Review Article

Simulation Training in Spine Surgery

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ABSTRACT

Simulated surgery is part of a growing paradigm shift in surgical education as a whole. Various modalities from cadaver models to virtual reality have been developed and studied within the context of surgical education. Simulation training in spine surgery has an immense potential to improve education and ultimately improve patient safety. This is due to the inherent risk of operating the spine and the technical difficulty of modern techniques. Common procedures in the modern orthopaedic armamentarium, such as pedicle screw placement, can be simulated, and proficiency is rapidly achieved before application in patients. Furthermore, complications such as dural tears can be simulated and effectively managed in a safe environment with simulation. New techniques with steeper learning curves, such as minimally invasive techniques, can now be safely simulated. Hence, augmenting surgical education through simulation has great potential to benefit trainees and practicing orthopaedic surgeons in modern spine surgery techniques. Additional work will aim to improve access to such technologies and integrate them into the current orthopaedic training curriculum.

Spine surgery encompasses a broad scope of technical procedures requiring surgical proficiency. Recent evidence suggests that advanced training in spine surgery with dedicated fellowship after residency is necessary to gain proficiency and competency.[1-3] Orthopaedic residents pursuing a spine surgery practice believe that additional training is necessary to confidently move into independent practice.[4] Many simulation modalities have been described in various contexts in orthopaedic surgery, such as cadavers, bone models, virtual reality, and computer simulation.[5] The role of simulation training in spine surgery is thus expected to grow. This review will provide residents, program directors, and practicing physicians with up-to-date information on the growing body of evidence for simulation training.

Importance of Simulation in Spine Surgery

Owing to complex anatomy, proximity to critical neurological structures, and growing technological advances in spine surgery, mastery of surgical techniques is of utmost importance in spine surgery. Widely used techniques, such as

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pedicle screw placement, must be mastered because it has shown to be a powerful tool in various contexts such as deformity surgery.[6] However, these techniques can only be useful with proper technique and safe utilization, which makes the acquisition of technical proficiency imperative.

This is especially true because a poor technique in spine surgery can lead to notable complications. Acute neurological deficits and unplanned revision surgery have been reported with misplacement of pedicle screws.[7-9] Misplacement has been reported from 15.7% to up to 41%.[8,9] This highlights the importance of mastery of these techniques and maintenance of competency for trainees and staff alike. This is especially true when a spine fellow needs to place 80 pedicle screws and 25 cases to achieve accuracy rates similar to attending surgeons.[10]

Accuracy of pedicle screws has been previously described. Parker et al[11] noted only a 1.7% breach rate in freehand pedicle screws in either the thoracic or lumbar spine in an analysis of 6,818 screws. Silbermann et al[12] demonstrated an accuracy rate of 94.1% with a freehand technique and an even higher accuracy rate of 99% with navigation. Navigation using 3D fluoroscopy also showed a high accuracy rate of 95.5%.[13] Recent comparisons between freehand, navigation, and robotic pedicle placement showed accuracy of 6.4%, 4.2%, and 4.7% breach rates, respectively.[14] Augmented reality–assisted pedicle screw placement has also recently been described and demonstrated a high accuracy rate of 98%.[15]

Minimally invasive techniques have increased in popularity in the field of spine surgery.[16,17] These new techniques may improve patient outcomes and become a routine part in the spine surgeon's armamentarium.[17] However, these techniques have an important learning curve.[18,19] To reach proficiency, structured training with cadavers, mentorship with senior colleagues, and practice are required to minimize this learning period. Simulation surgery has never been more pertinent in the current context of spine surgery and the change in the postgraduate educational environment.

Surgical simulation may also be of use for the practicing surgeon. Simulated surgery may help increase surgeon performance in the operating room. This can be translated into operating room efficiency, decreased technical errors, and decreasing operating time.[20] As a parallel to professional athletes, preoperative virtual simulation "warm-ups" may increase precision while reducing errors.[21] This may ultimately translate to increased patient safety and outcomes, which could lead to notable cost saving for the healthcare system.

Clearly, to improve proficiency and decrease patient complications, there has never been as strong a rationale for simulated training. Various modalities have been described, and each has its advantages and disadvantages.

Current Modalities for Simulated Training

Increased interest in the field of simulated training has led to the development of various simulation modalities. This increased usage led to additional study and validation of these simulators. This increased usage has consequently decreased the costs of these simulators so that training programs can now acquire them within their budgets. Cadaveric models, synthetic models, virtual reality, and mixed reality simulators have all been described. Each of these options has their own advantages and disadvantages for trainees, training programs, and staff (Table 1).

Cadaveric Models

Cadaver model simulation training is of particular interest because of the high fidelity of human tissues and the relationship with neurological and vascular structures. These are distinct advantages over synthetic or sawbone models. This fidelity allows learners to develop the haptics of surgery and experience an environment similar to real surgery.

Furthermore, a recent study by Calio et al[22] showed that a cadaveric training model improves resident satisfaction and confidence. Sixty-five percent of the residents strongly agreed that they were satisfied with the benefits of this training model, and 59% of the residents felt an increased level of confidence. However, whether this simulation training leads to decreased complications and improved outcomes once these trainees go on to independent practice remains to be evaluated.[22,23]

There are disadvantages that need to be considered when considering cadaveric models for training. Although there is a high fidelity of soft tissues, rapid deterioration of the quality of tissues can be a concern, especially with fresh cadavers.[23] Furthermore, the costs related to this model can be substantial.[24] This is not only due to the tissue degradation of the cadavers but also its limited usage and the costs of maintaining a wet laboratory including procurement.[5,24] Programs may thus only support a limited amount of training sessions. Fellowship and residency programs need to consider these disadvantages when considering cadaveric simulation.

Table 1. Summary of Simulation Modalities (Advantages and Disadvantages)

Modalities	Advantages	Disadvantages
Cadaver model	High fidelity Haptic feedback Proximity to neurological structures High resident satisfaction Psychomotor skills development	Cost Wet-laboratory requirement One time usage Tissue decay
Synthetic models	Haptic feedback Low cost Ease of availability Low maintenance Can also reproduce dural tears	Low fidelity Lack of soft tissues One time usage depending on the model
Virtual reality	Low maintenance Reusable Ease of access Limited laboratory space required 3D vision of anatomy	Lack of haptic feedback Low fidelity High expense
Mixed reality	Moderate fidelity Haptic feedback Can simulate critical structures (dura) 3D vision of anatomy Reusable Limited laboratory space required	High expense Limited models available

Synthetic Models

Synthetic models (Figure 1) have also been used and described to simulate surgery.[25] Plastic or other synthetic bone models, such as sawbones, have typically been used because of the availability and low cost. However, realism of this model and the lack of critical soft tissues are some of its main limitations.[24,26]

Recent work by Coehlo et al[27] provided a new synthetic spine physical model that simulates not only bone structures but also the real spine with skin, muscle, ligaments, dura, and cerebrospinal fluid (CSF). This allows for a more realistic simulation and palliates some of the issues with conventional models that often lack soft tissues or other critical structures. This type of model allows for a greater variety of surgical simulation related to the spine, such as pedicle screw placement, laminectomy, and surgical approaches. Furthermore, 94% of the experienced surgeons judged this model useful for developing skills for trainees.

Several advantages with this new synthetic spine model need to be highlighted. It provides more realism and fidelity compared with previous generations of synthetic models but requires less maintenance and preparation compared with cadaveric models. The presence of CSF permits simulation of emergency situations, such as iatrogenic durotomy and repair, which are difficult to accurately reproduce. One disadvantage is that it is a new model with little track record and experience among training programs. Furthermore, whether using this model improves clinical outcomes and decreases complications remains to be evaluated.

Virtual Reality Simulators

Virtual reality is the creation of a 3D environment based on computer software that allows us to replicate the anatomy and surgical environment (Figure 2). Virtual reality simulation has been used in other fields and has now been introduced to spine surgery.[28] The advantage of this type of simulation is that it allows trainees to visualize anatomy in 3D and practice surgical techniques without needing large wet laboratories. These simulators can also be repeatedly used by trainees and can be easily available once acquired. Furthermore, recent studies have shown that trainees who have been exposed to this type of simulation outperform methods such as didactic courses and reading for technical errors.[29]

However, whether this type of training translates to improved outcomes remains to be investigated. Moreover, training programs need to evaluate the costs of acquiring these simulators and the upkeep necessary for maintenance and software updates. Furthermore, the lack of haptic feedback in these virtual simulators is a potential barrier to skills development into the real world.

Mixed reality simulators may offer the best of both synthetic models and virtual reality simulators by combining the advantages of virtual reality with the haptics of a physical model.[27] These simulators allow trainees to have haptic feedback while allowing the visualization of the surgical anatomy in 3D. Recent evidence has supported the educational benefits of this mixed reality simulator, especially in pedicle screw placement.[27,29,30]

Augmented reality is the projection of virtual reality onto the physical world. 3D images can be superimposed on a real physical object. As an example, a spine surgeon could wear a headset that projects images onto physical objects. Recent evidence has shown that this area of simulation has grown in interest.[31] Pedicle screw placement, cervical spine, and deformity surgery have been described using augmented reality. Although in its infancy, this modality has potential to improve surgical training.

To summarize, the advent of improved synthetic models coupled with virtual reality has created a learning environment that is closer to reality than ever before. However, it is relatively new and whether it can improve clinical outcomes remains to be defined.

Simulation of Specific Surgical Techniques in Spine Surgery

Pedicle Screw Placement

Pedicle screw is a widespread surgical technique that provides three column fixations of the spine. Previous studies evaluating the learning curve of these techniques describe a minimum of 80 screws or approximately 25 cases to be competent.[10] However, a recent study looking into simulation training has shown its effectiveness in accelerating skills acquisition in pedicle screw placement.

Cadaver training models can be an option for training programs with the necessary laboratories and equipment. This type of training has been studied in trainees for thoracic pedicle screw placement. Tortolani et al[32] showed that pedicle screw placement training can be effective using a cadaver model. Improvement in accuracy was noted between two training sets, with trainees improving in accuracy from 44% to 58%. Notably, an experienced surgeon had an accuracy of 82% in this study. The authors described that the advantages of cadaver-based training are its fidelity for haptics and anatomical relationships, and it therefore translates better into a clinical setting.

Virtual reality simulators with haptic feedback have also been evaluated in training learners for pedicle screw placement.[33] In their study, Hou et al showed that virtual training with haptic feedback can improve screw placement accuracy when compared with conventional learning methods. This study first used a virtual training module, and pedicle screw placement was then practiced on a cadaver model. Accuracy was then verified by a CT scan. The virtual training group had a decreased screw penetration (30% versus 7.1%) and an improved acceptable screw rate (100% versus 92.8%). This also provides the rationale that virtual training has the potential to translate in a clinical setting.

Gardeck et al[30] recently conducted a study on simulation training for thoracolumbar spine pedicle screw placement using a mixed virtual reality and synthetic spine model. In their study, 15 orthopaedic and neurosurgical trainees were enrolled in a standardized curriculum using standardized simulation training. Physician Performance Diagnostic Inventory Scale (PPDIS) and Objective Structured Assessment of Technical Skills Scale (OSATS) were evaluated for all participants in each of the two sessions. Notable improvements in both PPDIS and OSATS were noted between two sessions. Furthermore, notable differences in screw placement time were also noted after the second training session. However, pedicle screw accuracy was not noted to be improved. This is one of the first studies to provide a standardized simulation training module for pedicle screw placement.

Figure 1

Photograph showing a synthetic model for simulation training in spine surgery. This model was used to practice pedicle screw placement. Fluoroscopy guidance or even navigation could potentially be practiced using this model (Photograph courtesy of Dr Jean-Christophe Leveque and Dr Rajiv Sethi).

Cervical Spine Surgery

Simulation training may be of benefit in cervical spine surgery because common techniques such as screw

Figure 2

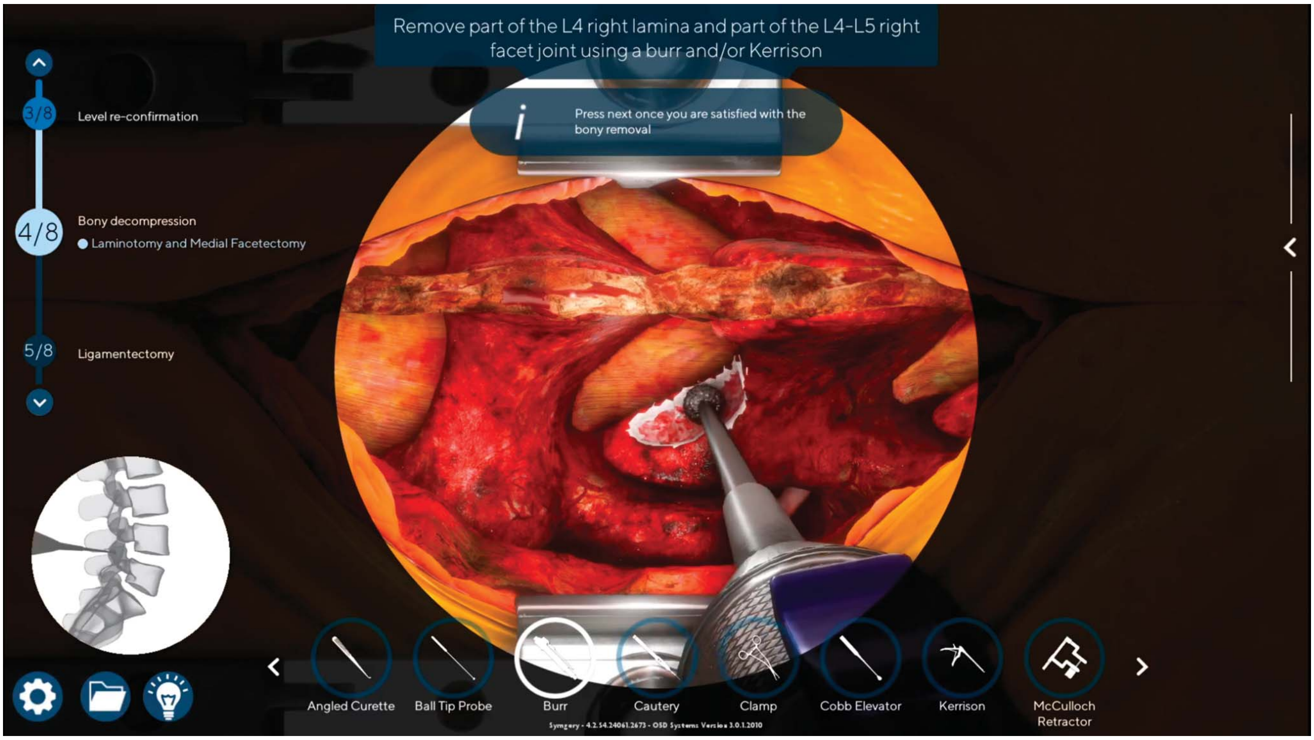

Figure showing the virtual reality simulator interface (T-Sym reproduced with permission). This visual field allows for simulation of an actual surgical technique. Combined with haptic feedback tools, this allows for greater surgical simulation reality.

placement need to be mastered to achieve safe fixation. Cervical pedicle screws may allow for a greater biomechanical stability. However, it is technically challenging and requires excellent three-dimensional grasp of the complex cervical anatomy. Ludwig et al[34] investigated the accuracy of transpedicular screw fixation and showed a high rate of critical breaches with using anatomic landmarks (65.5%) and laminoforaminotomies (39.6%).

Hou et al[35] showed that virtual reality training may improve resident trainee cervical pedicle screw placement compared with conventional teaching methods. In their study, a virtual reality simulation training system that includes haptic feedback was evaluated on novice residents. After simulation training, these trainees went onto screw placement on cadaver models and their accuracy was evaluated based on CT scans of the cadavers. This group was compared with a control subject group exposed to training methods. The group exposed to virtual simulation showed markedly less screw penetration (10% compared with 62.5%). Furthermore, the average screw penetration was markedly less with the virtual group compared with standard training. This supports the rationale for simulation training in cervical spine pedicle screw placement.

Gottschalk et al[36] studied simulation training for lateral mass cervical screw placement in orthopaedic trainees in a randomized trial. Trainees were divided into three groups: a control subject group exposed to cadaver training without 3D navigation, a cadaver group with 3D navigation training, and a sawbones group with 3D navigation training. Trainees exposed to 3D navigation showed superior accuracy in lateral mass screw placement compared with those in the control subject group. Moreover, the control subject group did not show notable improvement from baseline evaluations. This would suggest that simulation training is useful, and the adjunct of a virtual 3D component may be of additional benefit.

Harrop et al[37] studied simulation training in cervical spine laminectomy. In this study, the authors evaluated a combination of a structured didactic course with training on a mixed reality simulator. This simulator included a synthetic model with haptic feedback and virtual representation of the spine with navigation dedicated for the cervical spine. OSATS scores markedly increased in trainees exposed to simulation training.

Laminectomy

Mastery of laminectomy is a critical technique for the modern spine surgeon. However, few studies have evaluated simulation training in laminectomy. Recent studies have aimed to fill this knowledge gap and have shown potential advantages to simulated training.

Boody et al[38] conducted a randomized trial to evaluate the effectiveness of a simulation training curriculum using a sawbone model of the lumbar spine. This synthetic model also included a small balloon partially filled with fluid to simulate the dural sac. Twenty trainees were randomized to two different training groups. The intervention group was exposed to 40 minutes of combined training on the dedicated synthetic spine module. The control subject group was allowed to read 40 minutes on lumbar spine decompressions using standard textbooks. Trainees were evaluated using OSATS and PPDIS. The results of their study demonstrated notable improvement in the pretest and posttest OSATS and PPDIS scores. Furthermore, all participants in the intervention group had favorable reviews for this type of simulation training. Moreover, sawbones are cost-friendly with 240$ required per model. This can be a rationale to use this type of training balancing both educational benefit and low costs.

However, several disadvantages need to be considered. First, simulation training has only recently been studied and requires standardization in both the evaluation of trainees and the training modules themselves. Furthermore, whether the improvements seen in simulation correlated with improved outcomes clinically remains to be evaluated. Finally, high fidelity models and virtual reality simulators have not been evaluated for laminectomy training.

Minimally Invasive Surgery

Minimally invasive spine surgery (MIS) has garnered widespread interest because of its potential for rapid postoperative recovery with lower surgical site morbidity. However, these techniques may have a steeper learning curve.[39] Although it may not be expected of a trainee to acquire these skills through residency training, especially in the context of restricted work hours, simulated training may be beneficial to the practicing surgeon or fellow to accelerate the acquisition of these MIS skills and decrease complications.[18]

Walker et al[40] is one of the first reports describing simulation training for MIS spine surgery. In their study, a simulation model consisting of a cadaveric deer spine combined with a Plexiglas apparatus was used to simulate MIS spine surgery. Self-assessments of residents demonstrated increased confidence ratings for both laminectomy and pedicle screw placement using this type of simulation. The drawbacks of this model are the lack of fidelity of a cadaveric deer spine and the lack of objective evaluation criteria for resident performance. Despite these limitations, this study demonstrates the feasibility of simulation training and the potential benefits to trainees.

Buchanan et al[41] described simulated training in dural tear repair using a cadaver model. In their study, they described a simulated dural tear during MIS. CSF was reconstituted using saline pressurization in the dura to simulate normal anatomy. Notable reduction in closure time was noted between first and final attempts for residents included in the study.

More recently, Chitale et al[42] evaluated the benefit of simulated training for minimally invasive pedicle screw placement. Using a mixed reality simulator composed of a synthetic model with 3D navigation, residents simulated pedicle screw placement. The results of this study showed increased accuracy of pedicle screw placement with less usage of fluoroscopy and time under fluoroscopy. The disadvantage with this simulation program is the lack of haptic feedback, and no physical pedicle screws were placed in the synthetic model. Despite these limitations, this simulator may serve as additional training complimenting surgical experience.

Fuerst et al[43] evaluated a high-fidelity simulator for MIS with the aim of identifying specific simulation–based objective assessments for performance. In this study, a patient phantom with synthetic structures validated against human specimens was used. An optical tracking system was used to orient and determine the instrument position. Simulated projections of both instruments and reconstructions of the spine are visualized on a screen allowing additional 3D visualization. Placement of pedicle screws was compared between an experienced surgeon and 10 inexperienced operators. Discriminators of expertise were duration, number of instrument movements, and instrument movement distance. These were all parameters that distinguished between a novice and experienced operator. These elements can contribute to the evaluation of skills progression in MIS simulated training.

Simulation Training in Robotics and Navigation

As previously described, navigation and robotics have the potential to improve accuracy of pedicle screw placement and decrease complications. Navigation training has been described in recent studies. Gardeck et al[30] showed in their study that navigation training can improve proficiency in pedicle screw placement.

Moreover, Sundar et al[44] demonstrated that using navigation in spinal fixation training reduces the number of misplaced screws in a laboratory setting. Similarly, Kaliya-Perumal et al[45] demonstrated in a survey of trainees that most believed that navigation was beneficial for training of pedicle screw placement. However, 35% of these residents were unable to identify anatomic landmarks for pedicle screw placement. Nevertheless, training in navigation clearly has its benefits in addition to learning the anatomical landmarks for screw placement.

Robotics is a new technology that is beginning to show its potential in spine surgery. As such, the learning curve remains to be clearly defined. In a study of robotic pedicle screw placement in an academic setting, Urakov et al[46] did not demonstrate any difference in pedicle screw placement efficiency between staff, fellows, and residents. This presents not only the potential learning curve but also the novelty of such a technique. However, robotics may immediately help younger surgeons by offering them preoperative planning software.[47] This allows for multiple plans to be drawn out and discussed with more senior colleagues before surgery itself. This may accelerate the cognitive learning curve for junior surgeons.

Because of its relative novelty, simulation training for robotic spine surgery remains in its infancy. Current training for robotics is resource intensive because of the need for a cadaveric laboratory with available robotic machines. The development of simulators is currently underway, and identifying the skills, goals, and stakeholder needs is the first important step toward a feasible and useful simulator for robotic surgery.[48]

Challenges of Surgical Simulation

Several issues and challenges need to be considered in the adoption of surgical simulation in spine training. First, the complex issue of correlation between clinical outcomes and simulation training may be a barrier to widespread adoption. No clinical study has shown markedly improved outcomes with previous simulated training. For educational programs, it may be difficult to justifying the costs related to these technologies without clear evidence in improving patient care. However, it may be impossible to avoid simulation as an educational tool because work hours become restricted and clinical exposure limited.

The costs related to acquiring equipment and implementing a structured curriculum also need to be considered. Gasco et al[49] evaluated a curriculum for simulated spine surgery in a neurosurgical program. They evaluated the initial costs to be 341,978$ and annual expenses of 27,876$. However, their curriculum is comprehensive, which included 68 core exercises with 30 individual simulations for only six residents. Furthermore, their curriculum included not only virtual reality simulations but also mixed reality with haptic feedback computerized training in addition to cadaveric dissection laboratories. Programs will thus need to evaluate the educational needs and use the appropriate economic resources.

Training programs and institutions will need to carefully analyze the educational needs and their own resources. Cadaver simulation training may not be ideal for all programs because access to wet laboratories can be an obstacle. Therefore, institutions may consider investing into synthetic or mixed reality simulators as an alternative if these resources are not available.

Choosing the appropriate evaluation metrics can also pose a conundrum for training programs. As none of the current evaluation tools correlate with clinical outcome scores, using objective evaluation scales are imperative. OSATS, PPDIS, and global rating scales have all been described as evaluation methods.[24] Although these measuring scales allow for objective evaluations, they need to be adapted for each specific technical procedure.

Accuracy, time to task completion, and economy of movement may also be objective parameters that can be tracked for performance improvement and procedural mastery. These metrics can be important, especially for the practicing physician who is out of residency training. Thus, choosing the right evaluation tools need to be adapted to the specific needs of the learner and needs to be quantifiable to track progression.

Summary

Simulation training in spine surgery offers a complementary form of surgical experience that is gaining in importance and acceptance because resident work hours are restricted. Cadaveric, synthetic, virtual reality, and mixed reality simulators have been described. Various procedures have been described from pedicle screw placement to minimally invasive techniques. As technology continues to improve, the combination of high-fidelity spine models coupled with 3D virtual representation and navigation enhances the trainees' surgical experience outside of teaching methods.

Early results have shown an acceptance of these simulation methods by trainees and have also shown the potential for improvement in surgical skills. Standardized performance measurement tools have been developed to track progression and objective evaluations. This will ultimately help not only trainees but also practicing surgeons mastering surgical techniques that have a steep learning curve.

Training programs must evaluate their own institutional needs and assess their resources when deciding to invest in surgical simulation. Costs and laboratory availability can be potential obstacles in access to simulation training. Furthermore, convincing administrators of the cost-benefit of acquiring the platform for simulated training may also be a challenge because of the lack of correlation between training and clinical outcomes. Future work must aim to define the relationship between surgical simulation training and patient outcomes. Furthermore, as technology continues to evolve, the costs of virtual and mixed reality simulators may decrease and become accessible to most programs.

We recommend that residency programs consider simulation training based on their needs and institutional infrastructure. We also recommend that practicing surgeons consider implementing surgical simulation as part of their continued medical education. The body of evidence and the growing number of simulators support the implementation of simulation training in spine surgery.

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