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Published in:
SPINE JOURNAL

DOI:
[10.1016/j.spinee.2021.03.018](https://doi.org/10.1016/j.spinee.2021.03.018)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2021

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Ghaednia, H., Fourman, M. S., Lans, A., Detels, K., Dijkstra, H., Lloyd, S., Sweeney, A., Oosterhoff, J. H. F., & Schwab, J. H. (2021). Augmented and virtual reality in spine surgery, current applications and future potentials. *SPINE JOURNAL*, 21(10), 1617-1625. <https://doi.org/10.1016/j.spinee.2021.03.018>

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Narrative Review

Focus: Artificial Intelligence and Machine Learning

Augmented and virtual reality in spine surgery, current applications and future potentials

Hamid Ghaednia, PhD^{a,b,*}, Mitchell S. Fourman, MD, MPhil^{a,b},
Amanda Lans, MD, MS^a, Kelsey Detels, BSc^c, Hidde Dijkstra, BSc^d,
Sophie Lloyd, BSc^c, Allison Sweeney, BSc^c, Jacobien H.F. Oosterhoff, MD^a,
Joseph H. Schwab, MD, MS^{a,b}

^a Spine Service, Department of Orthopaedic Surgery, Massachusetts General Hospital, Boston, MA, USA

^b Orthopaedic Oncology Service, Department of Orthopaedic Surgery, Massachusetts General Hospital, Boston, MA, USA

^c Department of Biomedical Engineering, Tufts University, Medford, MA, USA

^d Department of Orthopaedic Surgery, University Medical Centre Groningen, University of Groningen, The Netherlands

Received 15 March 2021; accepted 17 March 2021

ABSTRACT

BACKGROUND CONTEXT: The field of artificial intelligence (AI) is rapidly advancing, especially with recent improvements in deep learning (DL) techniques. Augmented (AR) and virtual reality (VR) are finding their place in healthcare, and spine surgery is no exception. The unique capabilities and advantages of AR and VR devices include their low cost, flexible integration with other technologies, user-friendly features and their application in navigation systems, which makes them beneficial across different aspects of spine surgery. Despite the use of AR for pedicle screw placement, targeted cervical foraminotomy, bone biopsy, osteotomy planning, and percutaneous intervention, the current applications of AR and VR in spine surgery remain limited.

PURPOSE: The primary goal of this study was to provide the spine surgeons and clinical researchers with the general information about the current applications, future potentials, and accessibility of AR and VR systems in spine surgery.

STUDY DESIGN/SETTING: We reviewed titles of more than 250 journal papers from google scholar and PubMed with search words: augmented reality, virtual reality, spine surgery, and orthopaedic, out of which 89 related papers were selected for abstract review. Finally, full text of 67 papers were analyzed and reviewed.

METHODS: The papers were divided into four groups: technological papers, applications in surgery, applications in spine education and training, and general application in orthopaedic. A team of two reviewers performed paper reviews and a thorough web search to ensure the most updated state of the art in each of four group is captured in the review.

RESULTS: In this review we discuss the current state of the art in AR and VR hardware, their preoperative applications and surgical applications in spine surgery. Finally, we discuss the future potentials of AR and VR and their integration with AI, robotic surgery, gaming, and wearables.

CONCLUSIONS: AR and VR are promising technologies that will soon become part of standard of care in spine surgery. © 2021 Published by Elsevier Inc.

Keywords:

Machine Learning; Mixed Reality; Augmented Reality; Virtual Reality; Spine Surgery; Artificial Intelligence

FDA device/drug status: Not applicable

Author disclosures: **HG:** Nothing to disclose. **MSF:** Nothing to disclose. **ML:** Nothing to disclose. **KD:** Nothing to disclose. **HD:** Nothing to disclose. **SL:** Nothing to disclose. **AS:** Nothing to disclose. **JHFO:** Nothing to disclose. **JHS:** Speaking and/or Teaching Arrangements: Stryker Spine (B).

*Corresponding author. 55 Fruit St. Yawkey 3, Spine Service, Department of Orthopaedic Surgery, Massachusetts General Hospital, Boston, MA, USA. Tel.: (617) 643-0355.

E-mail address: hghaednia@mgh.harvard.edu (H. Ghaednia).

Introduction

We are at an exciting point in history where artificial intelligence (AI), and in particular deep learning (DL), have facilitated the advancements of several already existing fields. Augmented reality (AR) and virtual reality (VR) are expected to benefit significantly from the advancements in AI. The unique capabilities of DL in object tracking and segmentation along with upscaling of video resolutions can reduce the computing power required for VR and AR systems, reduce hardware and software costs, enhance device performance, and enable new features. These capabilities have significantly increased the scope of AR applications in orthopaedic and spine surgery, leading to the first Food and Drug Administration approved AR assisted spine surgery in June 2020 [1].

With the increasing prevalence and interest in minimally invasive spine surgeries, the need for high quality and easy to use navigation systems has increased [2,3]. Current navigation methods usually expose patients and the clinical team to excessive radiation, increase surgery time and have a long learning curve. One of the main applications of VR and AR in the operating room (OR) is as a navigation tool. AR and VR systems integrated with an advanced imaging modality such as CT, X-ray, MRI or ultrasound images use computer vision techniques, image processing and DL to track, segment and create a link between images and patients. The applications of VR in the OR are more limited because it needs to be integrated with a robotic surgery module. AR, however, is easier to use in the OR and does not significantly change the surgical procedure.

The terms VR and AR were first described by Milgram and Kishino [4] in their definition of the “virtuality continuum”, Fig. 1. One of the most global definitions of VR is provided by Jonathan Steuer [5]: “A virtual reality is defined as a real or simulated environment in which a preceiver experiences telepresence”. VR is a completely immersive experience in which the subject is placed within a fully developed interactive virtual environment. The interaction between the subject and the virtual environment takes place using several sensors and controllers. In AR, virtual images and objects are overlaid on to the real environment. An example of AR would be projecting patient information into the clinicians’ view using AR glasses.

AR and VR have already shown benefits in several areas of healthcare, such as robotic surgery [6–8], laparoscopic

surgery [9], oral and maxillofacial surgery [10,11], tumor resection, liver resection [12], guided biopsy [13], rehabilitation [14,15], psychology, neurosurgery [16–18], and cancer management [19]. However, the applications of VR are mostly limited to outside of the OR, where there is no need for physical interaction between the surgeon and the patient [20]. Examples of these are: training and education [21,22], pain management of burn patients [23], distraction of cancer patients during chemotherapy infusion [24], remote robotic surgery [7], rehabilitation via VR [14], and VR gaming during radiation [15]. AR is not as limited as VR because it allows for physical interaction with the real world. AR is used both in the OR as an assistant to the surgeon [25] as well as outside of OR for remote mentoring [26], preoperative planning, patient education, and resident training.

There are several examples of AR utilization in orthopaedics [27–31]. Lonedo et al. [32] developed an AR solution to assist surgeons in distal locking screw procedures during intramedullary nail placement, and demonstrated that taking advantage of video guidance along with appropriate real-time visualizations improved both the speed and accuracy of the surgeon compared with current state of the art navigation tools. Participants achieved a 100% success rate in down-the positioning and a 93% success rate in distal locking using only 2 X-rays per 100 seconds compared with 25 images per 100 seconds without AR assistance. Hirayama et al. [33] examined the efficacy of PicoLinker smart glass on wire insertion surgery and demonstrated a reduction in both radiation and operative time. Their study group attributed this time reduction to the decreased time the surgeon spent looking away from the surgical field. Van Duren et al. [34] created a virtual overlay on fluoroscopic images during a simulated guide wire insertion for a dynamic hip screw. Their method showed an average root mean square error of 2 mm. In their series of experimental work Cho et al. [35–38] demonstrated the applications of AR for pelvic tumor resection. They evaluated the accuracy of the method through simulated bone tumors in a pig femur model. In a proof of principle Song [39] described a C-arm-based surgical data visualization using AR for pelvic fractures and vertebroplasty. Ogawa et al. [40] used the AR-HIP system on a smartphone for acetabular cup replacement. They assessed the accuracy of their AR system during 56 total hip replacement surgeries, and found it to be more accurate than conventional mechanical guides.

Fig. 1. Virtual continuum.

Preoperative planning is another application of AR in orthopaedics. Shen et al. [41] demonstrated a patient specific reconstruction plate design system using AR templating for pelvic and acetabular fracture. The effectiveness and efficacy of their approach was demonstrated qualitatively with 6 clinical cases, including postoperative evaluation. The time needed for implant templating was 10 minutes, and the preoperative implant preparation process took 1 hour (data loading, pelvis modeling, implant design and contouring). Interobserver variability was 0.63 mm. This new technique could lead to a reduction in both surgical invasiveness and operative time. A further study by Rahul et al. [42] showed the potential of merging CT and MRI images with patients for better anatomic details using the Virtual Augmented Surgical Intelligence system.

In this review we explain the current commercial and custom made AR and VR systems and their requirements, as well as provide a detailed discussion of the preoperative and surgical applications of AR and VR in spine surgery. Additionally, we discuss the potentials of AR and VR and their manifestations as surgical robots, artificial intelligence, serious gaming, and wearables.

Technologies

Both AR and VR systems consist of three main parts; the tracking system, the display, and the computation system. Tracking is achieved via external motion sensors or via machine vision. For VR systems the display is either a head mounted device that allows full immersion in a room where a virtual environment is projected on the walls. For AR systems the display can be a tablet, smartphone, a normal monitor or a head mounted device. The computation system is usually a regular computer. In general, these systems can be divided into two main groups: a fully self-contained system where all three components are incorporated into a single device, or multiple devices that communicate with each other. The head mounted displays are most commonly used for both AR and VR systems due to their ease of use. Another category of devices is the mixed reality (MR) glasses such as the Microsoft HoloLens (Redwood WA, USA) or the Magic Leap One. Unlike the AR devices, MR glasses allow the user to interact with virtual objects in his and/or her view.

Table shows several examples of currently available head mounted VR, AR, and MR hardware, their cost and requirements. The majority of VR devices are designed and used for gaming and usually require a PC to create the virtual environment. The HTC Vive Cosmos series (Taoyuan City, Taiwan) starting from \$699 provides a very good tracking system combined with a sharp display. The Oculus Quest 2 (Irvine, CA, USA) is a fully self-contained VR system that does not need external sensors for tracking. The Oculus Rift (Irvine, CA, USA) on the other hand provides better resolution and frame rate however requires an external PC for analysis. An Oculus Rift was integrated with

OsiriX stereo-3D in daVinci surgery to perform the first remote navigated robotic surgery in the world. The PlayStation VR (SONY Corp. Nihonbashi, Tokyo, Japan) is mainly used for gaming and needs the PlayStation console and the PlayStation camera to operate. Almost all head mounted AR and MR systems are self contained. The Epson Moverio series (Los Alamitos, CA, USA), Vuzix Blade (West Henrietta, NY, USA), and Google Glass (Menlo Park, CA, USA) all use projection to augment information and images on users' vision. These types of glasses are particularly suitable for healthcare and can be used in a surgical setting as they are lightweight, easy to use and can be comfortably worn for several hours. The MR glasses are the most complex and not only project a 3D model of the patient's spine at the surgery area, but allows the surgeon to move around virtual objects such as screws at the surgery site in order to verify the procedure before placing permanent screws. There are two commercially available MR glasses: Microsoft HoloLens and Magic Leap One. While the Microsoft HoloLens is more powerful, the Magic Leap has a significantly lower weight, permitting long term use. The Magic Leap achieved this by placing the processing module around the hip instead of on the head.

Another type of AR device uses an external screen to overlay information onto the real world. These systems use tablets and smartphones as a display device, and have led to the development of several custom made AR software products. Several examples of such devices can already be found in healthcare. Pokhrel et al. [43] proposed an AR method based on the volume subtraction technique to decrease cutting errors in knee replacement surgery. Abe et al. [3] introduced an AR device (VIPAR) for percutaneous vertebroplasty and evaluated the device in both simulated environments and via clinical evaluation in 5 patients, which showed significant improvement. Stetten et al. [44] demonstrated a combination of ultrasonographic images with AR and discussed how their technique could improve surgical navigation. In a series of works, Cho et al. [35,36] developed an AR system for tumor resection using a Microsoft Surface Pro tablet. They demonstrated that a tablet can be used to create a fully self contained AR device. In their system they use the tablet's camera and computing power to track a few markers and match the augmented information on the real image. In another study Beguri et al. [45] developed an AR visualization for surgical navigation without the need for infrared tracking markers. They developed a novel navigation system that combined a cone beam computed tomography capable C-arm with a RGB camera and reported a significant reduction in time, radiation and number of fluoroscopic images with the 3D AR navigation system compared with X-ray imaging. Bichlmeier et al. [46] proposed a new method called Virtual mirroring, which permits the user to interact with superimposed 3-D virtual data. In this method a little device can be held by the surgeon and the AR uses that device like a mirror to project the 3D virtual objects in that position.

Table

Head mounted commercial VR, AR, and MR devices

Name	Type (VR/AR/MR)	Description	Approximate cost (USD)	Requirements
HTC Vive Cosmos	VR	works with and without tracking sensors. Has two controllers to interact with the world. 2K resolution with 80 fps refresh rate.	\$699	Needs PC
HTC Vive Cosmos (Elite)	VR	In addition to HTC vive cosmos, this series include the light house tracking system and two tracking sensors. Has two controllers to interact with the world. 2K resolution with 80 fps refresh rate.	\$899	Needs PC
PlayStation VR	VR	Mostly for gaming with play station	\$350	Needs Play Station and Play Station Camera
Oculus Quest 2	VR	Does not need sensors works with up to 90 Hz refresh rate. Uses two controller to interact with the environment. It is a fully stand alone system and does not need wiring.	\$299	Does not need PC
Oculus Rift (S)	VR	Does not need sensors works with up to 80 Hz refresh rate. Better resolution compare to oculus Quest 2	\$399	Needs PC
Epson Moverio series	AR	projects information on both eyes	\$700-\$1200	Does not need PC
Vuzix Blade	AR	projects information ix both eyes	\$899	Does not need PC
Google glass enterprise (Edition 2)	AR	Projects information only on one eye.	\$1,000	Does not need PC
Microsoft Hololense	MR	A mixed reality glass that is a self-contained computer with wifi connectivity. It includes eye and head tracking with 2k display resolution.	\$3,500	Does not need PC
Magic Leap one	MR	A mixed reality glass that projects information on both eyes. The processor is a placed around the hip so the glass weight is very light.	\$2,295	Does not need PC

With all these advancements, some technological limitations continue to constrain the applications of VR and AR in healthcare. For example, one of the main issues with training surgeons via VR is the lack of physical sensation. There are several efforts for overcoming this limitation, for example the development of gloves that provide the sense of touch or tesla suits that simulate the physical forces on the body. However, the very high precision that is required for a surgeon is still lacking. Another example is the dizziness often noted by the wearer while using VR glasses, which can be improved with the development of better devices and environments. For VR the long term use of glasses during surgery and blocking the view of the surgical field is a big concern, and may be improved by developing better AR systems and user interfaces (displays). Although there are still several limitations in AR and VR utilization and plenty of room for improvement, this unique technology has already proven itself to be beneficial in several fields, including healthcare.

Preoperative planning and educational applications

The ability of AR and VR in providing better 3D visualization and to serve as a platform for technical repetition, makes them a great tool for preoperative planning and the training of young doctors [47,48]. The preoperative applications of AR and VR can be categorized into four main groups: 1) Student training, especially with respect to the details of human anatomy and surgical procedure exposure via placing the students in VR environment or using AR; 2) Improved preoperative planning, in particular for less experienced surgeons via better visualization of CT, MRI and ultrasound images; 3) Remote mentoring using a combination of VR and AR where the experienced geographically remote surgeon overlays suggestions on the trainee's view using an AR system; and 4) Patient education via better visualization.

In a proof of concept study Ponce et al. [26] showed real-time virtual assistants of a geographically remote surgeon to resident surgeons. In this method they used

the Virtual Interactive Presence (VIP) system during arthroscopic shoulder procedures to overlay suggestions of an attending surgeon in a separate room on a resident surgeon's view in the OR. In their study both the attending and resident surgeon preferred the VIP system, safety was not compromised and the surgery time was the same with and without the VIP system. In another work to depict the training potential of AR and VR, Van Duren et al. [34] simulated guide wire insertion during dynamic hip screw surgery. They developed a digital fluoroscopic imaging simulator using orthogonal cameras to track coloured markers attached to a guide wire, which created a virtual overlay on the fluoroscopic images of hip models (sawbones Vashon, WA, USA). They showed that the accuracy of the AR overlay for projecting tip apex distance was 0.4 mm. They also showed that the trainee's accuracy increased with increased repetition. Luciano et al. [49] evaluated the use of an AR 3D simulator with haptic feedback as a training tool for thoracic pedicle screw placement. They used real patient CT data to create a virtual thoracic spine. Then 51 fellows and residents performed drilling and placement of virtual pedicle screws. They observed a 15% mean score improvement in performance accuracy, with 50% reduction in standard deviation from practice to test. This suggests the benefit of AR for training lesser trained residents and surgeons.

Passaux [50] studied fully robotic and AR-assisted hepatic segmentectomy in 3 patients. A 3D virtual model created to plan the surgery was superimposed on surgical images in real time. All surgeries were successful and precise, and deviations from preoperative surgical plan were underestimated and occurred in approximately 20% of cases. The authors demonstrated that VR can help surgeons achieve more realistic views of patient anatomy and reduce postoperative adverse events. Kosterhon et al. [51] developed a system to create virtual resection planes and volumes in spinal osteotomies. They then exported 3D operative plans to an AR-based navigation system controlling a surgical microscope display. They found the AR system can assist the surgeon during resection.

Anatomy education is one of the most interesting applications of AR and VR. There are already several software programs being developed for this application [52]. Moro et al. [53] assessed the effectiveness of using VR, AR and tablets for digital learning of structural anatomy. In their study they randomly assigned 59 participants to these three groups to complete lessons on skull anatomy, after which they completed a knowledge assessment test. Even though they found no significant difference in the assessment score between the three groups, members of the AR and VR groups reported increased learner immersion and engagement. The drawbacks of VR and AR systems were headaches, dizziness, and blurred vision. In a recent work Chytas et al. [54] overviewed the implementation of AR in

anatomy education. Even though there are a limited number of studies in this field, seven to be exact, they encourage educators to include AR in their methods.

Surgical applications in spine

In spine surgery AR has been used for pedicle screw placement [2,31,55–61], targeted cervical foraminotomy [62], bone biopsy [13], Osteotomy planning [51] and percutaneous intervention [3,63].

Accurate placement of pedicle screws is both a prevailing issue and important to the strength and durability of the construct. This is especially the case for minimally invasive spine surgeries, where navigation is more challenging and the anatomy of the posterior spinal column is not available. Ma et al. [58] presented a novel AR-based surgical navigation system for pedicle screw placement. They used ultrasound to link 3D anatomic landmarks to the CT images. They then superimposed the surgical plan onto the patient *in situ*. In their study, Ma et. al. used K-wires instead of pedicle screws and compared their system to skin marker tracking where the relative deformations of the soft tissue affects the linking between markers and CT scans. Their ultrasound AR system showed a mean targeting error of 3.79 mm and mean angle errors of 4.51 deg compared with skin marker tracking with 5.18 mm and 5.89 deg for mean targeting and angle error respectively.

In a series of three studies Elmi Terander assessed the feasibility and accuracy of augmented reality surgical navigation (ARSN) for pedicle screw placement. In their works a surgical navigation system was installed in a hybrid OR where the table was connected to a motorized ceiling-mounted C-arm system for 2D-3D imaging. Four video cameras were used to track randomly placed markers on the subject. In their first work [56] two neurosurgeons placed 94 pedicle screws in the thoracic spine of four cadavers using ARSN. To assess placement accuracy four independent reviewers assessed the postoperative scans using Gertzebin grading. The ARSN showed 85% overall accuracy compared to 64% with freehand placement. They concluded that ARSN without fluoroscopy was superior to freehand thoracic pedicle screw placement. In their second work [55] they studied the same ARSN for minimally invasive thoracolumbar pedicle screws. Two neurosurgeons placed 66 Jamshidi needles on 2 cadavers and 18 cannulated pedicle screws on one cadaver in the thoracolumbar spine. They evaluated placement accuracy by measuring the position and angle of the needle compared with the planned path. They reported an average insertion time of 90 seconds per screw with an accuracy of 2.2 mm and an average angular deviation of 0.9 deg from the planned path. In their third study they assessed the accuracy of their ARSN system in a clinical trial for the placement of thoracic and lumbosacral pedicle screws. Their work included 20 unique surgeries in which one

orthopaedic spine surgeon placed 253 pedicle screws using the ARSN system without fluoroscopy. The overall accuracy was 94.1% with no severely misplaced screws and an average screw placement time of 5.2 minutes. This demonstrates the great potential of AR systems in the operating room during open or minimally invasive spine surgeries.

Later Burstorn et al. [2] built upon the work of Elmi Terander et al. [55–57] and evaluated the feasibility and accuracy of their radiation free ARSN system developed in [55–57] for pedicle cannulation on two pig cadavers. A total of 78 4–7 mm diameter pedicle screws were placed using Jamshidi needles (49) and a high-speed drill (29) without ionizing radiation during navigation. They reported 1.7mm accuracy at the entry point, 2.0 mm at the device tip, angular deviation of less than 2 deg and insertion time of 195 sec. The clinical accuracy was 97.4% compared to freehand insertion (89.3%) and robotic-assisted navigation (92.3%). In another proof of concept Molina et al. [60,61] investigated the accuracy of AR systems for pedicle screw placement. In their work a total of 120 pedicle screws were placed in 5 cadaveric male torsos from T6 to L5. Two independent neuroradiologists assessed the Gertzbein scale and its combination with the Heary classification (Heary-Gertzbein scale) using postprocedural CT scans. Both scales showed the benefits of the AR navigation system compared to freehand placement, computer navigated and robotic assisted pedicle insertion. Gibby et al. [64] also investigated the utilization of AR for pedicle screw placement. They used microsoft hololens on the lumbar model without real time fluoroscopic guidance. To superimpose virtual trajectories on the samples they used preoperative CTs. Another benefit of AR-based navigation systems is the reduced radiation dose during spine surgery. Edström et al. [59] found reduction in radiation exposure during AR surgical

navigation compared to literature. They measured radiation exposure during the placement of pedicle screws in a hybrid operating room in 20 patients using real-time active personnel dosimeters. They reported significantly lower occupational doses compared with values reported in the literature.

AR has also shown potential in percutaneous vertebroplasty. Abe et al. [3] introduced a head mounted AR guidance system called virtual protractor with augmented reality (VIPAR) to visualize needle trajectory during vertebroplasty. They used a tracking camera and skin markers to link the needle trajectory path and the patient's body. They evaluated their method on 40 spine phantom trials and 5 patients. In their phantom trials they achieved an angular deviation of 0.96 deg from the planned trajectory. In their clinical evaluation 5 patients with osteoporotic vertebral fractures underwent VIPAR. Postoperative evaluation via CT showed average errors of 2.09 deg and 1.98 deg in the axial and sagittal planes, respectively. In another application of AR in minimally invasive spine surgery, Yamamoto et al. [62] used AR for minimally invasive keyhole surgery in both transvertebral anterior cervical foraminotomy and posterior cervical laminoforaminotomy. They performed O-arm imaging to develop an AR navigation system. Both surgeries were successful and patients were asymptomatic for an average of 20 months after surgery.

Conclusion, future directions and potentials

Several challenges in AR and VR still exist [28]. Head mounted devices that are the preferred hardware for use by surgeons cause headaches, dizziness and discomfort. The learning curves of AR and VR systems is high. Current VR systems cannot effectively simulate physical touch, which is of immense importance to surgeons. Skin marker tracking

Fig. 2. Merging of AR and VR with other technologies.

systems suffer from the relative displacement and/or deformation of soft tissue with respect to bones. However, almost all of these limitations can be solved through further technologic advancement and better collaboration between engineers and clinicians.

Even though AR and VR technologies still suffer from several limitations, with their unique capabilities, low cost, and flexibilities in integrating with other technologies, there is no doubt that the future of AR and VR in different areas of spine surgery is bright [11,65–67]. It is worth noting that AR and VR in healthcare are ways of providing information to the clinician and/or surgeon, students and trainees, or patient and have the capability to work as a link between the surgeon and an operative module such as robots. Therefore, AR and VR are naturally integrated with several different technologies in healthcare, (Fig. 2) and advancement in each of technologies can create new potentials and applications for AR in healthcare.

Fig. 2 shows some examples of these potential integrations. Gaming is the leading technology for AR and VR that can be used in healthcare for patient and student education, and pain distraction for patients. The combination of AI, wearable sensors, and gaming with AR and VR could enable the development of remote physical rehabilitation environments where the physician interacts and monitors the patient in a virtual environment. Integration of robot-assisted navigation systems with AI and AR can yield user friendly, fast and precise navigation systems. AI, wearables and AR can be combined to provide surgeons with live feedback during surgery. Merging AI, AR and VR can advance telementoring and its integration with wearables, and AI and surgical robotics can permit remote and semi-automatic surgeries.

AR is about to enter all aspects of orthopaedics, and it is conceivable that within a few years surgeons will be wearing AR-glasses during patient consultation, rehabilitation, training and surgery. The new generation of spine surgeons will be raised with intensive training in AR and VR. Spine surgery as a leading field in orthopaedics should be ready and willing to adopt these new technologies. With collaborations between clinicians, engineers, and game designers we will be able to bring all these fields together to profoundly improve all components of spine surgery within the next decade.

Acknowledgment

The authors report no funding sources or commercial interest in any product mentioned or concept discussed in this study.

Declarations of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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