many of the included studies compared experienced orthopaedic consultants with beginners from medical school who are at polar opposites of the spectrum, which reduces the reliability of the outcomes when the construct validity of simulators is assessed[91]. Having a larger number of participants would also help to confirm the transfer validity of simulators, since that increases the chances of proving a significant difference between the control and intervention groups[28,32,53,60].

Conclusions

A rigorous analysis of the data yielded numerous findings. First, approximately 95% of all included studies showed an improvement in arthroscopic performance. Efficiency was also improved with the use of simulator training, resulting in less time taken to complete tasks, fewer errors, and improved triangulation. Second, many arthroscopy simulators of varying types and modalities are being evaluated for training purposes. The promise of lower-fidelity benchtop models brings hope that use of simulators in training programs can become mainstream because of their high levels of efficacy in acquiring psychomotor skills and their relatively low cost in comparison with more sophisticated VR technology. Third, research has shown that skill acquisition varies among modalities; therefore, a standardized training framework is required to implement arthroscopy simulators in training programs. Further research needs to be aimed at reducing discrepancies in the way that simulation training is carried out, to create a streamlined curriculum that can allow for cross-comparisons with traditional training models in tertiary center trials with long-term follow-up.

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Fig. 1
PRISMA flow diagram of the databases searches (including MEDLINE, Embase, and Cochrane databases) to select the 44 articles used in the data analysis.

TABLE I Summary of the Types of Validity Demonstrated in All Articles Before December 2019

Type of Validity	Definition	No. of Studies	References
Face	The degree to which the simulator reflects reality intraoperatively	14	28, 29, 35-37, 40, 41, 43-45, 48, 56, 57, 66
Content	Whether the metric used by the simulator to measure performance is accurately measuring the criterion or domain required	5	36, 40, 56, 65, 77
Construct	The capability of the simulator to differentiate between varying levels of expertise	42	14, 16, 25-29, 31-35, 38-44, 46, 48, 52, 55-59, 61, 62, 66-78
Transfer	A measurement of how effective the simulator is in carrying out its purpose (i.e., whether the simulator is able to produce a learning effect and improve performance with continued use)	24	24, 30, 34, 43, 47, 49-51, 54, 60, 63, 64, 66, 67, 72, 73, 77-84

TABLE II Summary of All Articles That Fulfilled the Inclusion Criteria*

Study	Model	Validity Demonstrated	Participants	Method	Measured Outcomes	Evidence Level	Salient Results
Martin et al.[24] (2015)	Ankle Sawbones arthroscopic training benchtop model (Pacific Research Laboratories) (low fidelity)	Transfer	29 orthopaedic surgical trainees	Simulation group (n = 14) received 4 simulation training sessions, whereas the control group (n = 15) did not receive any simulation training. Pre- and post-training cadaveric diagnostic arthroscopies were performed	Total ASSET score, individual ASSET domain scores, 15-point diagnostic arthroscopy anatomic checklist, time taken to complete task	I	The simulation group was significantly better than the control group in all 4 measured domains
Coughlin et al.[14] (2015)	Novel dry arthroscopic training benchtop model (low fidelity)	Construct	49 medical students, orthopaedic residents, and arthroscopic surgeons	Novice (n = 15), junior orthopaedic resident (n = 12), senior orthopaedic resident (n = 16), and consultant (n = 6) groups each performed 6 basic arthroscopic tasks: (1) probing, (2) grasping, (3) tissue resection, (4) shaving, (5) tissue liberation and suture passing, and (6) tissue approximation and arthroscopic knot-tying	GRS (timing score minus penalty score)	II	Mean GRS improved significantly between groups with successively increasing level of expertise
Bouaicha et al.[26] (2017)	ArthroBox dry arthroscopic training benchtop model (Arthrex) (low fidelity)	Construct	46 orthopaedic surgeons	Novice (n = 12), intermediate skill level (n = 12), and expert skill level (n = 22) groups performed a single arthroscopic dexterity task	Time taken to complete task, portal replacements of the camera and probe	III	Novices performed the task significantly slower than intermediate and expert skill level groups. Portal changes were significantly more common in novice and

							intermediates groups than in expert group
Lopez at al.[27] (2016)	Benchtop model dry arthroscopic training (low fidelity)	Construct	75 medical students and junior and senior orthopaedic residents and fellows	Medical student (n = 20), junior resident (n = 27), senior resident (n = 19), and surgical fellow (n = 9) groups performed a number of tasks (e.g., testing peg transfer, circle drawing, and suture retrieval)	Time taken to complete task, score for object transfer from dominant to nondominant hand, score for suture retrieval	III	Medical students and junior residents attained significantly lower scores on object transfer at both 60° and 180°. These 2 groups took significantly longer to complete the tasks compared with the 2 more senior groups
Goyal et al.[25] (2016)	Sawbones "FAST" dry arthroscopic training benchtop model (Pacific Research Laboratories) (low fidelity)	Construct	20 orthopaedic surgeons (trainees, fellows, and arthroscopic and non-arthroscopic specialists)	Novice (n = 9), beginner level (n = 4), intermediate level (n = 3), and advanced level (n = 4) groups performed a number of tasks including maze navigation, number probing, object handling, and partial meniscectomy (transparent and opaque domes)	Time taken to complete task, no. of errors	III	Less experienced participants were significantly slower compared with more experienced participants in every task (opaque dome), no. of errors also decreased with advancing experience
Braman et al.[28] (2015)	Dry arthroscopic training benchtop model (low fidelity)	Face and construct	16 medical students (novices) and arthroscopic surgeons (experts)	Novice (n = 8) and expert (n = 8) groups performed 2 tasks: the first was based on triangulation and the second, on object manipulation	Time taken to complete task, no. of errors, no. of trials to steady state (i.e., perform 2 trials within 10% of each other for time and errors)	III	Expert group performed both tasks significantly faster and with significantly fewer errors; many more experts were able to demonstrate steady state
Wong et al.[29] (2015)	Novel dry benchtop model: arthroscopy knot trainer (AKT) (low fidelity)	Construct and face	37 orthopaedic residents and surgeons	Junior orthopaedic resident (n = 21), senior orthopaedic resident (n = 11), and expert orthopaedic surgeon (n = 5) groups performed 2	Time taken to tie first knot, total no. of knots tied within 10 minutes	II	Non-experienced residents took a significantly longer time to tie knots than experienced residents

				knot-tying exercises. Repeated after 6 mo			
Sandberg et al[30] (2017)	Sawbones (Pacific Research Laboratories) and novel dry arthroscopic training CBAT (cigar box arthroscopy trainer) benchtop models (low fidelity)	Transfer	24 medical students assigned to CBAT training, AKAT (anatomic knee arthroscopy trainer) training, or control group	CBAT (n = 8) and AKAT (n = 8) groups received 4 hr of training on their respective models. Control group (n = 8) received no training. All groups were then assessed during diagnostic knee arthroscopy on cadaveric specimen	BAKSS	II	Significantly more subjects in CBAT and AKAT groups (75% each) succeeded in reaching the minimum proficiency in the allotted time compared with the control group (25%)
Rose and Pedowitz[31] (2015)	ArthroVision VR box simulator (Swemac, Linköping, Sweden) (low fidelity)	Construct	30 medical students, orthopaedic trainees, fellows, and staff surgeons	Novice (n = 10), intermediate level (n = 10), and expert level (n = 10) groups performed all 3 tasks based on image centering, triangulation, and coordination in separate simulators. All performed with the dominant hand, then repeated with the nondominant hand	Time taken to complete task, probe path length	II	In the coordination task, both intermediate and expert groups were on average significantly faster than the novice group when using both dominant and nondominant hands; in the triangulation task, there was a significant difference in times taken for completion with nondominant hand across all groups
Khanduja et al.[32] (2017)	Arthro Mentor VR trainer (Simbionix) (high fidelity)	Construct	19 orthopaedic trainees and experienced surgeons	Novice (n = 10) and expert level (n = 9) groups each performed 1 basic visualization task followed by another basic probe task	Time taken to complete task, no. of soft-tissue and bone collisions, distance traveled by instruments	III	Expert group performed significantly better than the novice groups in all metrics on visualization task and were significantly faster on the probe task

Phillips et al.[33] (2017)	Sawbones (Pacific Research Laboratories) dry arthroscopic training benchtop model (Arthrex) (low fidelity)	Construct	47 orthopaedic trainees, fellows, and staff surgeons	Junior orthopaedic resident (n = 27), senior orthopaedic resident (n = 10), fellow (n = 5), and surgical staff (n = 5) groups performed a hip arthroscopic acetabular labral repair	Total ASSET score, overall GRS score, time taken to complete task, task-specific checklist	III	Total ASSET and overall GRS scores were significantly different between junior and senior residents, between senior residents and fellows, and between fellows and staff surgeons; staff surgeons were significantly faster than both junior and senior residents
Jacobsen et al.[38] (2015)	Arthro Mentor VR trainer (Simbionix) (high fidelity)	Construct	26 orthopaedic trainees (novices) and experienced orthopaedic surgeons (experts)	Novice (n = 13) and expert level (n = 13) groups completed 5 different knee arthroscopy procedures	Time taken to complete task, camera distance and roughness, probe distance and roughness, combined Z-scores	II	Combined Z-scores across the 2 groups were significantly different and time taken for completion of task was also significantly different between the 2 groups across all procedures
Stunt et al.[39] (2015)	VirtaMed ArthroS VR trainer (high fidelity)	Construct	27 orthopaedic surgeons with varying arthroscopic experience	Beginner level (n = 9), intermediate level (n = 9), and expert level (n = 9) groups performed 5 trials of a timed navigation task and 3 diverse tasks for objective feedback	Time taken to complete task	III	Novice group was significantly slower than the orthopaedic surgeons on all 5 trials of the navigation task
Stunt et al.[40] (2016)	Passport V2 dry arthroscopic training benchtop simulator (MediShield BV) (high fidelity)	Face and construct	31 orthopaedic surgeons with varying arthroscopic experience	Beginner level (n = 15), intermediate level (n = 8), and expert level (n = 8) groups performed 5 trials of a timed navigation task and 2 diverse tasks for objective feedback	Time taken to complete task	III	Beginner group was significantly slower than the orthopaedic surgeons on all 5 trials of the navigation task; the beginner group was significantly slower than the

							intermediate group on trials 2 and 4 (of 5)
Fucentese et al.[41] (2015)	Novel VR-benchtop hybrid simulator (ETH Zurich and VirtaMed) (high fidelity)	Face and construct	68 orthopaedic surgeons with varying arthroscopic experience	Novice (n = 33), intermediate level (n = 19), and expert level (n = 16) groups performed diagnostic knee arthroscopy followed by an object removal task. A separate meniscal resection task was also performed	Time taken to complete task, camera path length	II	The orthopaedic surgeons had significantly faster total operation and removal times as well as significantly less distance traveled by the camera
Dwyer et al.[42] (2015)	Sawbones dry arthroscopic training benchtop model (Pacific Research Laboratories) (low fidelity)	Construct	40 orthopaedic trainees, fellows, and staff surgeons	Orthopaedic resident (n = 29), surgical fellow (n = 5), and surgical staff (n = 6) groups all performed a hamstring ACLR	Total ASSET score, GRS score, task-specific checklist	II	Significant difference based on year of training for total checklist and total ASSET score; significant difference for GRS and checklist score between junior and senior residents and between senior residents and fellows
Martin et al.[43] (2016)	Animal model, derived from porcine tissue (high fidelity)	Face and construct	15 orthopaedic trainees, fellows, and staff surgeons	Each participant in orthopaedic junior resident (n = 5), senior orthopaedic resident (n = 6), and expert level (n = 4) groups performed a diagnostic knee arthroscopy on a human cadaveric knee and a porcine model in random order, then performed a partial meniscectomy in a porcine specimen	OAAS score, diagnostic arthroscopy checklist score	III	No difference in total or overall OAAS scores between groups performing on either the human or porcine specimens; significantly higher total OAAS scores in human and porcine models with increasing no. of sports medicine rotations

Rebolledo et al.[60] (2015)	Insight Arthro VR trainer (GMV) (high fidelity)	Transfer	14 junior orthopaedic residents	Simulation group (n = 8) received 2 and a half hr of training on both shoulder and knee arthroscopy simulators. Control group (n = 6) received 2 hr of classical didactic teaching. Both then performed cadaveric knee and shoulder diagnostic arthroscopy	Time taken to complete task, generated IGI graded 1-10	II	Simulation group significantly outperformed the control group in terms of time taken to complete task and IGI score for shoulder arthroscopy; trend toward improved time taken to complete task and IGI score for knee arthroscopy
Tofte et al.[61] (2017)	VirtaMed ArthroS VR trainer (VirtaMed) (high fidelity)	Construct	35 orthopaedic trainees, fellows, and faculty members	Each participant completed 3 FAST training modules, alongside completing diagnostic knee and shoulder arthroscopies	Total operation time, camera path length, composite total score	III	Significant correlation of both training year and knee and shoulder arthroscopy experience with all 3 metrics during both diagnostic tasks; significant correlation with training year for FAST activities for all 3 metrics
Garfjeld Roberts et al.[16] (2017)	VirtaMed ArthroS VR trainer (VirtaMed) (high fidelity)	Construct	60 medical students, surgical and nonsurgical trainees, senior fellows, and consultant surgeons	Divided into novice (n = 30), intermediate level (n = 20), and expert level (n = 10) groups. One of each type of group performed tasks on either a knee or shoulder simulator (knee: guided diagnostic, triangulation, and meniscectomy task; shoulder: guided diagnostic and 2 triangulation tasks)	Time taken to complete task, total ASSET score	II	Time to complete task and total ASSET scores were significantly different among all experience groups on all tasks

Dunn et al.[53] (2015)	Arthro VR trainer (Simbionix) (high fidelity)	Transfer	17 orthopaedic surgery residents	Experimental group received 4 sessions of simulator training, whereas control group did not receive any simulator training. Pre-training simulation assessment and post-training in vivo intraoperative diagnostic arthroscopy were performed	Total ASSET score, ASSET safety score, time taken to complete task	I	Simulation group showed significant improvement in terms of total mean ASSET score and time taken to complete task during in vivo testing after training; control group only improved in terms of time taken to complete task after training
Waterman et al.[54] (2016)	Arthro VR trainer (Simbionix) (high fidelity)	Transfer	22 orthopaedic trainees in simulation and control groups	Simulation group (n = 12) received 4 sessions of simulator training, whereas the control group (n = 10) did not receive any simulation training. Diagnostic shoulder arthroscopy was performed in simulator and in vivo intraoperatively before and after training	Total ASSET score, ASSET safety score, 14-point anatomic checklist score, time taken to complete task	I	Both groups had significantly improved total ASSET score on 2nd in vivo testing. Simulation group was also significantly faster on 2nd simulation than pre-intervention time. The simulation group had a significantly higher ASSET score compared with the control group on retesting in vivo, and was also significantly faster compared with the control group on 2nd simulation
Colaco et al.[55] (2017)	Dry arthroscopic training benchtop model (low fidelity)	Construct	28 medical students, surgical and nonsurgical trainees, and consultant orthopaedic surgeons	Medical student group (n = 9), orthopaedic trainee group (n = 12), and orthopaedic consultant group (n = 7) all performed 6 consecutive attempts at an abstract 6-step triangulation task	Time taken to complete task, no. of times participants looked at their hands	III	Students were significantly slower than both orthopaedic trainees and orthopaedic consultant groups in terms of time for completion; senior trainees (subgroup of trainee group) were significantly faster

							than the student group; fastest attempt time was significantly faster with increasing experience
Angelo et al.[56] (2015)	Physical dry arthroscopic training benchtop model (low fidelity)	Content and construct	44 senior orthopaedic trainees	Group A (n = 14), Group B (n = 14), and Group C (n = 16) received traditional, simulator, and proficiency-based progressive (including simulation) training, respectively, after baseline assessment. A 3-suture-anchor arthroscopic Bankart repair on a cadaveric model was performed after receiving simulation training	Time taken to complete task, no. of steps completed, no. of errors	I	The groups receiving simulation training (Groups B and C) generally performed better than Group A. Group C completed significantly more tasks than the other 2 groups and made significantly fewer errors than the other 2 groups
McCracken et al.[57] (2018)	CSTAR (Canadian Surgical Technologies and Advanced Robotics) dry arthroscopic training benchtop model (low fidelity)	Face and construct	23 novices (students and orthopaedic trainees) and experts (fellowship-trained orthopaedic surgeons)	Novice group (n = 17) and expert group (n = 6) performed 3 arthroscopic tasks (2 probing and 1 grasping)	Time taken to complete task, probe distance traveled, probe force	III	Expert group performed all 3 tasks significantly faster than the novice group and with significantly shorter probe distances in tasks 1 and 2
Dwyer et al.[58] (2017)	Sawbones dry arthroscopic training benchtop model (Pacific Research	Construct	51 orthopaedic trainees, fellows, and staff surgeons	All junior orthopaedic residents (n = 23), senior orthopaedic residents (n = 16), surgical fellows (n = 7), and staff surgeons	Total ASSET score, total of task-specific checklist scores, overall 5-point GRS	III	Significant difference by year of training for total ASSET scores for both rotator cuff repair and labral repair

	Laboratories) (low fidelity)			(n = 5) performed an arthroscopic rotator cuff repair, and of these, 46 performed a separate arthroscopic labral repair			
Angelo et al.[59] (2015)	Sawbones dry arthroscopic training benchtop model (Pacific Research Laboratories) (low fidelity)	Construct	19 orthopaedic trainees (novice) and experienced surgeons (expert)	Novice (n = 7) and expert (n = 12) groups performed a diagnostic arthroscopy followed by a 3-suture-anchor Bankart repair for the shoulder joint	Time taken to complete task, no. of errors	III	The expert group made significantly fewer errors and completed the tasks in significantly less time
Antonis et al.[44] (2019)	VirtaMed VR Knee ArthroS simulator (high fidelity)	Content, construct, and face	21 participants from the orthopaedic department	Novice (n = 16) and expert (n = 5) groups performed an ACL reconstruction task after performing a 5-minute partial meniscectomy procedure to get used to the equipment	Time taken to complete task, total ASSET score, Likert-scale questionnaire	II	No significant differences between novices and experts
Ariyana et al.[45] (2019)	VR Shoulder Arthrosim (ToLTech) (high fidelity)	Face	24 orthopaedic trainees who had not performed arthroscopy before	The trainees performed the same procedure 6 times in 1 hr using VR with haptic feedback	Time taken to complete task	III	A significant reduction in the time taken to complete the arthroscopic procedure, especially after the 2nd time (42.69%)
Ode et al.[46] (2018)	Cadaveric wrist arthroscopy and VR knee arthroscopy simulator (high fidelity)	Construct	27 orthopaedic residents, 10 interns, 10 juniors, and 7 seniors who were assessed by 3 hand surgeons	Trainees performed knee arthroscopy using a virtual reality simulator and were assessed on a cadaveric wrist arthroscopy simulator before and after to see if the	Total ASSET score	II	No significant improvement in total ASSET score

				virtual simulation helped improve their performance			
Cychosz et al.[47] (2018)	Nonanatomic simulator and high-fidelity VR knee arthroscopy (high fidelity)	Transfer	43 medical students (novices)	Students completed self-directed training modules and then performed a diagnostic knee arthroscopy, and results were tested before and after	Composite score, time, damage to tibial and femoral cartilage, camera path length	I	Significant improvement in performance for all criteria except damage to femoral and tibial cartilage
van der Heijden et al.[48] (2019)	Simendo knee arthroscopy VR simulator (high fidelity)	Face and construct	60 participants divided into 3 groups according to their number of prior arthroscopies: 0, novices; 1-59, intermediates; and ≥60, experts	60 participants conducted 5 navigation trials for 10 min, and results were tested before and after	Educational value, face validity, user-friendliness	II	A significant difference among the groups. 95% said user-friendliness was sufficient;92% approved its use for surgical exploration
Erturan et al.[34] (2018)	Benchtop simulated hip arthroscopy (low fidelity)	Construct and transfer	52 participants: 20 novices, 28 trainees, and 4 consultants	Performance on benchtop simulated hip arthroscopy was compared according to the number of previous arthroscopies performed	GRS	III	The number of previous arthroscopies necessary to obtain an expert GRS score is 610
Bauer et al.[35] (2019)	VR hip arthroscopy (high fidelity)	Construct and face	42 participants: 9 experts and 33 non-experts	The 2 groups conducted 3 different tasks on the VR arthroscopy simulator and assessed	Total ASSET score	II	Significant difference between the expert and non-expert groups (9.7). The simulator demonstrated high face and construct validity
Frank et al.[65] (2019)	ArthroVision VR simulator (high fidelity)	Content	28 participants: all novices	All took a pre-test on the simulator; 1 group received training with the simulator, and the	Total ASSET score	I	Significant difference between the training and control groups in terms of time for completion

				results are compared with the control group			
Gallagher et al.[36] (2019)	VR hip arthroscopy simulator (high fidelity)	Face, content	22 participants: 16 novice and 6 expert	Both groups were given time to prepare themselves and then performed a diagnostic procedure within 5 min	Detailed visualization, safety, economy, operation time, overall score, Likert-scale questionnaire	II	The questionnaire revealed face and content validity. All areas showed a significant difference except detailed visualization ($p = 0.097$)
Keith et al.[63] (2018)	VR simulator (high fidelity)	Transfer	58 orthopaedic residents	A questionnaire asked about the perceived value of using VR simulators in training	12 questions: Likert-type responses, yes-no responses	III	72% of the residents had performed their 1st arthroscopy in their 1st year and 93% of them did not feel comfortable doing it
An et al.[49] (2018)	Benchtop model (low fidelity)	Transfer	16 participants from two 1-day knee arthroscopy courses	Participants performed a task before the course, and certain variables such as time for completion and gaze fixation on the arthroscopic stack or away from the model were measured	Completion time, gaze fixation, proportion of time that gaze was fixated on the screen or knee model	II	Significant decrease in time taken for completion and a significant increase in time spent gazing at the screen vs. the knee model
Rahm et al.[50] (2018)	VR knee and shoulder arthroscopy simulator (high fidelity)	Transfer	25 participants: 20 residents, 5 experts	Both groups performed a task on a VR knee simulator and shoulder arthroscopy simulator, then underwent a competency-based training program. The arthroscopy simulator group was then retested to see if performance levels	Total ASSET score	II	All of the residents had a significant improvement in ASSET scores after the training (20%)

				improved after using the simulator			
Canbeyli et al.[64] (2018)	Benchtop simulator (low fidelity)	Transfer	100 fifth-year medical students from 22 to 33 years old	Students were split into 5 groups: using the benchtop simulator, reading the technique only, reading plus watching a surgical video, watching the video only, and controls. They then had to complete tasks on the knee and shoulder arthroscopy models	Successful completion of tasks, time taken to complete task	I	The rate of successful task completion was highest in the group that was trained on the benchtop simulator compared with all of the other training methods
Baumann et al.[51] (2019)	VirtaMed ArthroS VR simulator (high fidelity)	Transfer	34 orthopaedic surgeons	Participants were divided into 2 groups, experts (>20 knee arthroscopies) and non-experts (≤20), and both underwent training programs in simulation	Operative time, camera path length, tibial and femoral cartilage damage	II	Significant improvement in all the criteria; however, some major anatomic landmarks were not completely visualized, which poses a question about the level of accuracy of arthroscopic simulations
Bartlett et al.[37] (2019)	VR hip arthroscopy simulator (high fidelity)	Face	25 orthopaedic surgeons: 18 residents, 7 faculty members	All surgeons performed a supine diagnostic arthroscopy using a 70° arthroscope, then filled out a questionnaire for feedback	Verisimilitude of simulator, training environment, 10-point Likert scale, level of realism	II	The hip arthroscopy training was beneficial and realistic except that it lacked haptic capabilities. The study established that the VR simulator had face validity
Wang et al.[62] (2018)	Arthroscopic triangulation simulation model (low fidelity)	Construct	36 participants with no previous exposure to arthroscopy training	36 participants were split into a training group (17) and non-training group (19)	Completion time, efficiency of movement	I	After a week of training, there was a significant difference in completion time between the training and control groups

Dammerer et al.[52] (2018)	VR knee arthroscopy simulator (high fidelity)	Construct	19 participants: 10 medical students, 9 orthopaedic residents	Several measures were used to assess the difference in steepness between the learning curves of the groups	Completion time, camera and probe movement, roughness	II	On average, after the training, the medical students showed a steeper learning curve because they started from little or no experience. The residents were much smoother and faster, and touched cortical tissue less

*ASSET = Arthroscopic Surgical Skill Evaluation Tool, GRS = Global Rating Scale, OAAS = Objective Assessment of Arthroscopic Skills, IGI = Injury Grading Index, ACL = anterior cruciate ligament, ACLR = anterior cruciate ligament reconstruction, and FAST = Fundamentals of Arthroscopic Surgery Training.

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Arthroscopic Simulation: The Future of Surgical Training

A Systematic Review

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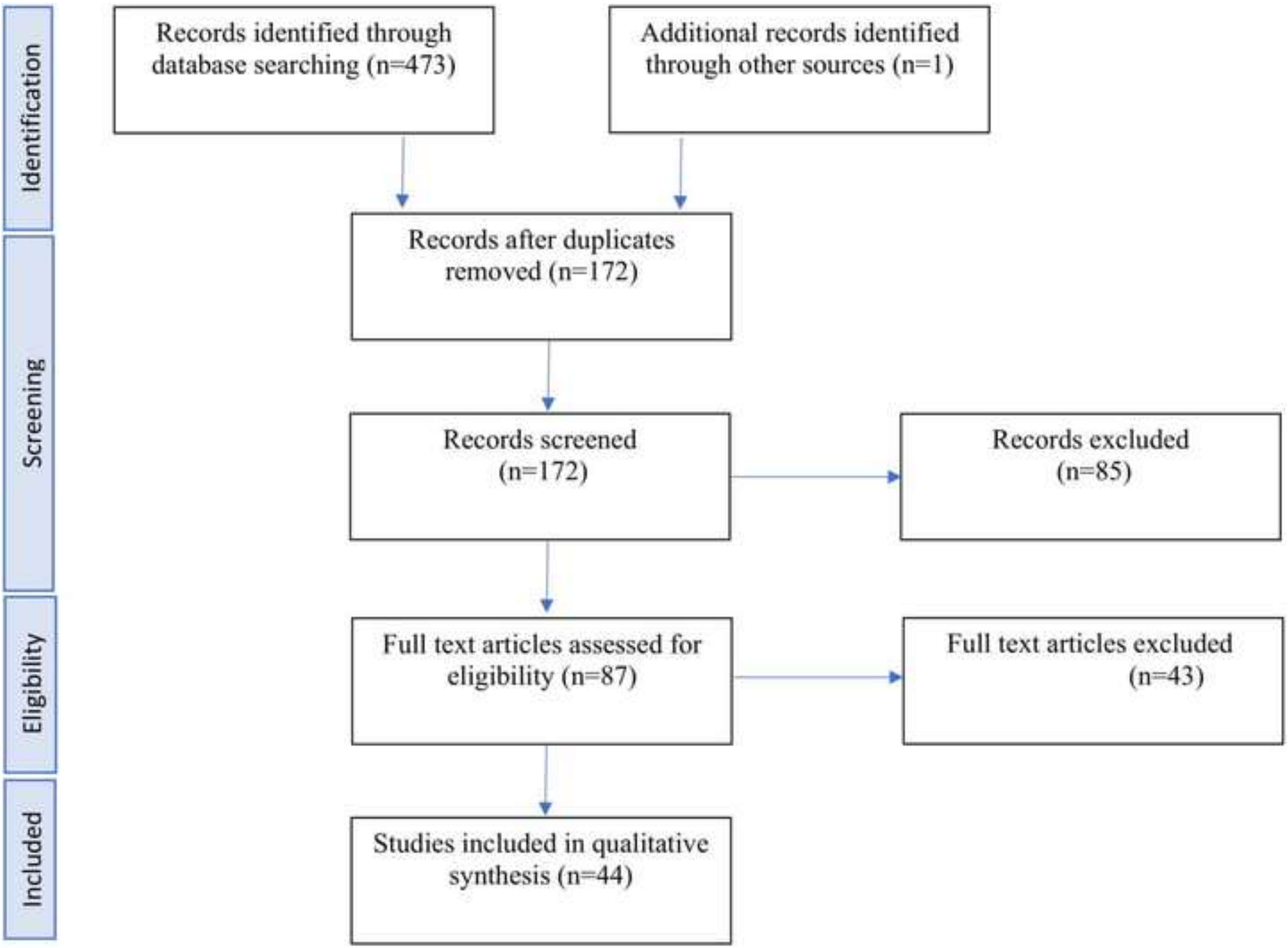
Identification
Screening
Eligibility
Included
Records identified through database searching (n=473)
Additional records identified through other sources (n=1)
Records after duplicates removed (n=172)
Records screened (n=172)
Records excluded (n=85)
Full text articles assessed for eligibility (n=87)
Full text articles excluded (n=43)
Studies included in qualitative synthesis (n=44)